DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2016/11

Geochronology of the Skjoldungen Alkaline province, South-East Greenland

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DANISH MINISTRY OF ENERGY,UTILITIES AND CLIMATE

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Contents

Introduction

This geochronological report is based on samples that were collected during field work in 2011 and 2012 in the Skjoldungen region between c. 63 and 63º40´N in South East Greenland. The work was carried out within the framework of the "SEGMENT" project – a joint project between the National Geological Survey of Denmark and Greenland and The Ministry of Mineral Resources (MMR) in Greenland. The overall target of the SEGMENT project was to assess the mineral potential of South East Greenland through new field work and to do follow-up scientific research in the area. A number of reports (Klausen and Kokfelt, 2014), BSc and M.Sc. theses (Greeff, 2012; Grobbelaar, 2012; Árting, 2013; Tusch, 2013; Maarupgaard, 2015; Geldenhuys, 2015) and international research papers (Kolb et al. 2013; Bagas et al. 2013; Berger et al. 2014; Thrane and Keulen, 2015) have come out covering various geological aspects of the Skjoldungen Alkaline Province, with more to come.

This report is the first of a series of GEUS reports that presents geochronological data resulting from the SEGMENT project, with the specific focus on the Skjoldungen Alkaline Province (SAP). Subsequent geochronological GEUS reports will address the larger Skjoldungen area (c. 62º30´N to 64ºN) and Tasiilaq area (c. 64 to 67ºN), respectively. The SAP, situated at c. 63º30´N in South East Greenland, is part of the Archaean North Atlantic Craton (Figure 1). The SAP is worldwide a rare occurrence of Archaean alkaline rocks that was relatively sparsely studied prior to this project initiative (Nielsen and Rosing, 1990; Blichert-Toft, 1995; Thomsen, 1998). The province constitutes a number of mildly alkaline intrusions of mafic-ultramafic, intermediate and evolved compositions, as well as a late stage of strongly alkaline character, the nephelinitic-carbonatitic Singertât Complex (Nielsen and Rosing, 1990). The original geological mapping of the Skjoldungen area was done by GGU, mainly at a reconnaissance scale, in the late 1980's and early 1990's, resulting in a 1:500 000 scale geological map compiled by Escher (1990). A number of considerable more detailed field maps by Troels Nielsen and Minik Rosing also constituted a valuable map basis for the recent field work (unpublished field maps in the GEUS map archive).

The overall goals of the renewed work in the Skjoldungen area were to develop a more detailed understanding of the petrogenesis of the SAP, as well as evaluating the economic potential of the area. This was done through detailed field work within selected key areas, including (but not restricted to) the following intrusive centres: Vend Om Gabbro, Halvdans Fjord Gabbro, Hermods Vig Diorite 1 and 2, the Sfinksen, Tværdalen and Thrymheim areas, and Ruinnæsset Intrusion (Figure 1). From a research perspective, some of the specific key objectives set out included resolving the time frame for the emplacement of the SAP, as well as characterising the geological evolution and the geotectonic setting of the province. To this end we here report detailed zircon U-Pb data from 47 samples of felsic to intermediate intrusive SAP related rocks that enable us to address the defined research topics quantitatively. Included are also a few samples of basement gneisses from the same area, serving as a reference for the local crust signature, but regional age data on gneiss samples are otherwise presented in the second volume on the geochronology of the larger Skjoldungen area (Næraa et al. 2016). Hf isotope analyses on zircon and whole rock samples have also been undertaken on a subset of SAP samples and will be presented elsewhere (Kokfelt et al. 2016).

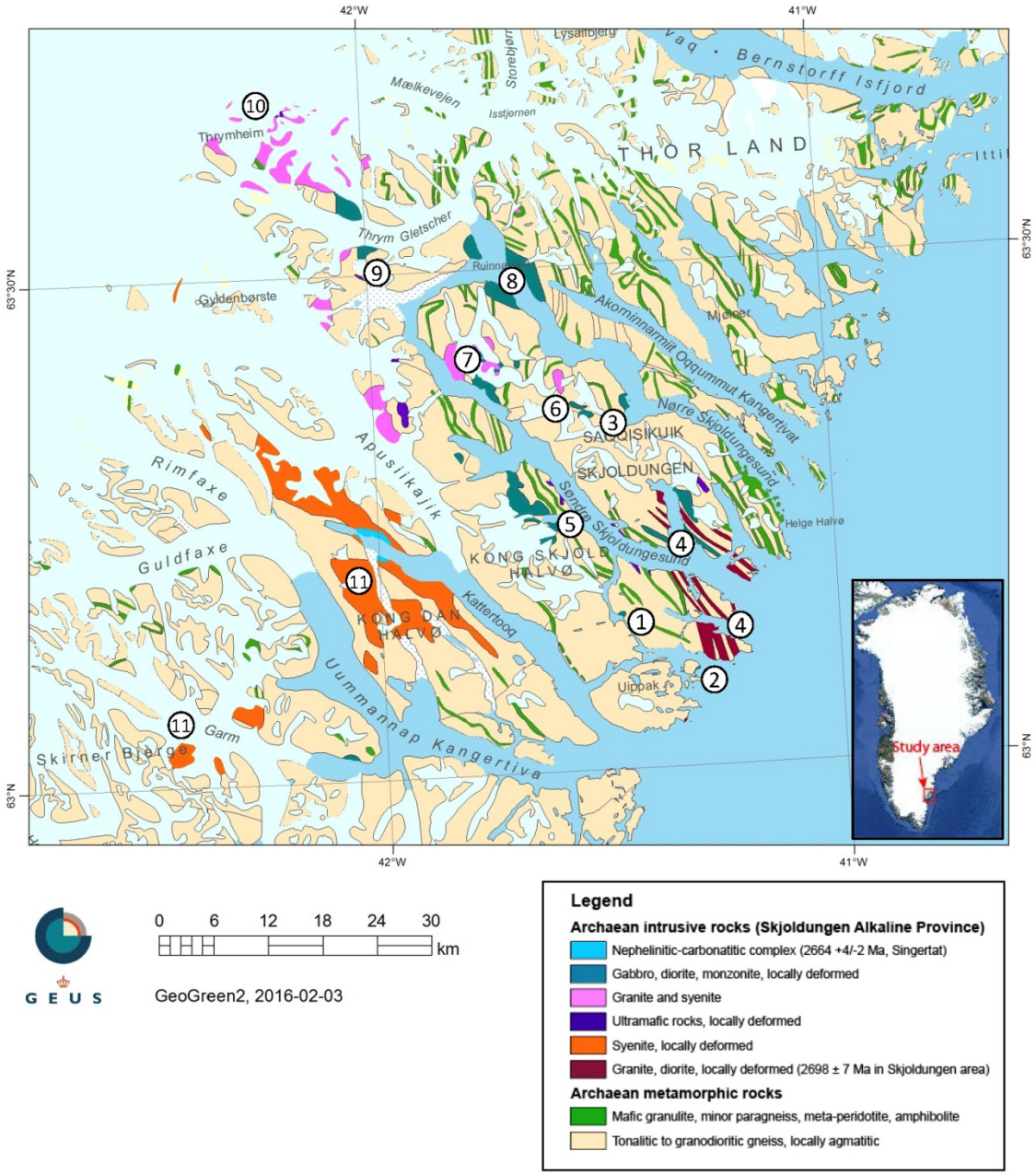

Figure 1. *Geological map of the Skjoldungen Alkaline Province (modified from Escher, 1990). Encircled numbers (1-11) relate to the investigated areas listed according to the order of appearance in the report: (1) Vend Om intrusion, (2) Iglermiut, (3) Hermods Vig and Njords Gletscher, (4) Halvdans Fjord, Anarnitsoq Island and Kong Skjold Halvø, (5) Stærkodder Vig, (6) Central Skjoldungen Island, (7) Sfinksen area, (8) Ruinnæsset, (9) Tværdalen, (10) Thrymheim ('nunatak') area, (11) Kong Dan Halvø and Skirner Bjerge.*

Analytical methods

Zircon separation

Zircon analyses were conducted at the Department of Petrology and Economic Geology, Geological Survey of Denmark and Greenland (GEUS). Hand-hammered chips from the rock samples were crushed directly in a tungsten-carbide disc mill. The crushed material was poured onto a Wilfley shaking table where the heavy mineral grains were separated. The heavy mineral fraction was transferred to disposable plastic Petri dishes using ethanol, and magnetic minerals were removed using a hand magnet. Zircon grains were subsequently hand-picked from the final heavy mineral concentrate in the Petri dish. The hand-picked zircon grains were cast into epoxy and polished to expose a central cross-section of each grain. The mount was documented prior to ablation using backscattered electron imaging in a scanning electron microscope. The mount was subsequently cleaned in an ultrasonic bath with propanol, and then loaded into the sample cell of the laser ablation system for age dating.

Analyses by LA-ICPMS

All U–Pb age data were acquired by laser ablation - single collector - magnetic sector field - inductively coupled plasma - mass spectrometry (LA-SF-ICP-MS) employing a Thermo Finnigan Element2 mass spectrometer coupled to a New Wave Research UP213 frequency-quintupled solid state Nd:YAG laser system, employing a two-volume cell technology. The principle setup is very similar to described by Frei and Gerdes (2009) and is described as follows. The laser was operated at a repetition rate of 10 Hz and nominal energy output of 55%, corresponding to a laser fluency of c. 8 J cm^{-2}. All data were acquired with a single spot analysis on each individual zircon grain with a beam diameter of 30 µm and a crater depth of approximately 15–20 µm. For the spot diameter of 30 µm and ablation times of 30 s the amount of ablated material approximates 200–300 ng. The ablated material was analysed on an Element2 (Thermo Finnigan, Bremen) single-collector, double focussing, magnetic sector-field ICP-MS with a fast field regulator for increased scanning speed. The mass spectrometer was equipped with a Fassel type quartz torch shielded with a grounded Pt electrode and a quartz bonnet. The total acquisition time for each analysis was 60 s, with the first 30 s used to measure the gas blank. The instrument was tuned to give large, stable signals for the ^{206}Pb and ^{238}U peaks, low background count rates (typically around 150 counts per second for ^{207}Pb) and low oxide production rates ($^{238}U^{16}O/^{238}U$ generally below 0.5 %). ^{202}Hg, $^{204}(Pb + Hg)$, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th and ^{238}U intensities were determined through peak jumping using electrostatic scanning in low resolution mode and with the magnet resting at ^{202}Hg. Each peak was determined at four slightly different masses and integrated sampling and a settling time of 1 ms for each isotope. Mass ^{202}Hg was measured to monitor the ^{204}Hg interference on ^{204}Pb where the $^{202}Hg/^{204}Hg \equiv 4.36$, which can be used to correct significant common Pb contributions using the model by Stacey and Kramers (1975). $^{207}Pb/^{235}U$ was calculated from the $^{207}Pb/^{206}Pb$ and $^{206}Pb/^{238}U$ assuming $^{238}U/^{235}U \equiv 137.88$. The elemental fractionation induced by the laser ablation and the instrumental

mass bias on measured isotopic ratios were corrected through standard-sample bracketing using the GJ-1 zircon (Jackson et al., 2004). Samples were analysed in sequences where three standards bracket each set of ten samples. The raw data were corrected for instrumental mass bias and laser-induced U-Pb fractionation through normalization to the GJ-1 zircon using in-house data reduction software. All isotope data were plotted and evaluated using ISOPLOT/EX 3.71 (Ludwig, 2008). Model age calculation and error propagation follow Sambridge and Lambert (1997). Long-term external reproducibility was monitored by repeated analyses of the Plešovice zircon standard (Sláma et al., 2008), yielding an average $^{238}U/^{206}Pb$ age of 339.4 ± 1.5 Ma (2σ) (n = 351 zircons, MSWD = 0.44), which is in perfect agreement with reported value by ID-TIMS of 338 ± 1 Ma (Aftalion et al., 1989).

After correcting the data for the effects of mass bias fractionation and Hg-interference a filtering of the data was applied by which analyses with 2σ errors > 10% (abs) for the $^{206}Pb/^{238}U$ ratio were removed from the data set. In some cases a correction for common Pb (cPb) was applied, but unless otherwise stated, these corrected data were not included in the plots or used to base any ages on. Throughout this report the data are displayed in Tera-Wasserberg diagrams, and in some cases also Concordia-Wetherill plots. Plotting of the U-Pb diagrams and calculation of ages and their associated uncertainties from either weighted means, Concordia intercepts, or from unmixing of multiple age components were done in an off-line Excel sheet using Isoplot/Ex version 4.15 (Ludwig, 2008). Unless otherwise stated, all reported ages are $^{207}Pb/^{206}Pb$ ages and the reported errors are internal errors at the 2σ level or 95% confidence interval. The Pb/Pb ages have been preferred to the ages that can be derived from the $^{238}U/^{206}Pb$ system as the former is less susceptible to post-formation alteration and weathering processes.

Samples selected for zircon U-Pb dating

The 47 samples selected for zircon U-Pb dating presented in this report are shown on the geological map of the central Skjoldungen region (Figure 2) and summarised in appendix Table A1. In addition seven samples that were previously dated (Kolb et al. 2013) are shown on Figure 2 and are included in the consecutive summary section.

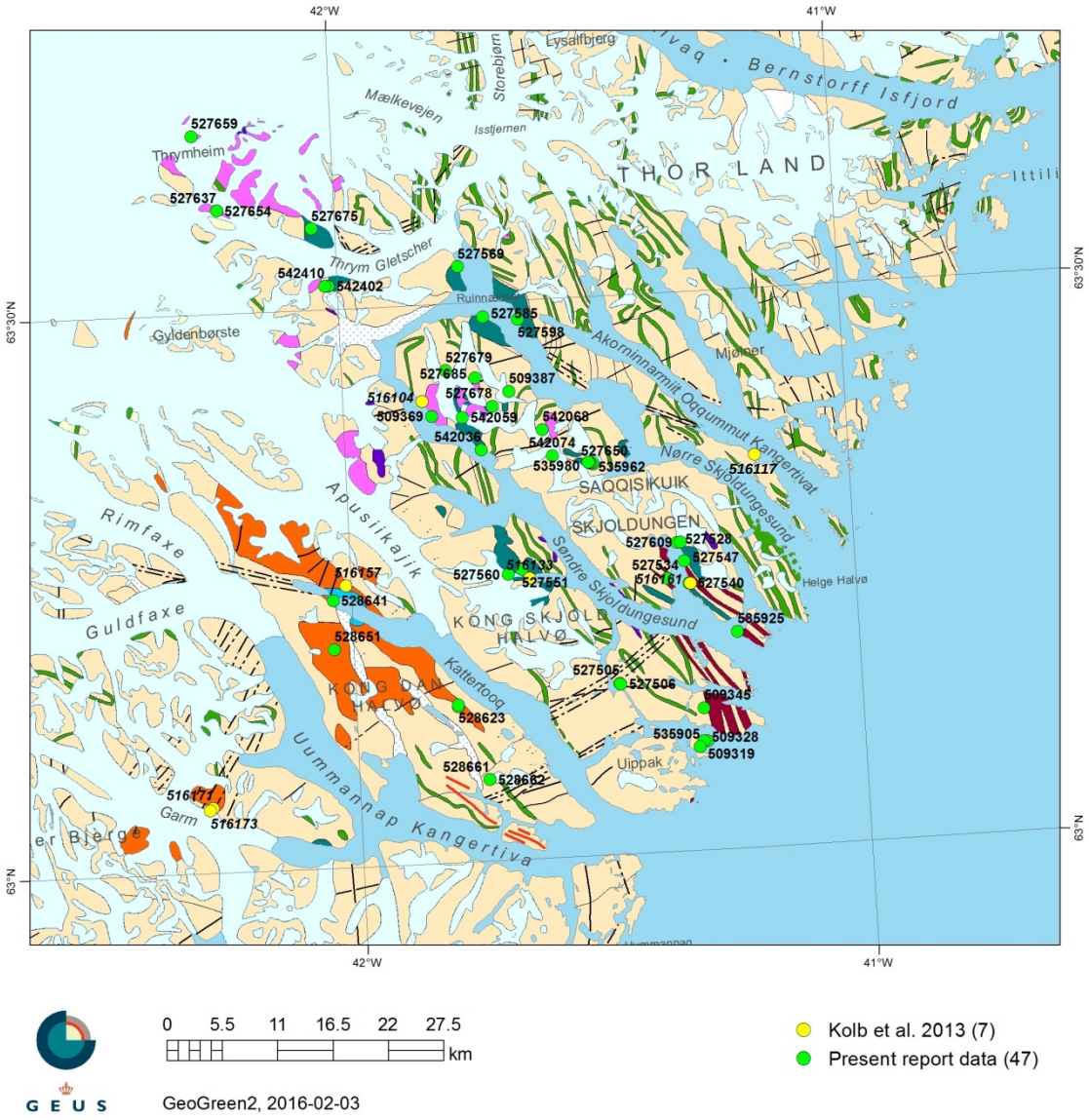

Figure 2. *Geological map of the central Skjoldungen region showing the locations of the 47 samples (GGU sample numbers as labels) that were U-Pb dated as documented in this report (light green circles), and seven samples from Kolb et al. (2013). See also Table A1 for more sample details. Geological legend as in Figure 1.*

Vend Om Intrusion

Geological background

The Vend Om Intrusion is exposed on the northern shore side of the Vend Om fjord in the south-eastern part of SAP. The intrusion has an oval outline measuring *c.* 250 × 400 m and is composed of an outer <100 m wide Marginal Zone of melanocratic to ultramafic hornblende-porphyroblastic rocks and an inner Layered Sequence of gabbroic rocks (Figure 3). It was first discovered by GGU during the field expeditions to the area in 1986. Blichert-Toft et al. (1995) reported a few chemical data from the Vend Om intrusion. The revisit in 2011 and 2012 included mapping and sampling of the intrusion by TFK and MBK (2011) and by TFK, CT and BMP (2012). A M.Sc. thesis on the Vend Om Intrusion was defended by BPM at Aarhus University in June 2015 (Maarupgaard, 2015). The thesis focuses on a description of the petrology of the intrusion and presents new major and trace element bulk rock chemistry data on 93 samples and mineral chemistry data on 51 samples. This report includes three samples for dating from the Vend Om intrusion; two leucocratic pegmatites (527505 and 527506) that constrain the emplacement age of the Vend Om Intrusion, and one sample of the older remobilized basement in the contact zone (527509).

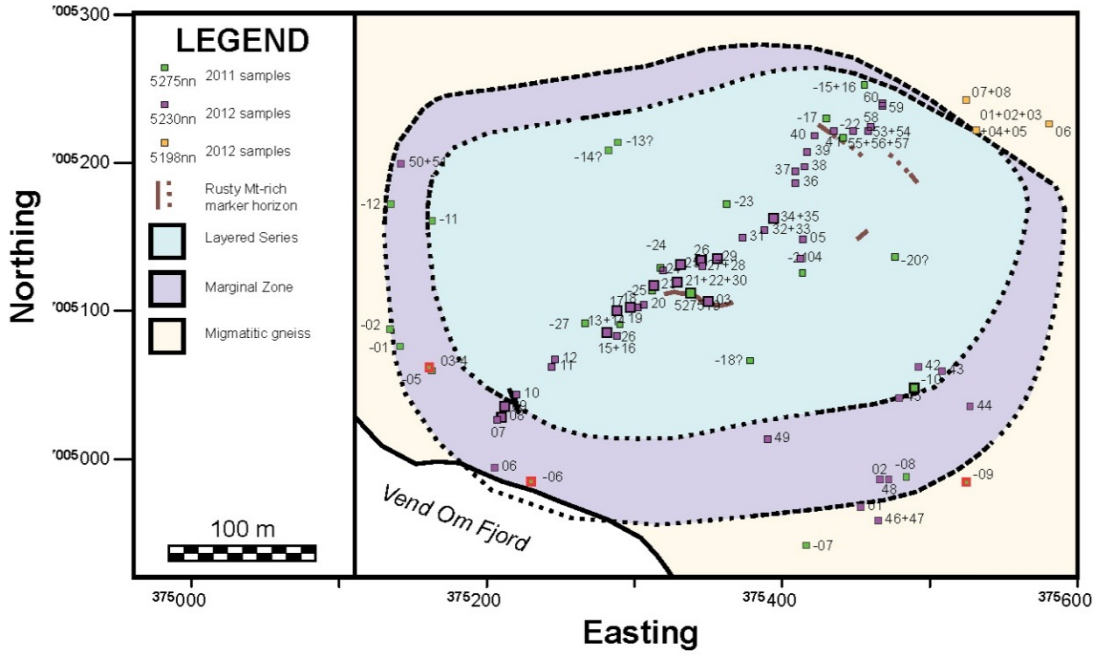

Figure 3. *Schematic geological map of Vend Om Intrusion from Maarupgaard (2015) after Klausen & Kokfelt (2014). The intrusion is made up as a concentric plug with an outer marginal zone of coarse-grained hornblende-bearing melagabbro and an internal Layered Series of leucocratic to mesocratic gabbros. Three samples high-lighted by red outlined symbols were U-Pb dated.*

Results

Felsic pegmatite vein (527505)

Locality: Vend Om gabbro Intrusion
Ganfeld station: 11MBK003
Coordinates N 63.15322; W 41.47867
Collector: TFK and MBK
Collection date: 17/07/2011
Description: Very coarse-grained pale whitish granitic pegmatite vein consisting of alkali feldspar, plagioclase, quartz, biotite and epidote. The pegmatite intrudes as an irregular dyke, up to 10-30 cm wide, at the marginal zone of the Vend Om mafic intrusion, which locally consists of hornblende poikilitic melagabbro (Figure 4). The pegmatite dyke can be traced some 20-30 m into the interior of the Vend Om Gabbro; it is thickest in the contact zone to the surrounding basement and gets progressively thinner away from the contact. A possible interpretation of the field relationship is that the pegmatite represents partially melted gneissic basement that was remobilised due to heating by the gabbro intrusion (back-veining). Zircons are large, sometimes very large (up to 1mm), sub- to euhedral, elongate prismatic, often showing faint magmatic zonation consisting of a homogeneous darker (U-poor) core surrounded by a brighter (U-rich) rim.
Purpose: To date the latest magmatism in the area. Provided that the pegmatite reflects a product of back-veining, the pegmatite intrusion age will also provide a constraint on the intrusion age of the Vend Om Gabbro.

Figure 4. *Sample 527505: Felsic pegmatite vein (20-30 cm wide) intruding hornblende poikilitic melagabbro at the marginal zone of the Vend Om Intrusion.*

Data interpretation: The zircons have magmatic textures and often display faint growth zones with relatively homogeneous and U-poor cores surrounded by relatively thinner U-rich rims (Figure 5). No significant difference in age exists between core and rim of individual grains. The isotope data displays a single age population with a normal distribution with an age of 2690 ± 8 Ma based on only the highly (98-102%) concordant analyses (Figure 5). The age represents the timing of the pegmatite intrusion into the marginal series of the Vend Om intrusion. The age is consistent with another age dating of a felsic pegmatite (sample 527506) that also intrudes at the margin of the Vend Om intrusion, and that is interpreted as the result of back-veining.

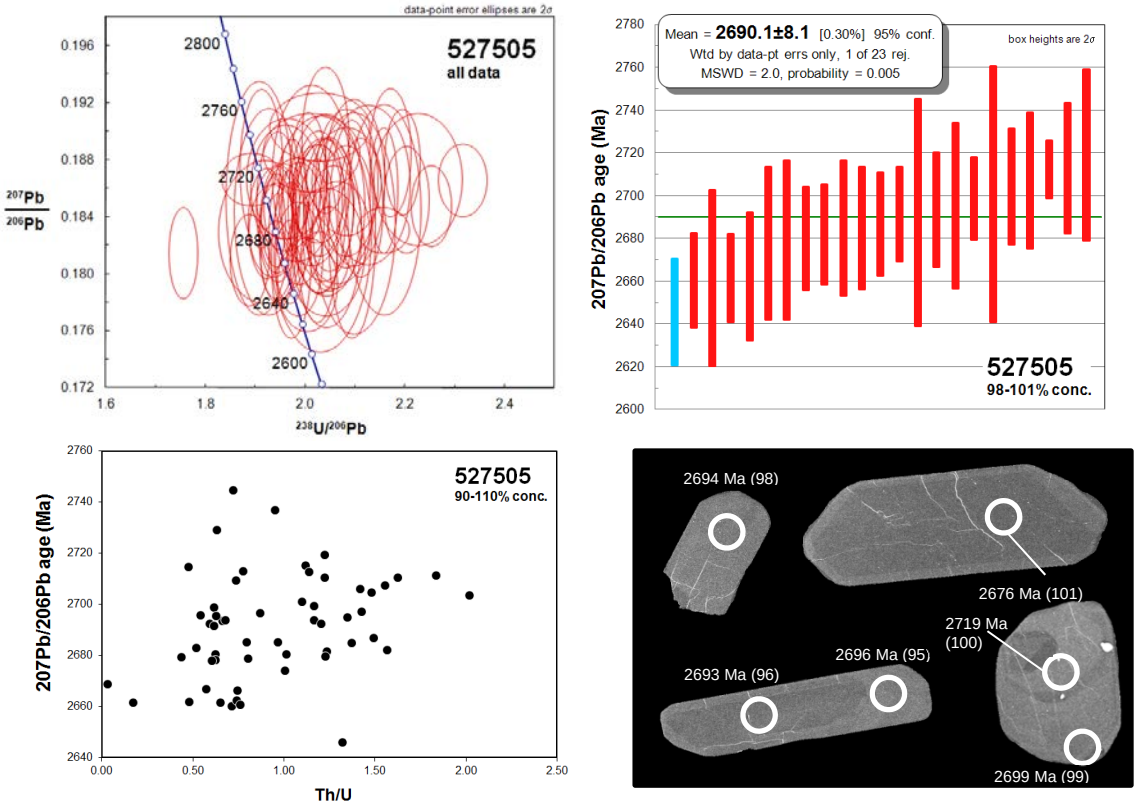

Figure 5. *Sample 527505: In the Tera-Wasserburg plot majority of points are concordant to slightly discordant. The data consists a single age population with and age of 2690 ± 8 Ma based on the highly (98-102%) concordant grains.*

Felsic pegmatite dyke (527506)

Locality: Vend Om gabbro Intrusion
Ganfeld station: 11MBK005
Coordinates N 63.15252; W 41.47714
Collector: TFK and MBK
Collection date: 17/07/2011
Description: Very coarse-grained pale whitish granitic pegmatite dyke consisting of alkali feldspar, plagioclase, quartz and biotite. The pegmatite intrudes as an irregular dyke (c. 0.5

m wide) across the marginal zone of the Vend Om Gabbro Intrusion (of hornblende poikilitic melagabbro) and can be followed only some tens of meters from the margin inwards (Figure 6).

Purpose: Date the latest magmatism in the area. Similar to 527505, a possible interpretation of the field relationship is that the pegmatite represents partially melted gneissic basement that was remobilised due to heating by the gabbro intrusion (back-veining). In this case the age of the pegmatite will also likely give the emplacement age of the gabbro intrusion itself.

Figure 6. *Sample 527506: Felsic pegmatite dyke intruding hornblende poikilitic melagabbro at the marginal zone of the Vend Om Intrusion. The pegmatite can be followed for some tens of meters into the intrusion, where after it thins out and disappears.*

Data interpretation: Majority of zircon grains are fairly small, anhedral and irregular shaped, and possess a faint magmatic zoning that suggests they grew interstitially and late (Figure 7). Some grains are more prismatic and rounded, and exhibit a more pronounced complex zoning of bright (U-rich) cores surrounded by darker (U-poor) rims that are radially cracked. A few fragments of once much larger (~0.5 mm) grains occur with homogeneous cores and narrow (<10µm) rims. The U-Pb data includes a main population with an age of 2690 ± 4 Ma based on only the (90-110%) concordant analyses (Figure 7). In addition a smaller group of zircons - corresponding to the distinctly zoned zircons - give older ages in the range of c. 2750 - 2850 Ma. The main age population represents the timing of the pegmatite intrusion into the marginal series of the Vend Om intrusion and agrees perfectly with the age obtained from sample 527505. The older grains could be inherited from the agmatitic gneiss host rock (see sample 527509).

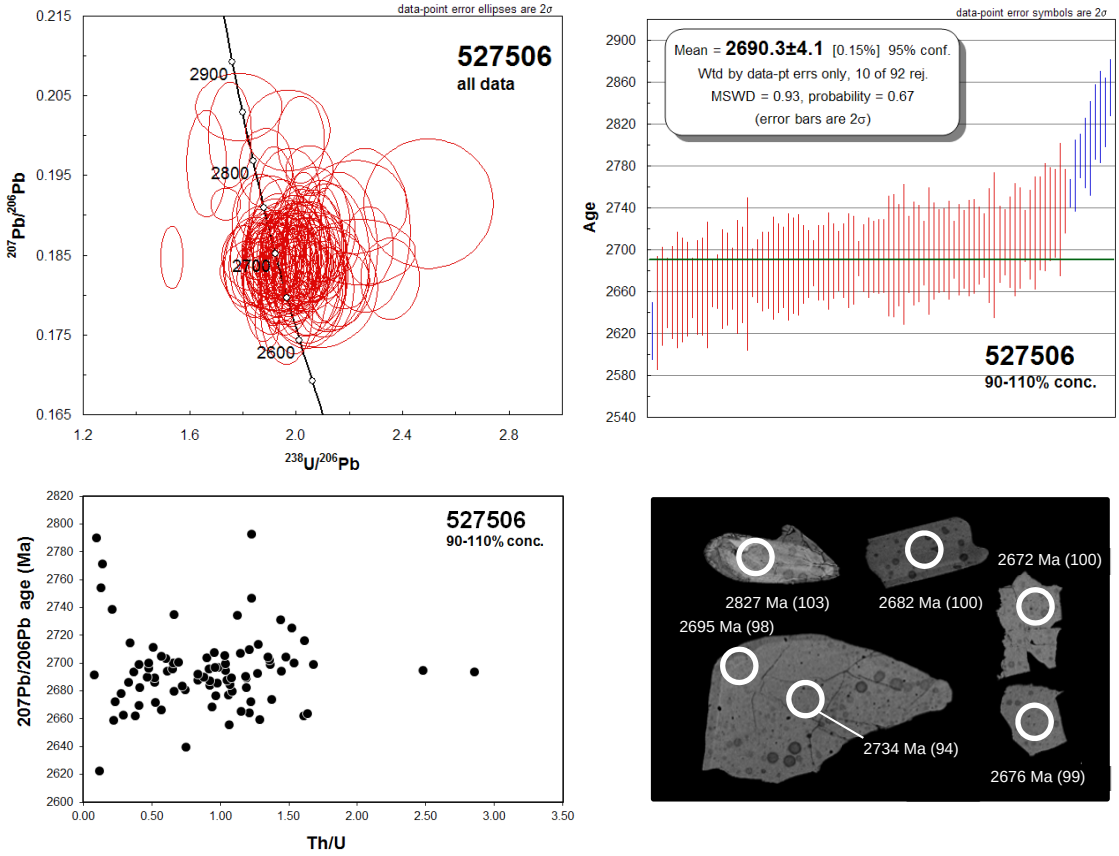

Figure 7. *Sample 527506: In the Tera-Wasserburg plot majority of points are concordant and tend to cluster in one group, with fewer older grains up to c. 2850 Ma. The main group consists an age population of 2690 ± 4 Ma (MSWD = 0.93, probability = 0.67) based on the (90-110%) concordant grains, thus agreeing perfectly with 527505.*

Gneissose granitoid (527509)

Locality: Gneissose granitoid from eastern contact zone of Vend Om Intrusion.
Ganfeld station: 11MBK012
Coordinates: N 63.15253, W 41.47102
Collector: TFK, MBK
Collection date: 17/07/2011
Description: Black and white, coarse-grained gneissose granitoid with plagioclase, alkali feldspar, quartz and amphibole (Figure 8). The sample was collected in a few meters wide contact zone next to the mafic Vend Om intrusion and appears to record the heating effect from the mafic intrusion through partial remobilisation of the country rocks.
Purpose: Characterise the country rock to the Vend Om intrusion that appears to constitute agmatitic gneiss, and test if the zircon population records the heating event from the Vend Om intrusion in the form of either newly grown, or partially reset zircons.

Figure 8. *Sample 527509: Strongly foliated and deformed granitic gneiss(?) basement with mafic schlirren at the eastern contact zone of the Vend Om intrusion. The host gneiss appears to be partially remobilised in the contact zone reflecting heating from the mafic intrusion.*

Data interpretation: Zircon grains vary widely in size (50-250 µm) and aspect ratio (1:2 – 1:4) and are generally subhedral with slightly rounded outlines (Figure 9). Many grains have complexly zoned cores that are resorbed and overgrown by fractured rim domains. Some grains have thin (≈10 µm) outer and relatively bright (U-rich) rims.

The U-Pb data define a complicated age spectrum including a wide range of ages between c. 2700 and 2900 Ma and with a skewed distribution towards the younger ages. Based on the 'unmixing' function of Isoplot, three possibly sub-populations may be identified (Figure 9): (1) A main population (consisting 46 %) at 2734 ± 6 Ma, (2) an intermediate age population (36 %) at 2796 ± 12 Ma, and (3) a smaller population (16 %) with an age of 2890 ± 14 Ma. A single grain has an uncertain age of 2562 ± 67 Ma, which could reflect ancient Pb-loss effects. The dominant 2734 Ma age peak is too young to represent with the protolith age for the agmatitic gneiss basement in general, but is entirely consistent with the SAP magmatism (2750-2700 Ma) (Kolb et al. 2013). From the age data it is suggested that the sample's zircons most likely represent a mixture from agmatitic gneiss (~50% of the zircon population is ≥ 2800 Ma) and earlier SAP intrusives (predating the Vend Om intrusion). We content that the ~2796 Ma age group is likely to represent the gneiss protolith intrusion age, whereas the smaller ~2890 Ma population represents an inherited group.

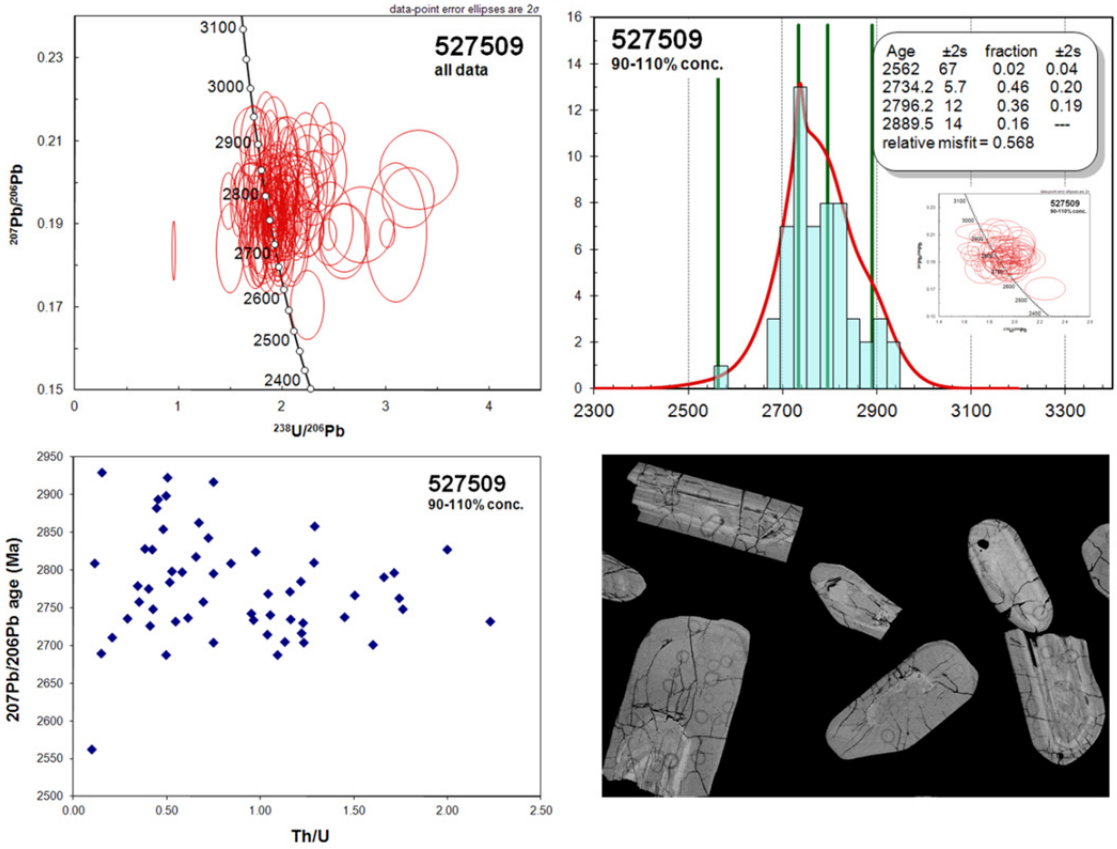

Figure 9. *Sample 527509: Deformed gneiss basement (granodioritic) showing a complex multi-age distribution pattern. A main age peak at 2734 Ma is interpreted as zircon resetting age caused by the intrusion of hot mafic melts of the Vend Om intrusion. An intermediate age peak of 2796 Ma could represent the gneiss protolith intrusion age. The small peak at 2890 Ma likely represents inherited grains.*

Summary

In summary, the excellent agreement in ages for the two pegmatites (527505 and 527506) and the field evidence for them being derived as back-veins from remobilised basement wall rock, provide good evidence for the pegmatite dykes representing the crystallization age of the Vend Om Gabbro Intrusion itself. This young age of 2690 Ma ± 4 Ma places the Vend Om Gabbro Intrusion late in relation to the overall development of the SAP, post-dating the main tectonism associated with the Skjoldungen Orogen (Kolb, 2013). This is entirely consistent with the well preserved igneous textures and the lack of evidence for tectonic overprinting in the Vend Om Gabbro Intrusion (see Klausen & Kokfelt, 2014). Sample 527509, on the other hand, is a sample of the deformed country rock near the contact of the Vend Om intrusion, and it seems to represent a mixed lithology of agmatitic gneiss basement with a protolith intrusion age of ~2800 Ma and earlier SAP-related magmatism with intrusion ages of ~2730 Ma. Somewhat surprisingly this sample does not record the heating event related to the mafic intrusion at 2690 Ma.

Iglermiut Island

Geological background

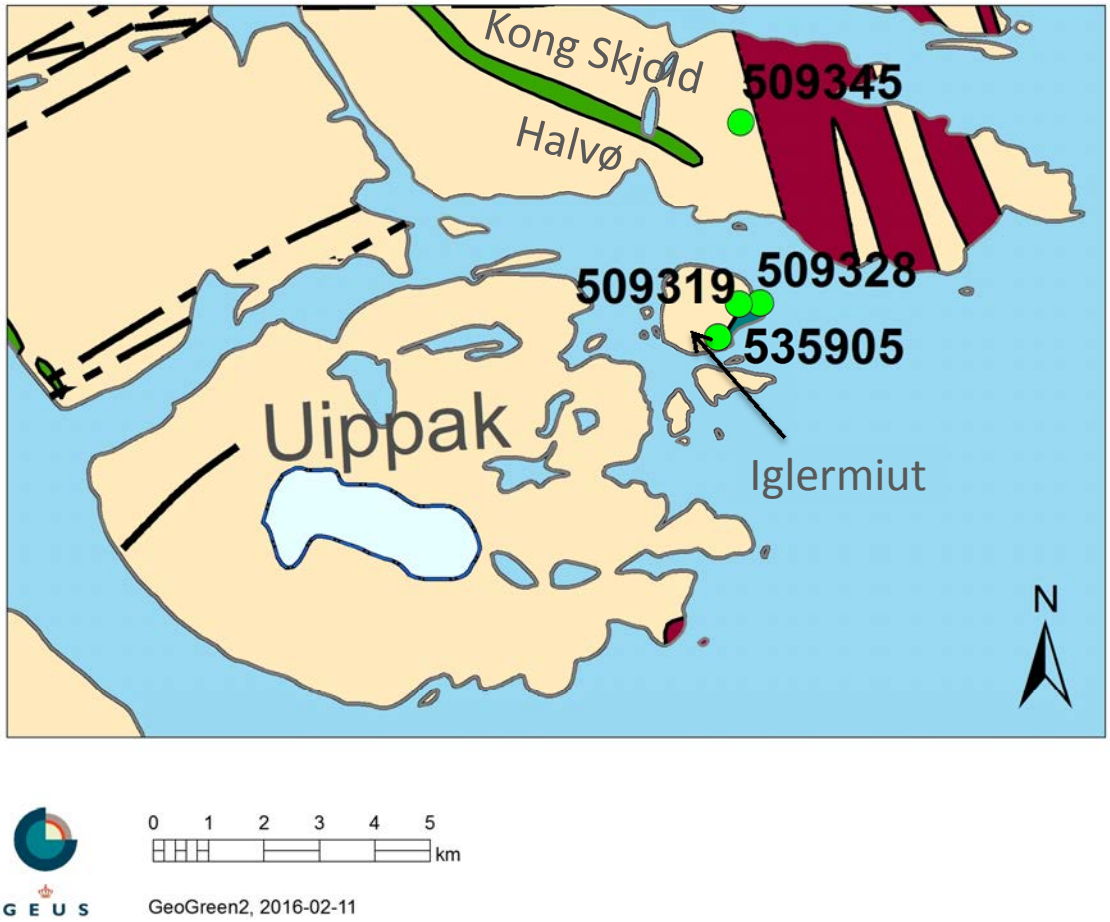

Figure 10. *Geological sketch map of the area around the islands of Iglermiut and Uivaq (new spelling: Uippak) south of Kong Skjold Halvø showing the locations of the dated samples.*

In 2012 an initial boat reco was carried out around the small (1.6 x 1.8 km) island of Iglermiut situated in south-eastern part of the SAP between Kong Skjold Halvø and the larger island of Uivaq (old spelling) (Figure 10). The reason for targeting this area was partly to cover the island of Iglermiut that - judging from old field maps - was not visited by the earlier GGU operations, and partly to find out more about the poorly known Uivaq Diorite described by Nielsen & Rosing (1990). The boat reco revealed mafic intrusions outcropping along the southern shore of Iglermiut albeit no mafic intrusion along the eastern shorelines of Uivaq. This prompted further visits to Iglermiut, arranged as two days of helicopter drop-offs. This work revealed the existence of two different mafic intrusions on the island; one in its southern part and one in its eastern part. Despite an incomplete mapping of their outlines they both appear small (maximum a few hundred of meters in diameter), semi-circular intrusions that are hosted within agmatitic gneiss basement or rocks of earlier SAP affinity. The southern Iglermiut intrusion is dissected by the southern shoreline, and could theoretically be larger. It also consists of coarse-grained gabbronorite that is intensely crosscut by

a network of felsic pegmatites. In some outcrops the felsic veins appear to be sourced from the felsic gneiss basement, and can thereby be interpreted as back-veins. Thus, by dating the youngest zircons found in the felsic pegmatites, the crystallization age of the mafic intrusion can likely be deduced. The eastern mafic intrusion is much less disturbed, showing intact magmatic textures and structures, and hence more time was spent on this intrusion. The intrusion is roughly oval in outline measuring c. 300 x 500 m, being elongate in an E-W direction. The Iglermiut intrusion is very similar both with respect to lithology and architecture as the Vend Om intrusion, which is situated just 10 km NW of Iglermiut Island. The Iglermiut intrusion is characterised by a 10 – 30m wide marginal zone consisting of hornblende porphyritic melagabbro, surrounding a core of modally layered gabbroic rocks including leuco- to mesocratic varieties in which magnetite is a common phase, often constituting distinct disseminated to semi-massive horizons up to a few cm in thickness. The marginal zone is best preserved to the north, whereas the eastern part is dominated by a mixed zone where the gneiss basement has reacted with the intrusion (see sample 509324). Similar to Vend Om, the marginal zone is in several places cut by 10-30 cm wide leucocratic pegmatites that were injected orthogonally from the contact and gradually thins out over some tens of meters into the eastern Iglermiut intrusion. These pegmatites are interpreted as result of back-veining as the mafic intrusion generated sufficient heat for the gneissic basement to become partially melted and remobilised. Dating of these felsic pegmatites is therefore likely to provide the crystallization age of the mafic intrusion itself. In the north-western part of the intrusion the host rock is constituted by a strongly gneissose SAP monzonite.

The Uivaq Diorite is by Nielsen & Rosing (1994) described to form an intrusive body along the northern shore of Uivaq island, where it is surrounded by a grey, hybrid zone of several metres width reflecting interaction with the gneiss basement. The failure to localise the intrusion on Uivaq island leads us to speculate if the Uivaq Diorite could be identical to the eastern mafic intrusion on Iglermiut, not least because their descriptions fit well with our observations from eastern Iglermiut.

Results

Syenitic pegmatite dyke (509319)

Locality: Iglermiut Island, eastern part
Ganfeld station: 12TFK140
Coordinates: N 63.09765, W 41.31193
Collector: TFK, CT, ABO, BPM, LT
Collection date: 16/08/2012
Description: 20-30 cm wide syenitic pegmatite dyke that can be followed for c. 30 m into the gabbroic intrusion from its margin, where after it tapers out (Figure 11). Based on the eastern Iglermiut intrusion's resemblance to the Vend Om intrusion, a likely similar interpretation of the felsic pegmatitic veins represented by this sample is that they are the result of back-veining during the crystallization of the mafic-ultramafic intrusion.

Purpose: Obtain the intrusion age of the cross-cutting syenitic pegmatite, and by inference a minimum age of the mafic intrusion that it dissects. If the pegmatite is a back-vein, it will also give the actual crystallization age of the mafic host intrusion.

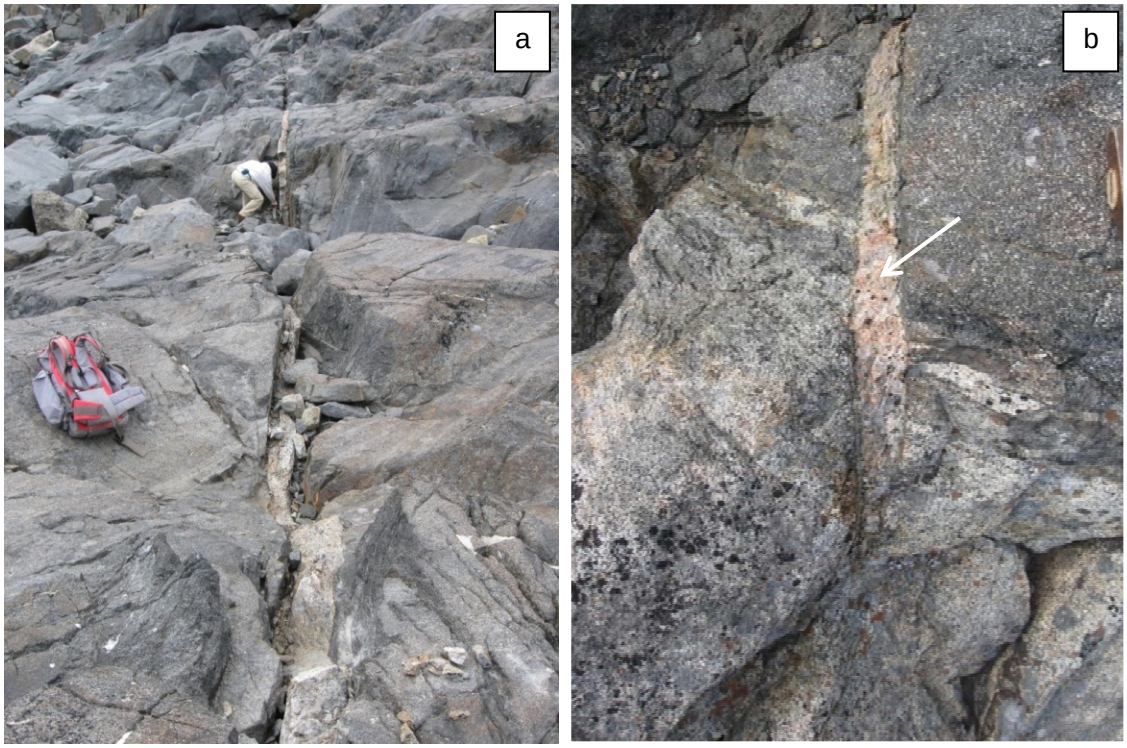

Figure 11. *Sample 509319: (a) Overview of how the sampled felsic pegmatite cuts across the SE contact zone of the eastern Iglermiut mafic intrusion and some 30 m into it. (b) Close-up photograph showing the sheared contact between the ultramafic rim of the Iglermiut intrusion (upper right) and adjacent wall rock (lower left); both of which are obliquely cut by the 3-5 cm thin felsic pegmatite vein (arrow) that was dated. Hammerhead for scale.*

Data interpretation: Zircon grains are generally sub- to euhedral, but also include anhedral grains. Sizes vary widely from 50 - >200 µm and with aspect ratios of 1:2 - 1:3 (Figure 12). The grains are magmatic looking and usually include faint zoning. The range of different grain morphologies suggests that zircon growth occurred over a wide crystallisation (and temperature) range, where the anhedral grains reflect the latest interstitial growth stage. Of the 148 spots analysed only 13 are outside the 100 ± 10 % concordancy range and only 49 are outside the 100 ± 5 % range. No common Pb was detected in any of the analyses. A weighted mean Pb-Pb age of 2700 ± 5 Ma (MSWD = 0.47, N = 99) is calculated for the 100 ± 5 % concordant analyses (Figure 12). This age is consistent with an upper intercept Concordia age based on the entire dataset yielding 2701 ± 4 Ma (MSWD = 0.60, N = 148) and is interpreted as the intrusion age of the pegmatite. As discussed, this age at least provides a minimum age for the emplacement of the gabbroic intrusion, and if interpreted as a result of back-veining, the age would be identical to the actual crystallization age for the mafic-ultramafic eastern Iglermiut intrusion.

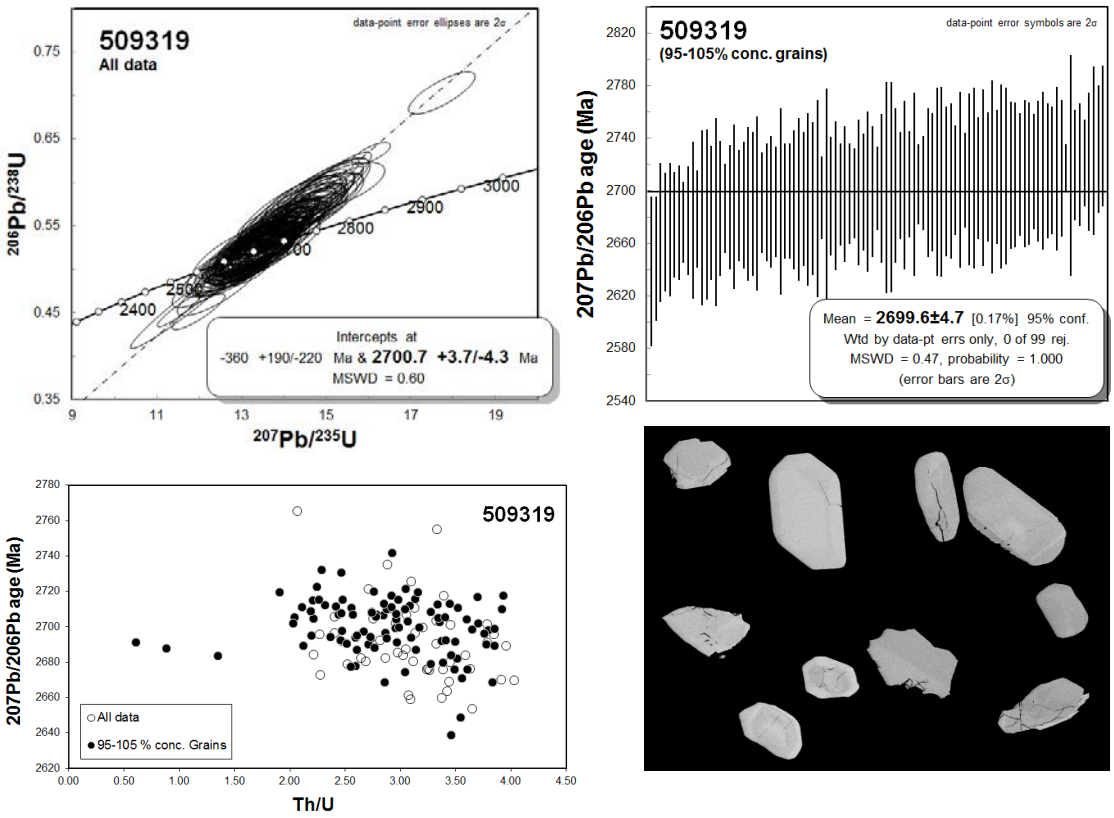

Figure 12. *U-Pb data for sample 509319: The U-Pb data show a single age population of magmatic zircons giving an intrusion age of 2700 ± 5 Ma, based on the 100 ± 5% concordant grains.*

Agmatitic gneiss, contact facies (509324)

Locality: Iglermiut Island, eastern part
Ganfeld station: 12TFK143
Coordinates: N 63.09797, W 41.31165
Collector: TFK, ABO, CT, BPM, LT
Collection date: 16/08/2012
Description: Agmatitic gneiss basement immediately adjacent to the mafic-ultramafic intrusion situated on the eastern part of the small island (Figure 13). The zone includes fragmented slivers of more mafic rocks aligned with the general NW-SE oriented foliation.
Purpose: Provide age constraints on the basement and evaluate if the basement has been partially affected by the SAP intrusion.

Figure 13. *Sample 509324: Agmatitic gneiss in the contact zone a few meters away from the mafic intrusion in the eastern part of Iglermiut.*

Data interpretation:
Zircons extracted from sample 509324 show a textural diversity, including strongly zoned (older) grains and unzoned (younger) grains (Figure 14). One texturally distinct population corresponds to the youngest age population (see below) and is composed of subhedral, large (up to 250 µm) grains with aspect ratios of 1:2 – 1:4; these grains are homogeneous and have high Th/U (> 1.75) and low U contents (average of 118 ppm).

A total of 114 spots were analysed of which 91 gave acceptable data without any evidence for common Pb influence. The data are generally concordant with only seven analyses falling outside the 100 ± 10% concordancy interval. In the Concordia plot (Figure 14), the aforementioned homogeneous zircon population yields a well-defined upper intercept age of 2707 ± 6 Ma (MSWD = 0.92). Based on the weighted mean of the 90-110 % concordant grains this group gives an identical age of 2707 ± 7 Ma (MSWD = 0.76; n = 32). This age is interpreted to reflect a thermal event, which also matches with the timing of emplacement of the Iglermiut intrusion (see 509319). Of the remaining data points, two older age groups stand out: (1) four partly discordant grains yield an age of 3006 ± 21 Ma (MSWD = 0.83; n = 32) based on a weighted mean; (2) three concordant grains yield an age of 3207 ± 19 Ma (MSWD = 0.40). These two groups are interpreted as inherited grains in the gneiss.

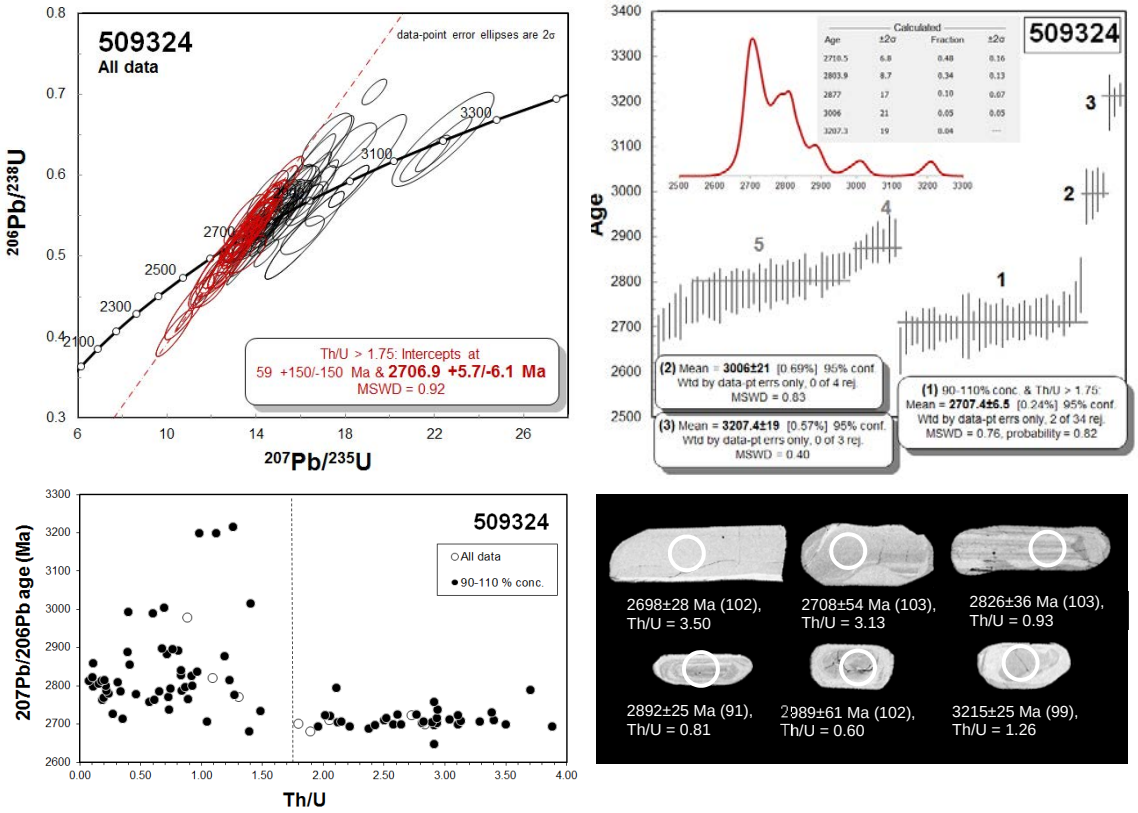

Figure 14. *U-Pb data for sample 509324: Three (possibly five?) age groups can be identified of which the dominant is the 2707 ± 7 Ma (MSWD = 0.76; n = 32) interpreted as thermal over-printing event associated with the intrusion of the Iglermiut intrusion.*

Two additional age groups might be defined at c. 2804 ± 9 Ma and 2877 ± 17 Ma, respectively, calculated based on the 'unmix' function of Isoplot. The 2804 Ma group, which constitutes 34 % of the total zircon population, is interpreted as the intrusion age of the gneiss protolith, whereas the minor 2877 Ma group is likely inherited. Overall, the large proportion of young zircons indicates that a significant thermal overprinting occurred at the time of intrusion of the mafic-ultramafic Iglermiut intrusion.

Gneissose feldspar porphyric quartz monzonite (509328)

Locality: Iglermiut Island, eastern part
Ganfeld station: 12TFK148
Coordinates: N 63.09769, W 41.31964
Collector: TFK, CT, ABO, BPM, LT
Collection date: 16/08/2012
Description: Feldspar porphyric gneissose quartz monzonite that constitute a host rock to the mafic-ultramafic Iglermiut intrusion on the eastern side of the island (Figure 15). The rock contains two sets of foliation, a main foliation, which is defined by the orientation of the feldspar megacrysts and gives an orientation of (165/78˚E) parallel to the orientation of the northern contact zone of the mafic-ultramafic intrusion. The quartz monzonite also exhibits

a crenulation cleavage indicating a dextral shear component to the deformation (Figure 15). Locally monzonite is intruded by deformed stringers of fine-grained dykes of (seemingly) intermediate composition. The quartz monzonite is believed to be part of the SAP magmatism that was intruded while tectonism and deformation was still active in the area.
Purpose: Provides the intrusion age of the older generation of intermediate SAP intrusions in the part of the province and also indirectly provides a maximum age for the intrusion of the mafic-ultramafic Iglermiut intrusion.

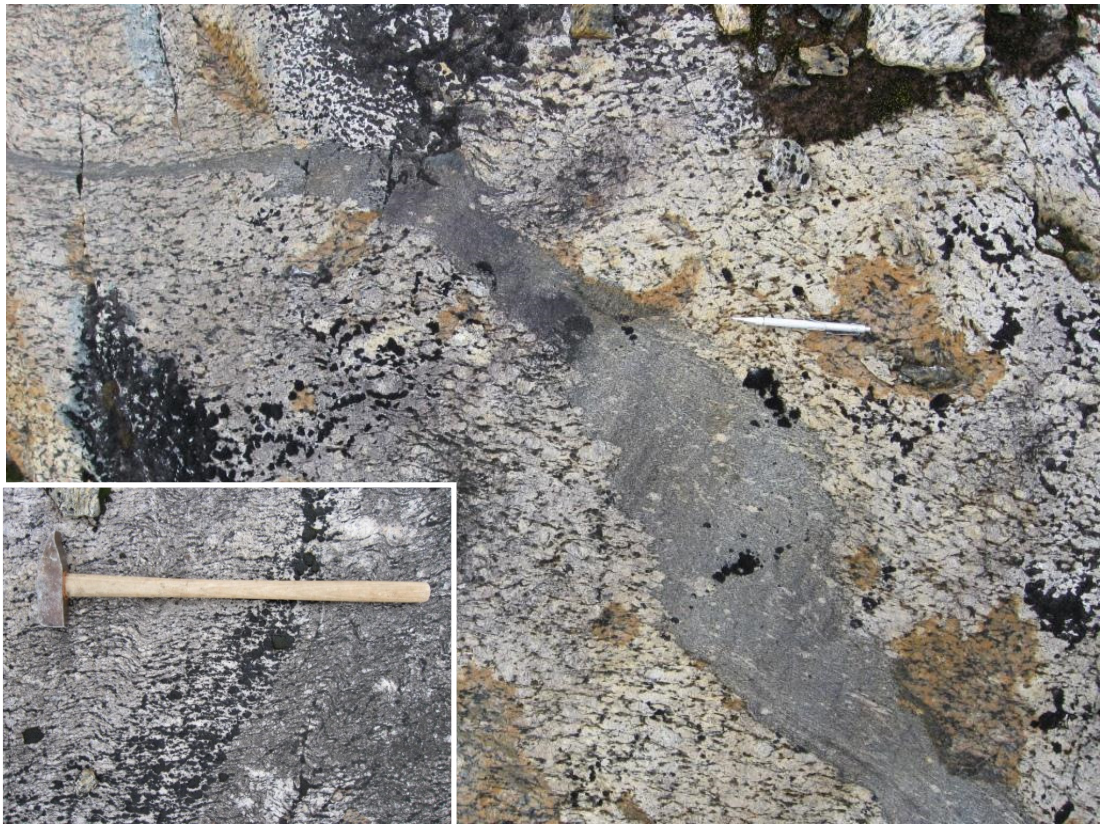

Figure 15. *Sample 509328: An earlier generation of SAP magmatism is represented by a gneissose feldspar porphyritic quartz monzonite, which constitute the host rock to the eastern mafic intrusion at the northern contact zone. The grey vein (not sampled) is likely to represent an intrusive vein from the Iglermiut intrusion. Insert: The rock exhibits S-C foliation with a dextral shear sense compared to the main foliation (165/78˚E).*

Data interpretation:
Zircon grains are subhedral, relatively small (generally <100 µm) and elongate, semi-rounded with aspect ratios of 1:3 – 1:4 (Figure 16). Magmatic zoning with clear core and rim domains are widespread. Some grains have metamict cores surrounded by an intensely cracked mantle domain. A total of 129 spots were analysed of which 72 returned acceptable data without any evidence for common Pb influence (47 spots had common Pb). The data are generally concordant with only 12 analyses falling outside the 100 ± 10% concordancy interval. In the Concordia plot (Figure 16), the analyses constitute a single age population with a well-defined upper intercept age of 2727 ± 6 Ma (MSWD = 1.4; n = 54). Based on the weighted mean of the 95-105 % concordant grains a similar age of 2726 ± 8 Ma (MSWD = 1.3; n = 43). This age is interpreted to reflect the intrusion age of the

quartz monzonite and seems to suggest that SAP magmatism spanned for ~25 Myr (2726 – 2700 Ma) in this part of the province.

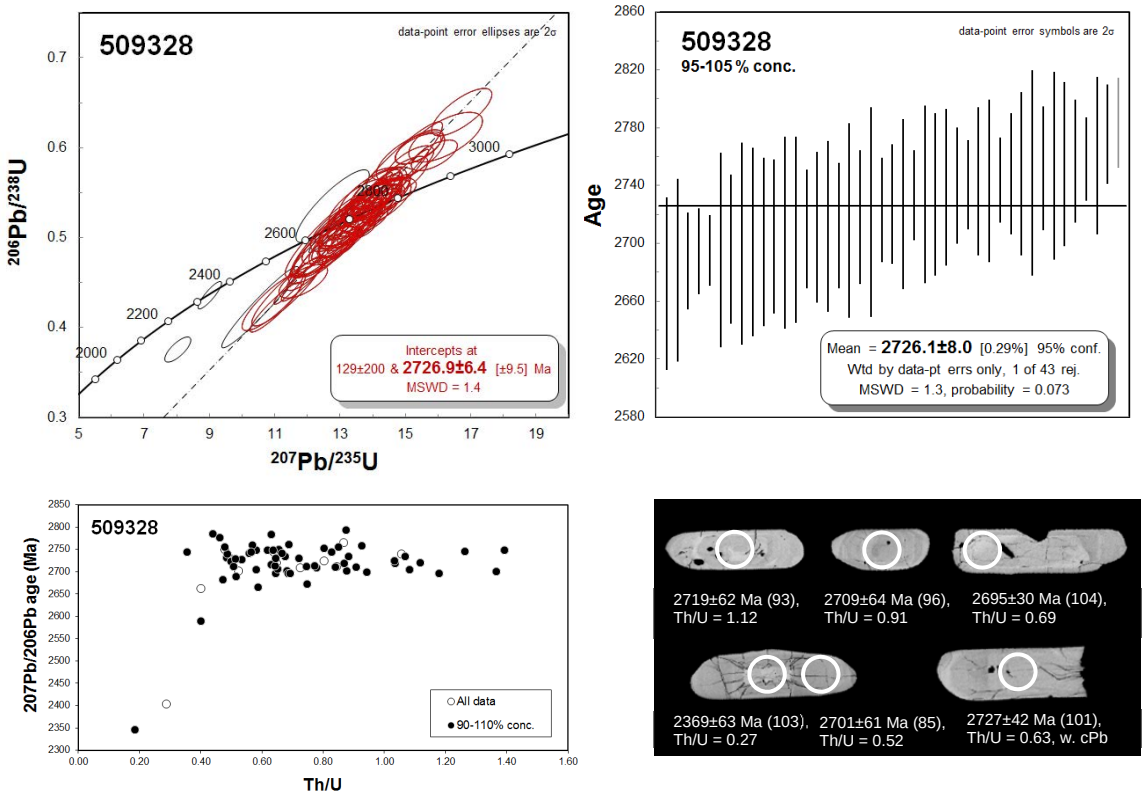

Figure 16. *U-Pb data for sample 509328: The U-Pb data show a single age population of magmatic zircons giving an intrusion age of 2726 ± 8 Ma, based on the 100 ± 5% concordant grains.*

Granitic pegmatite (535905)

Locality: Iglermiut Island, south-western part
Ganfeld station: 12TFK024
Coordinates: N 63.09250, W 41.32771
Collector: TFK, CT, ABO
Collection date: 03/08/2012
Description: The coarse-grained gabbroic rocks of the mafic intrusion at south-western side of Iglermiut are heavily intruded and brecciated by felsic veins that appear to be derived from partial melting of host agmatitic gneiss basement (Figure 17). The sample for dating is one of these granitic veins.
Purpose: Zircon age will provide a minimum age of the gabbroic intrusion and maybe even constrain the crystallization age of the mafic intrusion, assuming that these granitic pegmatites represent brecciating back-veins as inferred for other gabbroic intrusions. The irregular (ductile) mode of emplacement, illustrated in Figure 17, supports the latter interpretation.

Figure 17. *Sample 535905: Irregular felsic pegmatite dyke forming a network in the gabbroic rock of the south-western mafic intrusion on Iglermiut. The pegmatite is interpreted in terms of remobilisation of the host gneiss basement, i.e. back-veining.*

Data interpretation: Zircon grains are generally sub- euhedral, but also include anhedral grains. Sizes very widely from 60 - >200 µm and with aspect ratios of 1:2 – 1:3 (Figure 18). The grains are magmatic looking and usually include faint zoning. All of the 103 analysed spots are concordant within 100 ± 10 % and constitute a Concordia intersect age of 2705.5 +8.0/-7.9 Ma (MSWD = 1.2) (Figure 18). A weighted mean Pb-Pb age gives a better defined (preferred) age of 2710.5 ± 5.2 Ma (MSWD = 0.93). This age is interpreted as the intrusion age of the pegmatite and likely also the crystallization age of the mafic intrusion, which it cuts.

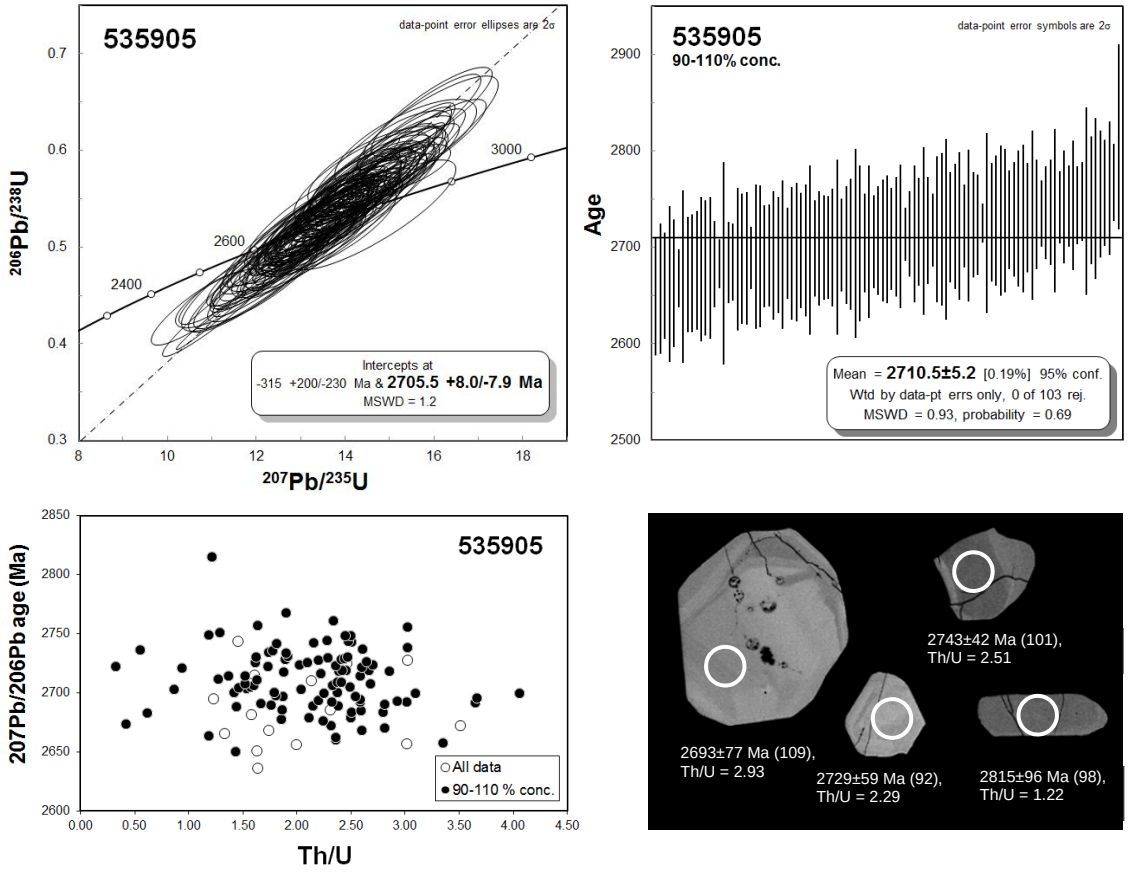

Figure 18. *U-Pb data for sample 535905: The U-Pb data show a single age population of magmatic zircons giving an intrusion age of 2710.5 ± 5.2 Ma, based on the 100 ± 10% concordant grains (n = 103; MSWD = 0.93).*

Summary

The eastern mafic Iglermiut intrusion was emplaced as a circular plug-like body into a country rock of agmatitic gneiss basement and earlier relatively felsic SAP intrusives. Newly grown zircon in gneissic rock from the contact zone and felsic pegmatites cross-cutting the same zone provide consistent evidence for a heating event taking place at ~2700 Ma (2707 ± 6 Ma – 2700 ± 5 Ma), which we interpret as the crystallization of the mafic intrusion. The earlier (monzonitic) SAP magmatism is dated to 2726 ± 8 Ma, which is identical to the age peak found in the SAP-modified gneissic country rock at Vend Om intrusion (see sample 527509). Dating of felsic back-veins that cut the more disturbed southern mafic Iglermiut intrusion indicates that this intrusion is only slightly older, about 2710.5 ± 5.2 Ma, than the eastern mafic Iglermiut intrusion.

Hermods Vig and Njords Gletscher

Geological background

The gabbroic intrusions at Hermods Vig and Njords Gletscher are also referred to by Nielsen & Rosing (1994) as Hermods Vig Diorite 1 and Hermods Vig Diorite 2, respectively. Both intrusions were investigated in some detail during the 2011 and 2012 seasons as described in Klausen & Kokfelt (2014), and one result of this work was a revision of the outline of the latter mentioned intrusion, as this is significantly exaggerated in size on the printed 1:500 000 scale map (Escher, 1990). Both intrusions include magmatically layered, medium – coarse-grained gabbroic rocks that are variably dissected by sheets and dykes of intermediate – felsic compositions. Especially Hermods Vig Diorite 1 is crosscut by numerous later sheets and dykes (up to six generations have been mapped out at a single outcrop). In comparison Hermods Vig Diorite 2 is relatively less disturbed by late magmatism, but is dissected by faults. This intrusion exposes a continuous section of c. 500 m of layered gabbroic rocks, including several horizons that are rich in magnetite (Klausen & Kokfelt, 2014; Árting, 2014). Because the mafic rocks are not feasible to date directly by zircon, the age dating work undertaken here involves various felsic intrusives, including some of the cross-cutting sheets but also affected wall rocks. Overall the new age data provide minimum ages for the mafic intrusions, and arguably also date the actual intrusion.

Results

Syntectonic syenite (527637)

Locality: Hermods Vig Diorite 1
Ganfeld station: 11TFK103
Coordinates: N 63.35427, W 41.44157
Collector: TFK, MBK
Collection date: 04/08/2011
Description: Coarse-grained weakly foliated syenite, intruding as a vein into fine-grained diorite and cutting an earlier felsic vein (Figure 19).
Purpose: Date the late stage of syntectonic SAP-related magmatism in the Hermods Vig area and provide a minimum age for the Hermods Vig Diorite 1 intrusion.

Figure 19. *Sample 527637: Coarse-grained syenitic vein (white arrow) intruding into fine-grained diorite of the Hermods Vig Diorite 1 intrusion and cross-cutting an orthogonally orientated medium grained felsic vein. The syenite vein contains a significant fraction of inherited zircons.*

Data interpretation:

The zircon grains are generally subhedral with semi-rounded outlines and widely variable aspect ratios of 1:2 – 1:5 (Figure 20). Some grains have overgrown cores showing remnants of magmatic zoning, others have more homogenous bright (U-rich) cores surrounded by darker (U-poor) rims. In total 61 spots were analysed of which 55 gave acceptable data. None of the grains have any significant contents of common Pb and only six analyses lie outside 100 ± 10% concordancy range. In the Concordia plot (Figure 20) the data spread around the Concordia between c. 2.7 and 3.0 Ga with some analyses spreading below as well as above the line. Scrutinizing the U-Pb data using the 'unmix' function of Isoplot and comparing the age data with the grain morphologies three age populations are proposed: (1) an inherited older population at 3010 ± 25 Ma (MSWD = 1.6; n = 3), (2) a younger inherited population at 2783 ± 6 Ma (MSWD = 1.17; n = 15) and (3) a younger magmatic population at 2709 ± 5 Ma (MSWD = 1.4; n = 18) Ma. The younger age gives the crytallisation age of the syenitic vein and provides a minimum age for the Hermods Vig diorite 1.

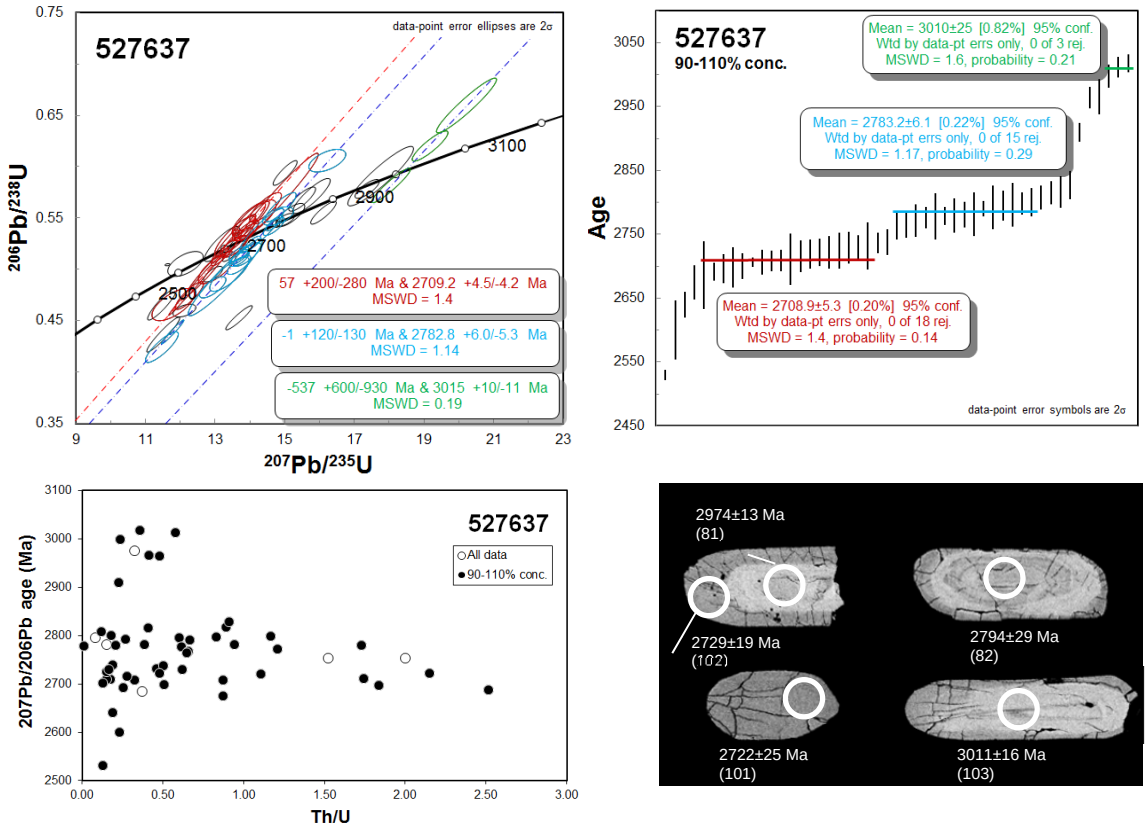

Figure 20. *U-Pb data for sample 527637: Three zircon populations are identified: (1) an inherited older population at c. 3010 Ma (based on three grains), a younger inherited population at 2783 ± 6 Ma and a younger magmatic population at 2709 ± 5 Ma. The younger age gives the intrusion age of the syenitic vein and provides a minimum age for the Hermods Vig diorite 1.*

Fine-grained monzodiorite (527650)

Locality: Hermods Vig Diorite 2, Njords Gletscher
Ganfeld station: 11TFK129
Coordinates: N 63.35041, W 41.50797
Collector: TFK, MBK
Collection date: 05/08/2011
Description: Fine- to medium-grained monzonitic SAP intrusion intruding into coarse-grained – pegmatitic heterogeneous gabbro of the Njords Gletscher Gabbro (Figure 21). The monzonite intrusion has blurry contacts to the gabbro indicating the latter to be semi-ductile at the time of intrusion. The (tectonic?) contact to the gneissic basement is situated in an E-W trending gulley; a sample of the granodioritic basement is represented by sample 527651.
Purpose: The age will give the intrusion age of the monzonite as well as provide a minimum age of the Njords Gletscher Gabbro.

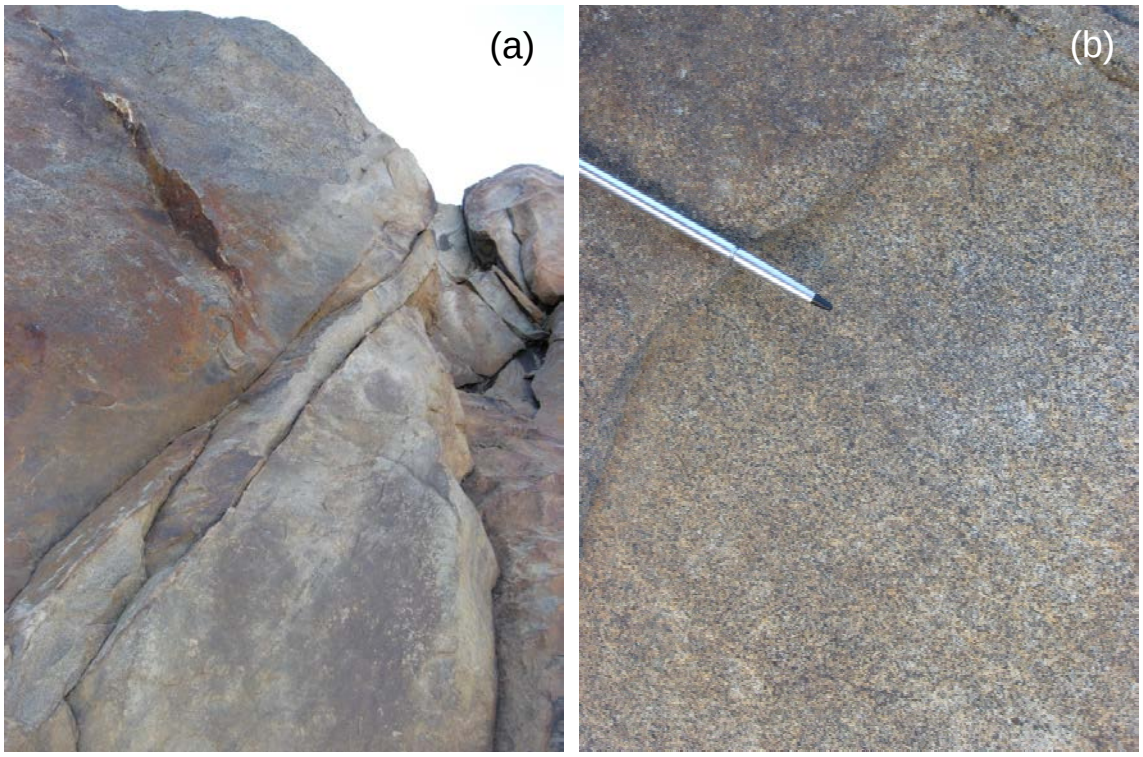

Figure 21. *Sample 527650: (a) A fine-grained monzonite cutting a coarse-grained gabbro as a dyke-like intrusion with blurry contacts. (b) Close-up showing the isotropic monzonite texture that was sampled for U-Pb dating.*

Data interpretation:

Zircon grains are generally an- to subhedral with a range of sizes (50 – 250 µm) and aspect ratios (1:2 – 1:5) (Figure 22). A total of 56 spots were analysed of which 53 are concordant at the 100 ± 10 % level, and none of the analysed spots have any significant common Pb contents. In the Concordia diagram (Figure 22) the data plot as a single population with an upper intercept age of 2714 ± 4 Ma (MSWD = 1.3; n = 55). A similar age of 2712 ± 4 Ma (MSWD = 1.2; n = 51) is derived from a weighted mean of the 90-110% concordant grains. This age is interpreted as the intrusion age of the monzonite and provides a minimum age for the Njords Gletscher Gabbro. A single grain yields an age of 2810 ± 13 Ma, interpreted as an inherited grain from the basement gneisses.

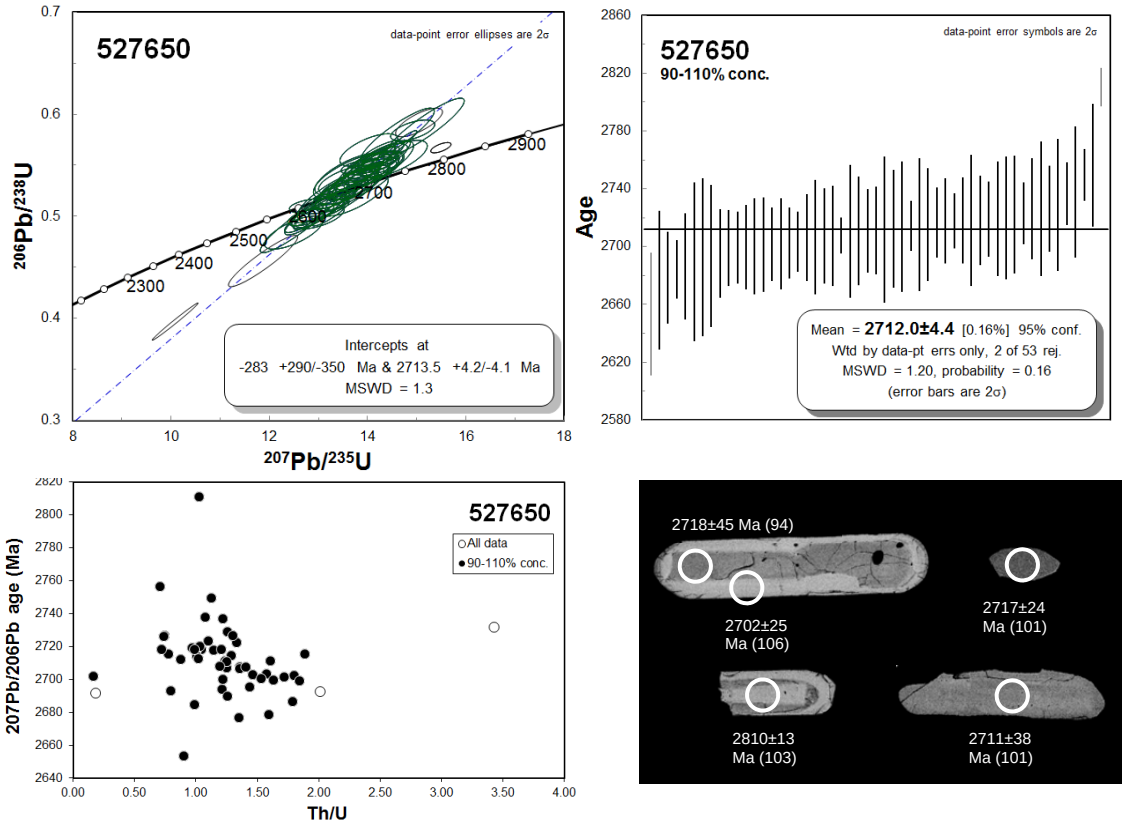

Figure 22. *U-Pb data for sample 527650: The zircon grains constitute a single age population with an age of 2712 ± 4 Ma (MSWD = 1.2; n = 51) based on a weighted mean of the 90-110% concordant grains.*

Banded gneiss (527651)

Locality: Hermods Vig Diorite 2, Njords Gletscher
Ganfeld station: 11TFK131
Coordinates: N 63.35160, W 41.50832
Collector: TFK, MBK
Collection date: 05/08/2011
Description: Banded grey gneiss with mesocratic and leucocratic components (Figure 23). The gneiss constitutes the country rock to the Hermods Vig Diorite 2. The sample collected for age dating contains mainly the mesocratic part whereas the leucocratic part occurs as thinner veins and streaks of flesh-coloured alkali feldspar, in places developed as augen. The grey gneiss is generally uncommon in the main Skjoldungen area (which is dominated by agmatitic gneiss), but has been found further to the north (see Næraa et al. 2016). It is therefore interesting to find out if the mesocratic part could represent some other (older?) remnant of sialic crust in the Skjoldungen area. The sample taken for age dating contains both the mesogratic and leucocratic parts, and thus expectedly contains a mixed zircon population.
Purpose: To date the gneiss basement in the area (from paleosome zircons) and provide a maximum age for the intrusion of the Njords Gletscher Gabbro (from neosome zircons).

Figure 23. *Sample 527651: Banded grey gneiss containing a grey palaeosome part and streaks of flesh-coloured alkali feldspar syenite (neosome).*

Data interpretation:

Two main zircon age populations are observed; an older broadly defined age group of 3027 ± 23 Ma is constituted by a group of more complexly zoned (paleosome) zircons (Figure 24). A younger age population with a better defined age of 2745 ± 11 Ma is constituted by the neosome zircons that have absent or weakly defined, simple zonation. The older age is interpreted as the protolith intrusion age of the basement in the area, whereas the younger age corresponds to an early stage of the SAP magmatism; either sourced by this, or reflecting remobilisation of pre-existing basement at this time.

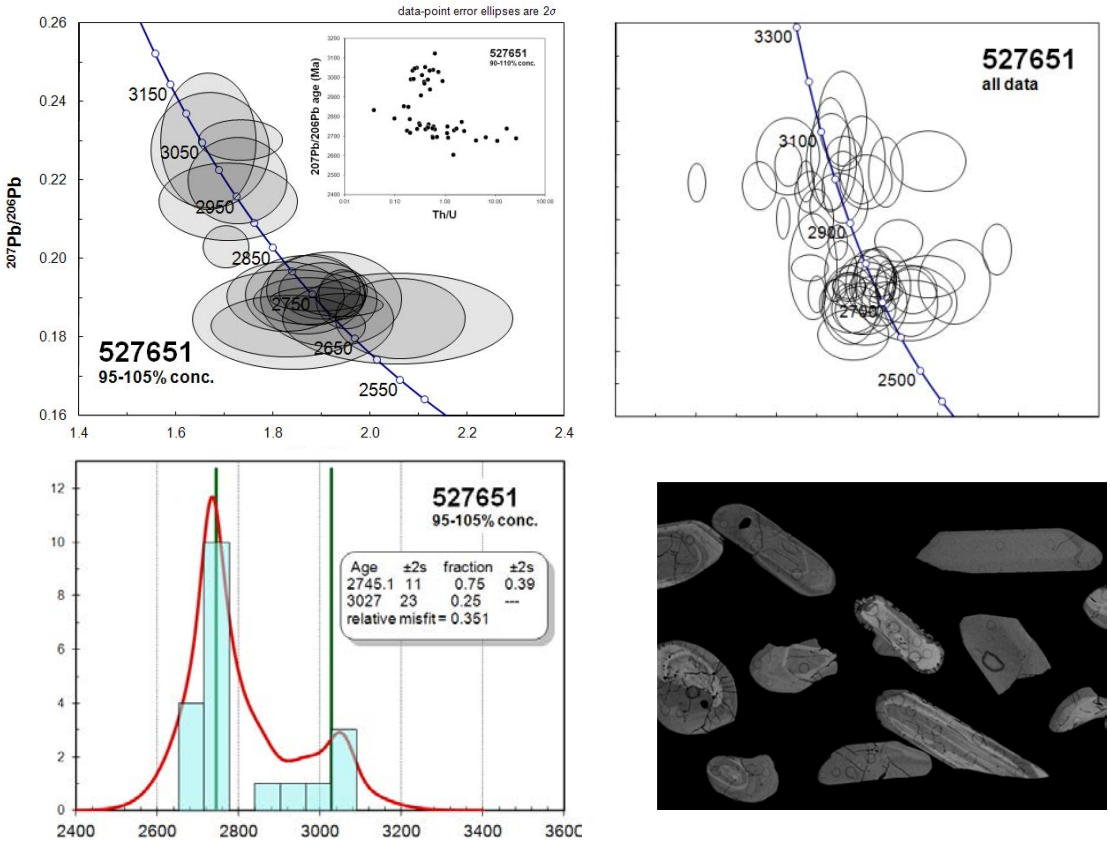

Figure 24. *Sample 527651: Based on the highly concordant grains of 100 ± 5% two zircon populations are identified: a smaller paleosome population constituting a broadly defined age of 3027 ± 23 Ma, and a neosome population with better defined age of 2745 ± 11 Ma. The older zircon population include an- subhedral, complexly zoned grains, whereas the younger include sub- euhedral grains with absent or simpler zonation patterns.*

Granitic aplite (535962)

Locality: Hermods Vig Diorite 2, Njords Gletscher, upper part (1/2 day drop off)
Ganfeld station: 12TFK076
Coordinates: N 63.35124, W 41.51390
Collector: TFK, CT, ABO, BPM, LTH
Collection date: 10/12/2012
Description: Felsic pegmatoidal vein (1 m wide) intruding the host gabbro with sharp contacts (Figure 25).
Purpose: To date the latest stage sialic magmatism in the area, and by inference, to obtain a minimum age of the gabbroic intrusion. The age will reflect the timing of brittle deformation at the observed crust.al level.

Figure 25. *Field photo of 535962. Granitic aplite sharply cutting coarse-grained mesocratic gabbro.*

Data interpretation:

A total of 130 spots were analysed and of these 79 produced good data, whereas 30 spots had variable amounts of common Pb (filtered out). Of the 79 acceptable data spots 63 are concordant at the 100 ± 10% concordancy level. The concordant zircons constitute a single age population with a weighted 207Pb/206Pb age of 2688 ± 6 Ma (n/N = 61/64; MSWD = 0.67) (Figure 26). This age reflects the crystallisation age of the aplitic dyke and also provides a minimum age for the host gabbro. Unlike previous back-veins into gabbroic intru-

sions, the sharper and more regular contacts along this aplite vein reflects brittle fracturing, indicating that cooling of the mafic host pluton was fairly progressed at this point in time.

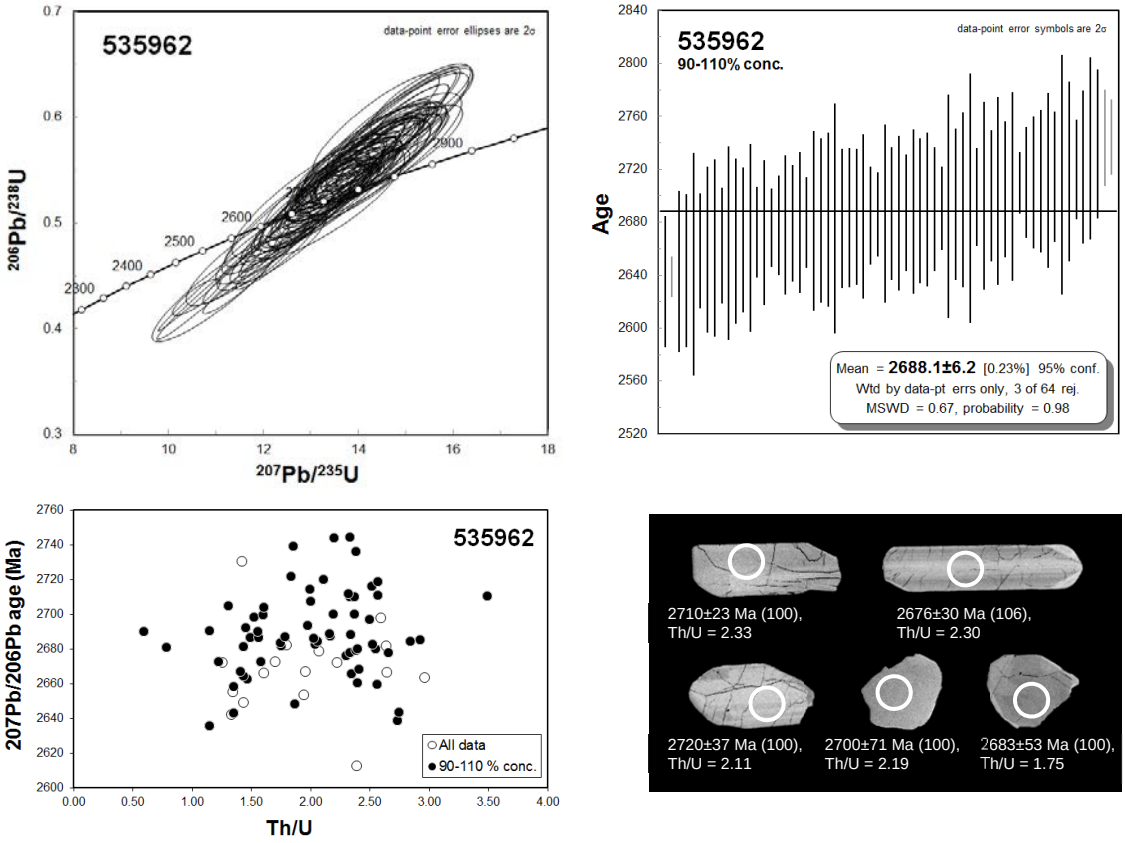

Figure 26. *U-Pb data for sample 535962. The analysed zircons constitute a single age population with an age of 2688 ± 6 Ma (n/N = 61/64; MSWD = 0.67) which reflects the intrusion age of the aplitic dyke and yield a minimum age for the host gabbro.*

Granitic pegmatite (535968)

Locality: Hermods Vig Diorite 2, Njords Gletscher
Ganfeld station: 12TFK081, helicopter reco stop near exposed top of intrusion
Coordinates: N 63.35168, W 41.51521
Collector: TFK, CT, AB, BMP, LT
Collection date: 10/08/2012
Description: Coarse-grained, isotropic, granitic pegmatite with alkali feldspar, plagioclase, quartz and biotite, intruded into gabbro c. 100 m from upper contact to gneiss basement (Figure 27).
Purpose: To date the granitic pegmatite and by inference obtain a minimum age of the gabbroic intrusion.

Figure 27. *535968: Granitic biotite pegmatite cutting the gabbroic intrusion of Njords Gletscher Gabbro (Hermods Vig Diorite 2).*

Data interpretation:

The analysed zircons constitute a single age population of sub- to euhedral zircons with an age of 2696 ± 4.4 Ma (n/N = 74/74; MSWD = 1.07) (Figure 28). This age reflects the intrusion age of the felsic pegmatite and also provides a minimum age for the host gabbro.

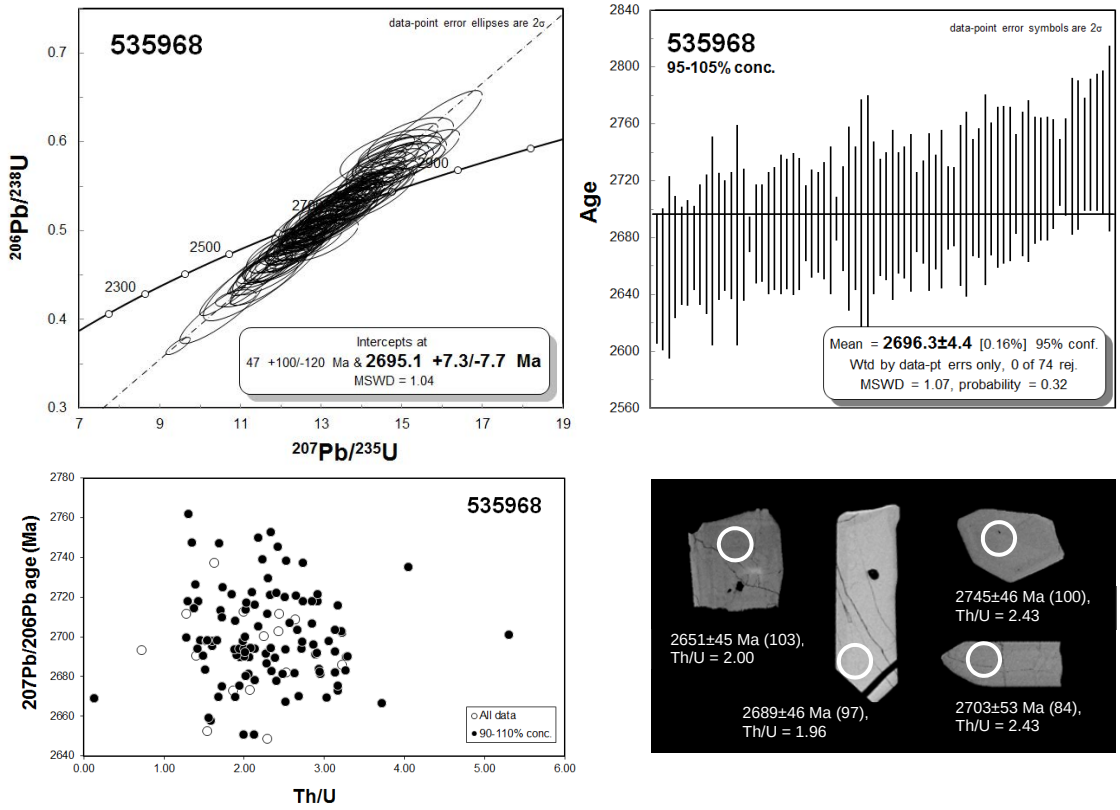

Figure 28. *U-Pb data for sample 535968: The analysed zircons constitute a single age population with an age of 2696 ± 4.4 Ma (n/N = 74/74; MSWD = 1.07). This age reflects the intrusion age of the felsic pegmatite and also provides a minimum age for the host gabbro.*

Leucocratic granitoid vein (535980)

Locality: Hermods Vig Diorite 2, Njords Gletscher
Ganfeld station: 12TFK088, helicopter reco stop near exposed top of intrusion
Coordinates: N 63.35243, W 41.51734
Collector: TFK, CT, AB, BMP, LT
Collection date: 10/08/2012
Description: Leucocratic granitoid vein in the uppermost marginal zone of the gabbro intrusion where a variety of hybrid rocks occur over a 10-20 m wide zone (Figure 29). The vein could represent remobilisation of wall rock basement as response to the heating from the gabbro intrusion.
Purpose: Date the intrusion of the Njords Gletscher Gabbro and test remobilisation hypothesis by looking for inherited zircons from basement gneisses.

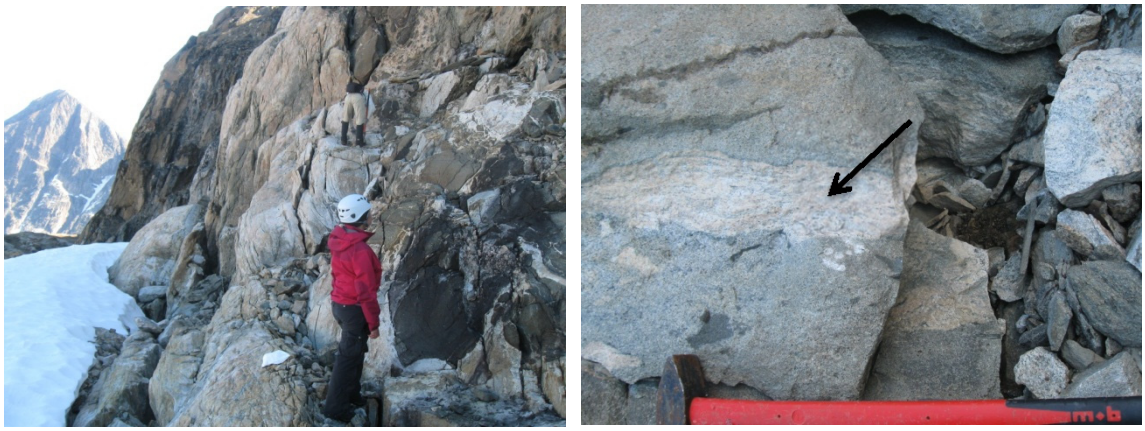

Figure 29. *Left: Outcrop at the upper contact zone of the Njords Gletscher Gabbro (in middle background) and the agmatitic basement (to the right of person in red jacket). Right: Sample 535980 is taken in the contact zone where leucocratic granitoid veins infiltrate a zone of interpreted hybrid rocks.*

Interpretation:
An age of 2734 ± 16 Ma is based on the zircon grains with high Th/U (>0.9), and is interpreted as the intrusion age of an earlier (SAP related) intrusive event (Figure 30). The age thus predates the Njords Gletscher Gabbro, yet the vein infiltrates a zone of interpreted hybrid rocks that must then also be older.

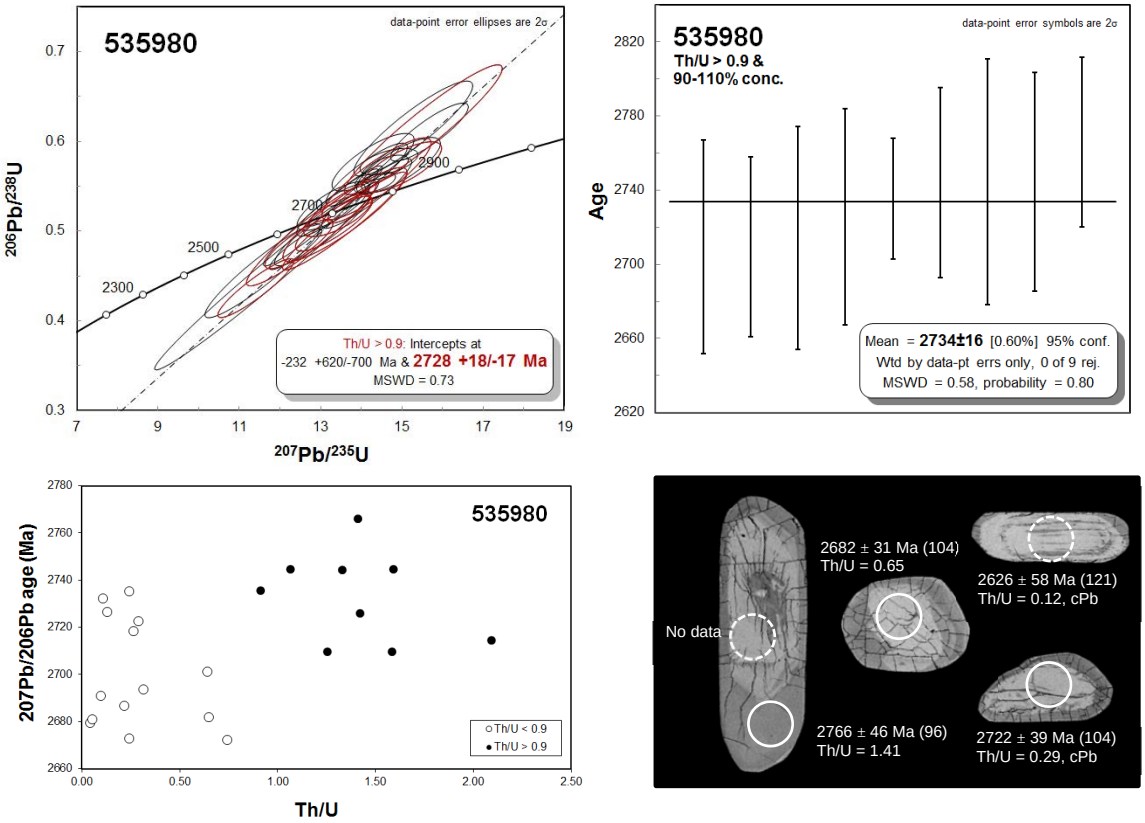

Figure 30. *U-Pb data for sample 535980: Data with Th/U > 0.9 constitute a homogeneous age population with an upper Concordia intercept age of 2728 +18/-17 Ma, which is overlapping but somewhat younger than the age based on a weighted average of the 100 ± 10% concordant grains giving an age of 2734 ± 16 Ma. Grains with low Th/U are suspect of being open systems and thus no meaningful age can be derived from this group.*

Summary

A felsic sheet cutting the Hermods Vig Diorite 1 intrusion gives three ages: (1) an inherited population from the gneiss basement of 3010 ± 25 Ma, (2) a younger inherited population at 2783 ± 6 Ma (presumably also related to the gneisses), and (3) a younger magmatic population at 2709 ± 4 Ma. The younger age gives the intrusion age of the syenitic vein and provides a minimum age for the Hermods Vig diorite 1 intrusion.

Dating of cross-cutting felsic sheets in the Hermods Vig Diorite 2 intrusion, also referred to as the Njords Gletscher Gabbro, provide slightly younger felsic intrusion ages of 2688 ± 6 Ma and 2696 ± 4 Ma for a granitic aplite and a granitic pegmatite, respectively, of which the latter age date establishes a minimum age for the mafic intrusion itself. A sample of the country rock to the Njords Gletscher Gabbro of grey gneiss basement yields a neosome age of 2745 ± 11 Ma and paleosome age of 3027 ± 23 Ma. The former age provides a maximum age for the Njords Gletscher Gabbro and likely reflects an early stage of syntectonic SAP intrusions in the area as also recorded by a vein infiltrating the contact zone. The latter age represents the protolith intrusion age of the gneiss basement and matches up with the inherited grains found in Hermods Vig Diorite 1 syenitic vein (527637).

Halvdans Fjord, Anarnitsoq Island and Kong Skjold Halvø

Geological background

In the eastern part of the SAP, an area between Halvdans Fjord and Kong Skjolds Halvø includes a number of late-kinematic intrusions ranging from mafic and ultramafic to intermediate and evolved compositions. The geological map indicates that the agmatitic gneiss basement that makes up the country rock in this area, is intruded by sets of foliation-parallel intrusive NW-SE trending bands (of up to some hundred meters width) of either dioritic or granitic composition. In addition to these more subtle lithological bands, the more distinct Halvdans Fjord gabbro is situated on the eastern side of the fjord, constituting one of the largest mafic-ultramafic intrusions of the SAP. This intrusion includes a range of gabbro, gabbronorite and pyroxenite units, that commonly appear foliated in the field, and therefore is likely to represent a syntectonic intrusion. As also stated in Klausen & Kokfelt (2014), it is sometimes difficult to discriminate between agmatitic TTG gneiss host rocks and younger syntectonic intrusions belonging to the SAP, as the latter may appear foliated and often contain inclusions of mafic lithologies, thus resembling agmatitic gneiss. Dating of various lithologies from the Halvdans Fjord area will constrain the timing of the syntectonic intrusive SAP stage in this region and these new age data may furthermore help to distinguish between cases where deformed SAP rocks are mistaken for the agmatitic gneiss basement.

Results

Gneissose granitoid (527528)

Locality: Halvdans Fjord, inner part (new exposure in front of retreating glacier)
Ganfeld station: 11TFK005
Coordinates: N 63.27619, W 41.35051
Collector: TFK, MBK
Collection date: 21/07/2011
Description: Intermediate to coarse-grained, gneissose, felsic granitoid with plagioclase, alkali feldspar, quartz and amphibole (Figure 31). The rock constitutes the country rock and dominates an ice-polished surface area in front of a retreating glacier at the north-eastern end of Halvdans Fjord. The area is cut by a number of melano-mesocratic dykes and dykelets (< 1-2 m wide) with a general WNW-ESE orientation and with characteristic irregular blurry contacts to the country rock, indicating syntectonic intrusion into a partially solidified country rock.
Purpose: Date the syntectonic stage of granitoid intrusions within the eastern part of the SAP.

Figure 31. *Sample 527528: Tectonised gneissose granitoid rock from the north-eastern part of Halvdans Fjord, dissected by melanocratic veins.*

Data interpretation: Majority of zircons are fairly large (up to 0.5 mm), prismatic with widely variable aspect ratios of 1:2 – 1:6. Zircon grains are often irregularly zoned, sometimes showing relict zoning patterns, and surrounded by often intensely cracked rim domains (Figure 32). The U-Pb data is dominated by a single age peak at 2727 ± 6 Ma constituting 91% of all grains within the 90-110% concordancy interval (Figure 32). This main age group reflects the intrusion age of the granitoid and is concurrent with another granite sample from the western side of Halvdans Fjord (527534). In addition two grains give a rough age of 3017 ± 25 Ma, which are interpreted as inherited from the gneiss basement.

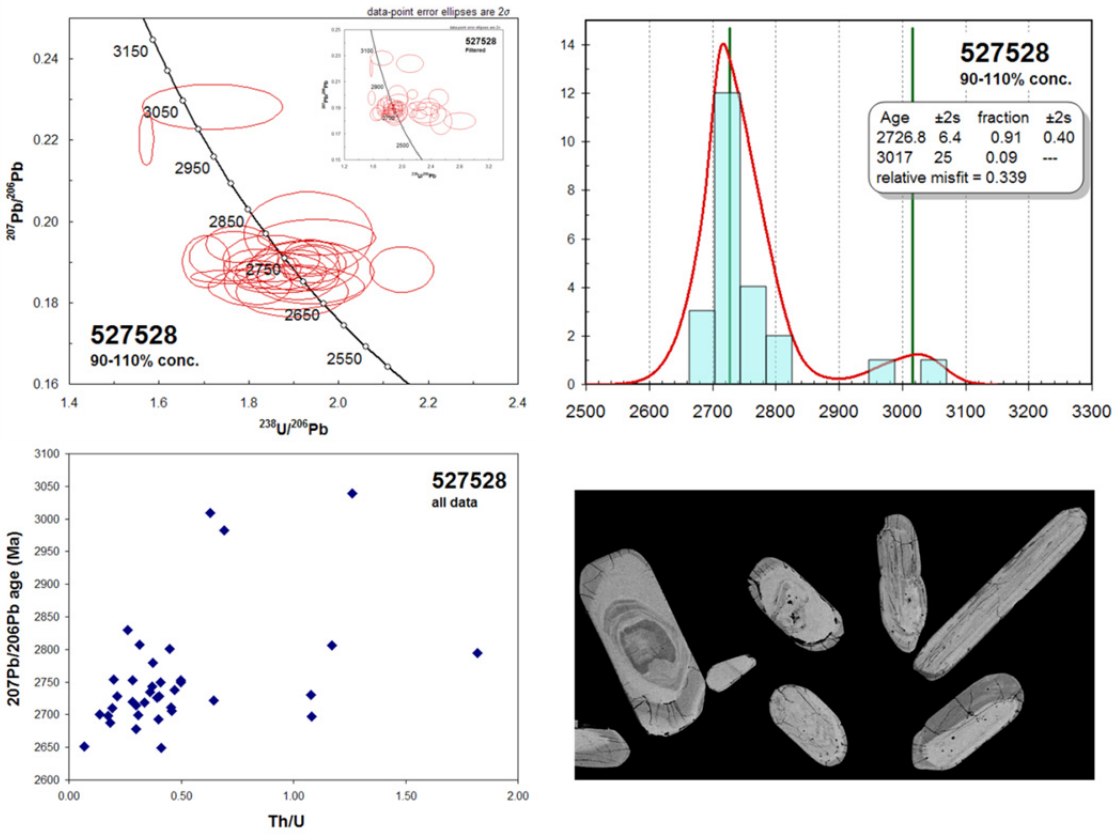

Figure 32. *Sample 527528: The syn-kinematic intrusive granitoid yields a main age peak at 2727 ± 6.4 Ma interpreted as the intrusion age of the granitoid. Two inherited grains give an age of ~3020 Ma.*

Syntectonic granite (527534)

Locality: Halvdan Fjord, western side
Ganfeld station: Not entered in Ganfeld station
Coordinates: N 63.24486; W 41.37314
Collector: TFK, MBK
Collection date: 22/07/2011
Description: Medium to coarse-grained, weakly foliated granite (Figure 33). The granite is associated with a series of dioritic bands that cut across the basement gneisses in a generally NW-SE direction. The granite intrusion most likely belongs to the felsic magmatism that is evident in the south-eastern part of the SAP and includes band-like granitic units between Halvdans Fjord and Kong Skjolds Halvø.
Purpose: Date the late magmatic stage of granitoid intrusions in the Halvdan Fjord area and link this temporally to the remainder of the felsic intrusives in the area (see 535925 and 509945).

Figure 33. *Sample 527534: Medium- to coarse-grained granite, weakly foliated.*

Data interpretation: Zircons are variably sized (50-200 µm), mostly anhedral to subhedral, prismatic, semi-rounded and with aspect ratios of 1:2 – 1:4 (Figure 34). Most grains have relict zonation patterns with dark cores and two consecutive overgrowth rims (a bright one followed by a dark) of which the outer rim is often radially cracked. In some cases a thin (<10 µm), bright outer rim is also observed. The grains resemble magmatic zircons that have been variably affected by metamorphic re-equilibration.

The main zircon population plots on or close to Concordia and yields an intersection age of 2729 ± 10 Ma (MSWD = 1.3) (Figure 34). A similar age of 2734 ± 8 Ma (MSWD = 1.3; n = 26) can be derived be taking a weighted mean of the most concordant grains (100 ± 10%). A minor age peak of 2872 ±13 Ma is inferred by using the 'unmix' function of Isoplot. The younger age (2734 ± 8 Ma) is interpreted as the intrusion age of the granite, whereas the older is interpreted as inherited.

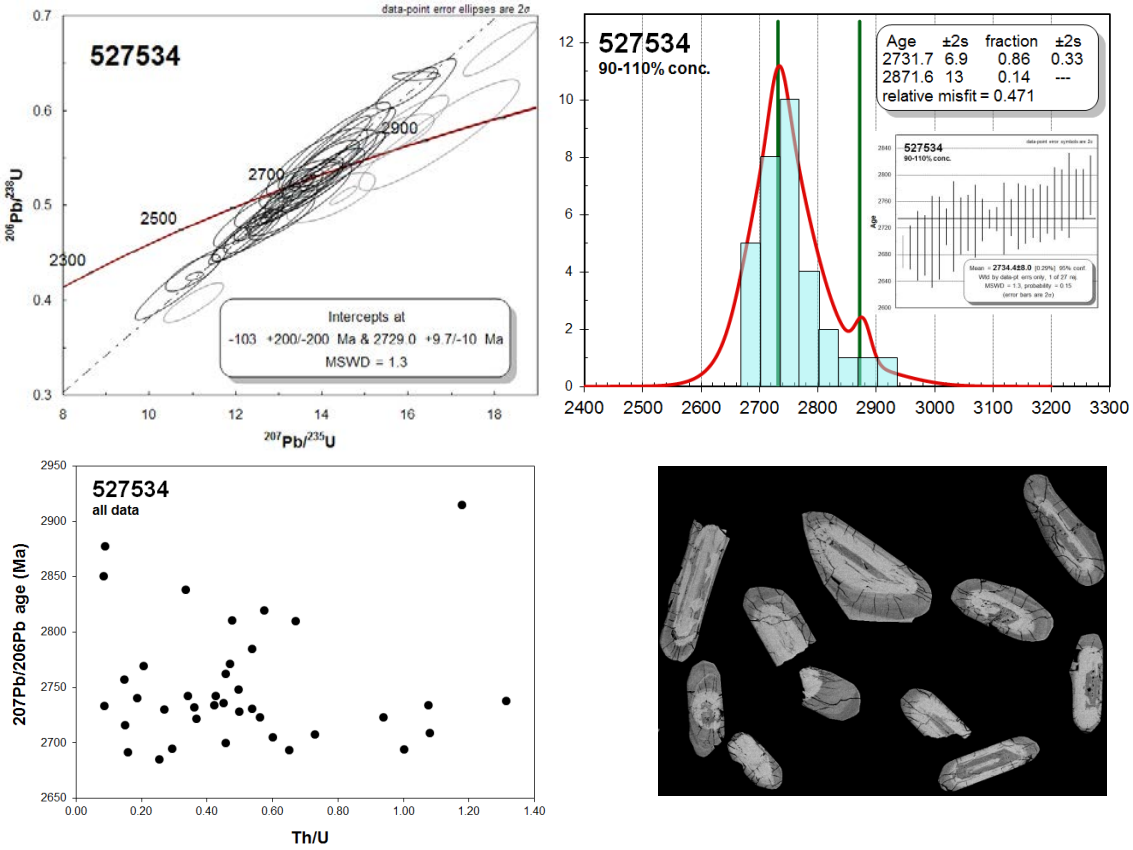

Figure 34. *Sample 527534: On the Concordia diagram most of the data plot close to Concordia and the main zircon population constitutes a Concordia intersect age of 2729 ± 10 Ma (MSWD = 1.3) (note that grey error ellipses are excluded from the age calculation). A similar age of 2734 ± 8 Ma (MSWD = 1.3; n = 26) is derived based on a weighted mean of the 90-110 % concordant grains. Three inherited grains give an age of 2872 ±13 Ma.*

Gneissose granite (527547)

Locality: Halvdans Fjord, eastern side
Ganfeld station: 11TFK002
Coordinates: N 63.25929º W 41.33795º
Collector: TFK, MBK
Collection date: 20/07-2011
Description: Medium to coarse-grained greyish granite with gneissic fabric, consisting of alkali feldspar, plagioclase quartz, amphibole and biotite (Figure 35). The granite is cut by at least three generations of later melano to mesocratic dykes and dykelets of presumed mafic – intermediate composition. The granite makes up a rather chaotic contact zone to the Halvdans Fjord gabbro that is situated some 100 m further eastwards. Field relations suggest that the granite either predates the mafic intrusion (based on the number of mafic veins cutting across the granite), or that it is contemporaneous to the mafic intrusion. In any case, it's evident foliated fabric suggests that it intruded at a stage when deformation was still active in the region.

Purpose: Dating of the granite will provide the timing for the syn-tectonic stage of granitoid intrusions within the SAP of this region, and will likely also give the maximum intrusion age of the Halvdans Fjord gabbro, if not the intrusion age itself.

Figure 35. *527547: Gneissose granite cut by multiple generations of meso-leucocratic dykelets. Insert: Close-up of granite showing the foliation of the granite constituted by the mafic phases (biotite and amphibole).*

Data interpretation:
Zircons are variably sized (50-150 µm), mostly subhedral, and with aspect ratios of 1:3 – 1:5. Most grains have relict zonation patterns with relatively bright (U-rich) cores and dark (U-poor) mantles and rims (Figure 36). Internal cracks are uncommon, but occur in some darker rim domains. The grains resemble magmatic zircons variably overprinted by metamorphic re-equilibration. Most spots are analyses of cores, but there is no significant age difference detected between cores and rims. Out of 103 spots analysed, 43 were to various degrees affected by common Pb, and these were filtered out of the data set. The remaining 60 analyses cluster around the Concordia with some scatter below the curve suggesting minor effects of recent Pb-loss (Figure 36). Based on a regression line through all data an upper intercept age of 2717 ± 5 (MSWD = 4.0) Ma is calculated. In comparison a weighted mean age based on the most highly concordant grains (100 ± 2%) gives 2711 ± 5 Ma

(MSWD = 1.02; n = 23). The latter of these two ages are taken as the most robust and interpreted as the intrusion age of the granite.

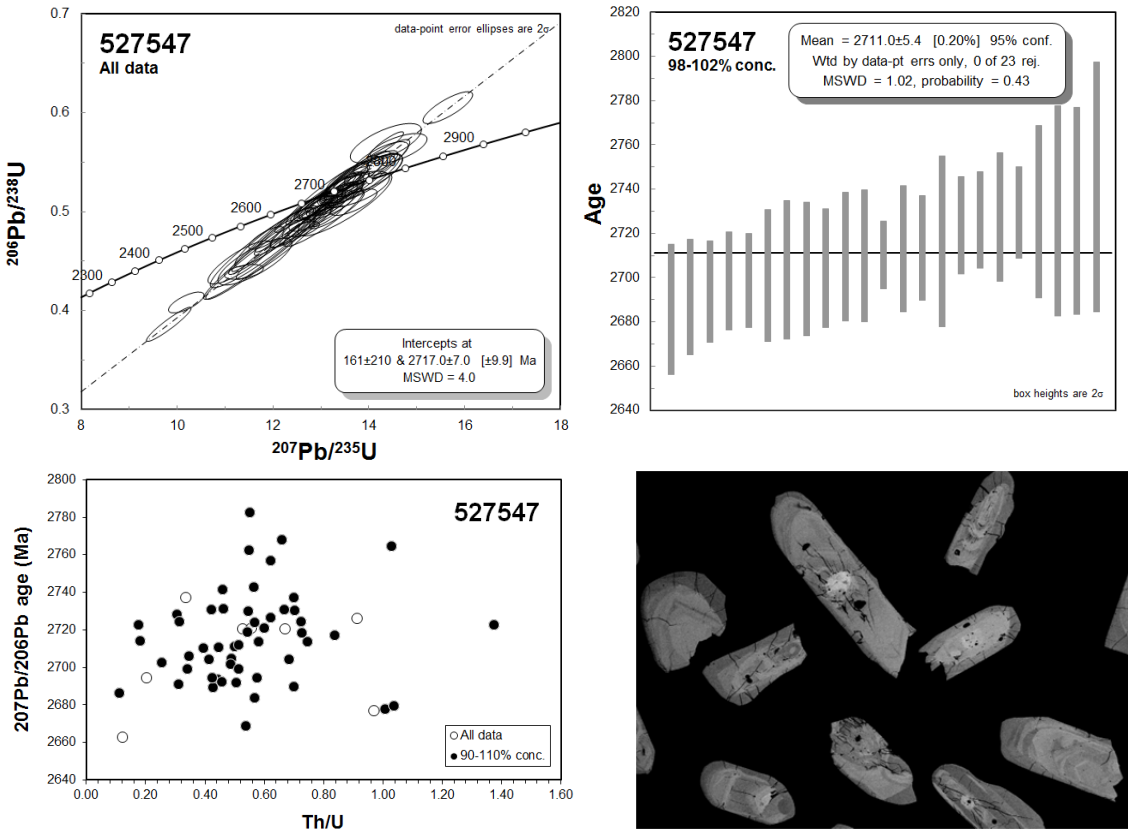

Figure 36. *Sample 527547: In the Concordia diagram the data cluster around the Concordia with some scatter to indicate recent Pb-loss. An intrusion age of 2711 ± 5 Ma (MSWD = 1.02; n = 23) is calculated based on a weighted mean of the most highly concordant grains (100 ± 2%).*

Felsic pegmatite/aplite (527540)

Locality: Halvdans Fjord, south-eastern part
Ganfeld station: Not entered in Ganfeld station
Coordinates: N 63.23928; W 41.33126
Collector: TFK, MBK
Collection date: 22/07/2011
Description: A bimodally coarse/fine-grained reddish granitoid dyke (Figure 37) with alkali feldspar, quartz and biotite. This pegmatite/aplite dyke is 30-50 cm wide and exposed on the south-eastern shoreline of the Halvdan Fjord, where it cuts the gabbroic rocks of Halvdan Fjord intrusion obliquely across the internal foliation. The sample used for zircon U-Pb dating was collected from an aplitic part of the dyke.
Purpose: Date the latest post-tectonic magmatic stage of granitoid intrusions within the Halvdan Fjord region.

Figure 37. *527540: Felsic pegmatite/aplite dyke (arrow) cutting mafic rocks of the Halvdans Fjord mafic intrusion (to the left) at contact zone to felsic basement (?) rocks (to the right). The dyke is c. 30 cm wide and cuts obliquely across the foliation of its mafic host rocks.*

Data interpretation:
Majority of zircons are fairly large (up to 500 µm), semi-rounded, elongate grains with irregular zonation patterns of alternating bright (U-rich) and dark (U-poor) domains. In some cases core domains show relict zoning and are surrounded by relatively darker rim domains that are relatively intensely cracked.

The isotope data (Figure 38) display a single age population with an upper Concordia intercept age of 2697 ± 5 Ma (MSWD = 1.4). This age represents the intrusion age of the felsic dyke. The age provides a minimum age for the Halvdans Fjord mafic – ultramafic intrusion, and also a minimum age for the post-tectonic stage of the SAP in this region.

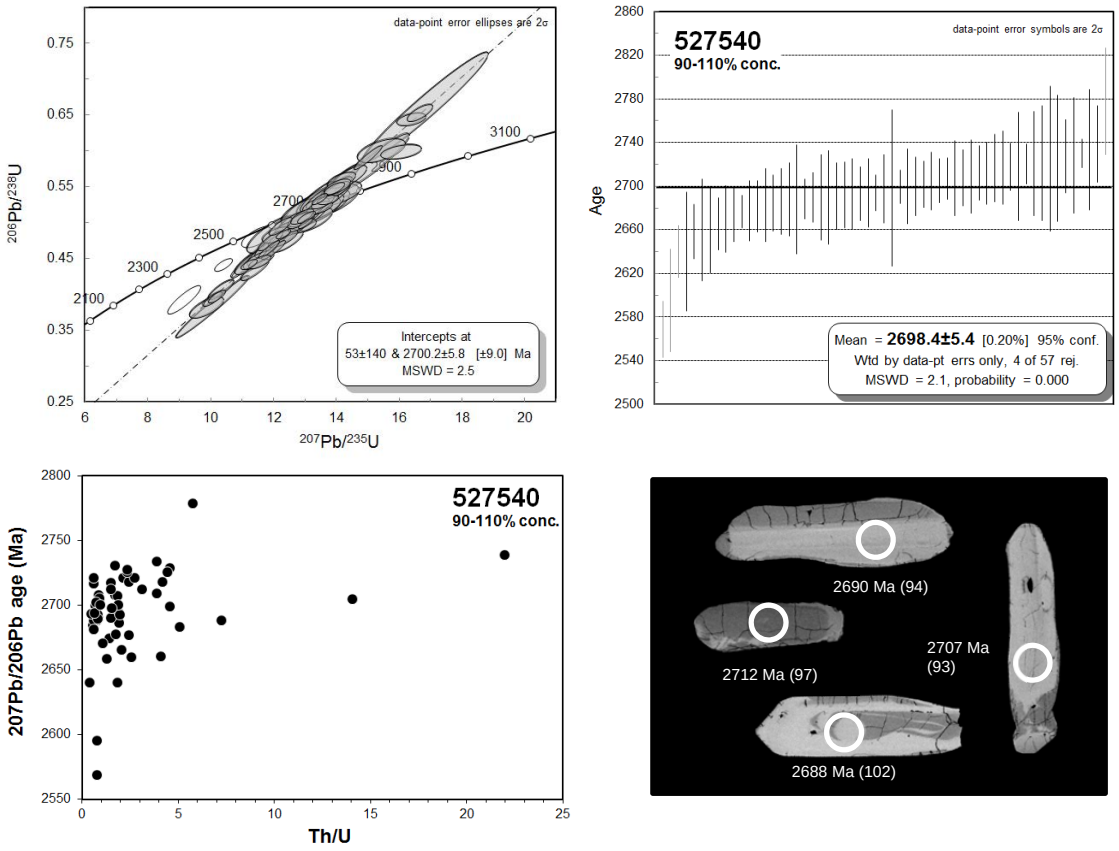

Figure 38. *Sample 527540: Data define a single age population with a well-defined upper Concordia intercept age of 2697 ± 5 Ma (MSWD = 1.4). Based on the 100 ± 10 % concordant grains a weighted average age of 2698 ± 5 Ma (MSWD = 2.1; N = 53) is derived.*

Felsic pegmatite dyke (527609)

Locality: Halvdans Fjord, North-east side
Ganfeld station: 11TFK008
Coordinates: N 63.27644, W 41.34316
Collector: TFK, MBK
Collection date: 21/07/2011
Description: The mafic-ultramafic intrusion of the Halvdans Fjord is in many places cut by a network of younger post-deformational felsic pegmatites. The sample selected for U-Pb dating represents such a zone of intense granitoid pegmatite stockwerk-style intrusions (Figure 39). The sample is taken from a 15-25 cm wide irregular sheet that cuts the gabbro and an obliquely trending deformed dyke with characteristic blurry contacts to the gabbro.
Purpose: Date the age of the post-tectonic pegmatite intrusions and by inference provide a minimum age for the mafic-ultramafic SAP intrusion in the Halvdans Fjord region.

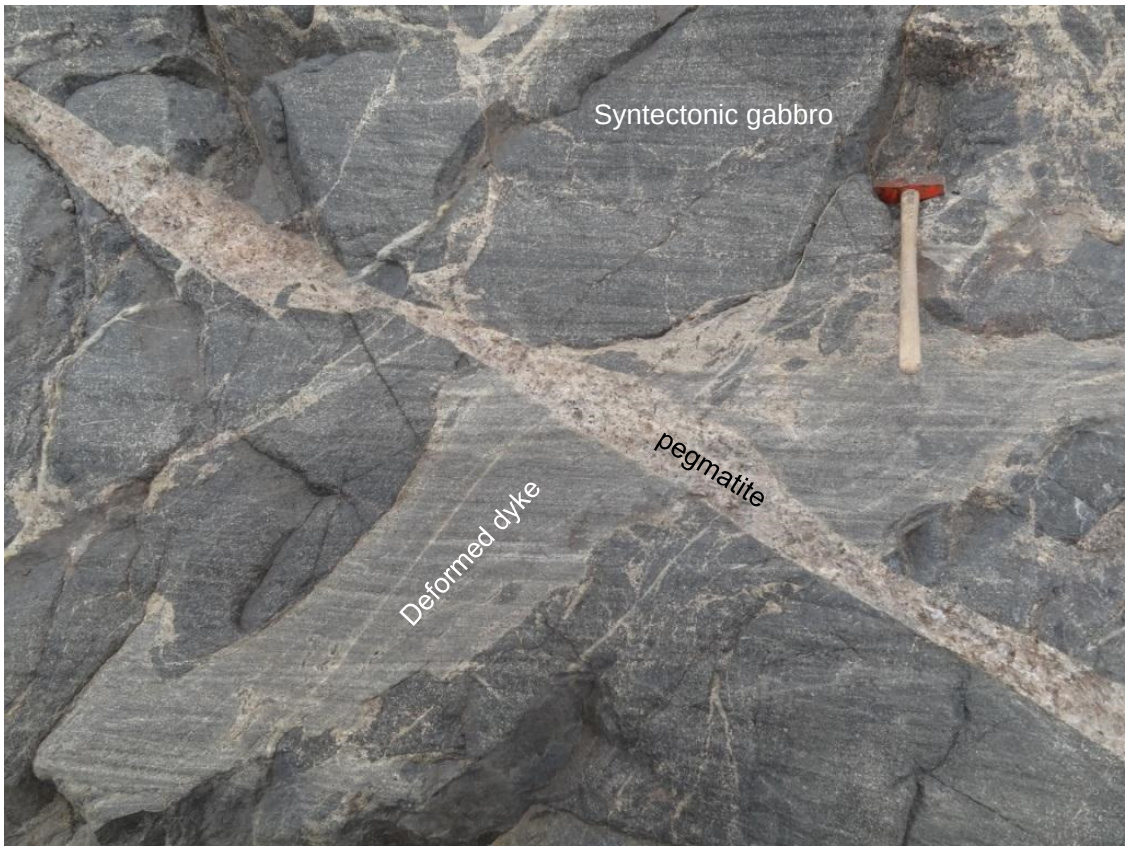

Figure 39. *Sample 527609: The gabbroic intrusion of Halfdans Fjord is locally cut by intense network of late-stage, undeformed felsic pegmatites as exemplified by sample 527609. A mesocratic so-called 'deformed dyke' of presumed intermediate composition is also cut by the felsic pegmatite and therefore predates it.*

Data interpretation:

Zircon grains are strongly anhedral of variable size (up to 150 µm) and shape and show evidence of being formed interstitially and late in the crystallisation sequence (Figure 40). Larger grains sometimes contain diffuse magmatic zoning with brighter central domains and darker outer domains. A total of 36 spots were analysed and of these only four analyses are outside the 100 ± 10% concordancy range. In the conventional Concordia diagram (Figure 40) all data spots, except one which is younger, define a single isochron with an upper intersect age of 2695 ± 12 Ma (MSWD = 1.08; n = 35). Fourteen grains have $^{206}Pb/^{204}Pb < 1000$, but as these grains have similar calculated ages as other grains, no common Pb correction was applied. The filtered data (i.e. 100 ± 10% concordant and $^{206}Pb/^{204}Pb > 1000$) produce a similar age of 2695 ± 12 Ma (MSWD = 0.78; n = 19), which is taken as the intrusion age of the felsic pegmatite and the latest magmatic activity in the Halvdans Fjord area. A single slightly reversely discordant grain gives an age of ~2550 Ma; the significance of this age is uncertain but could represent ancient Pb loss.

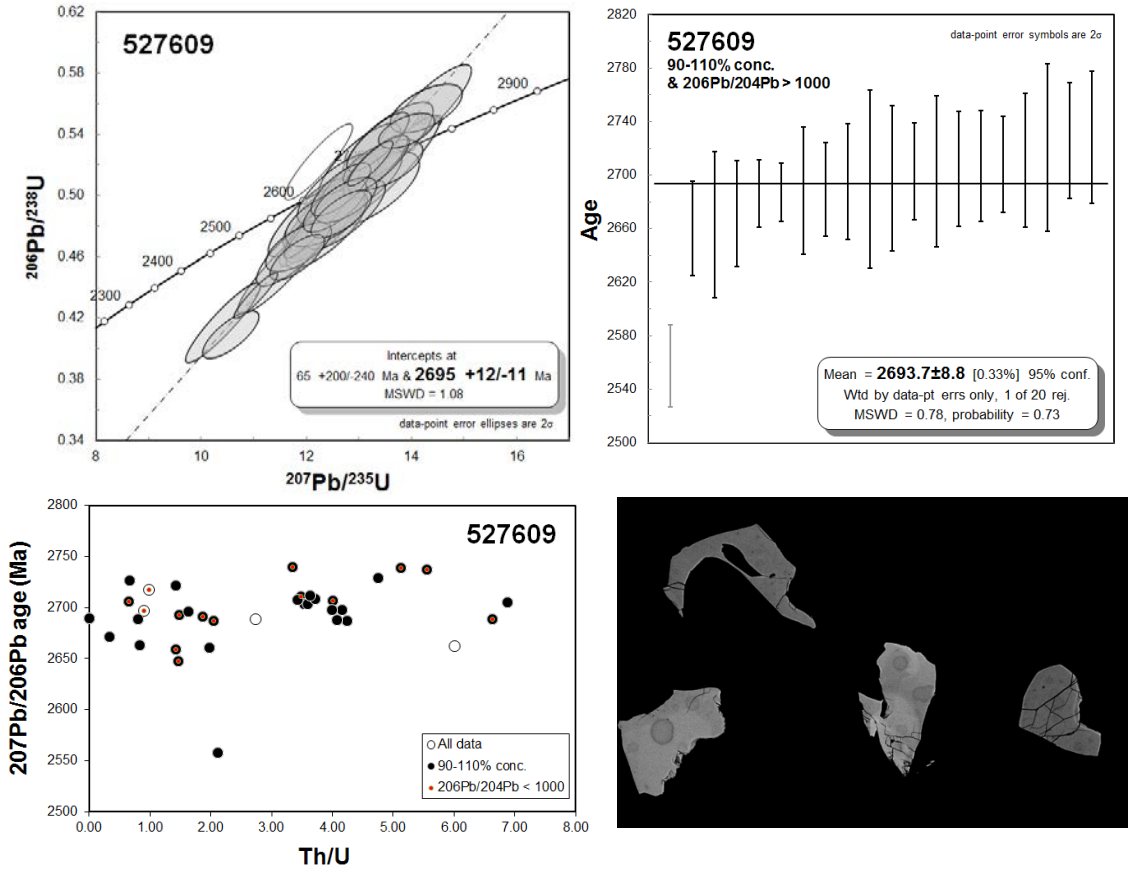

Figure 40. *Sample 527609: Strongly anhedral zircon grains indicate late-stage growth in interstitial pore spaces. An intrusion age for the felsic pegmatite of 2694 ± 9 Ma is derived from the filtered data (i.e. grains that are 100 ± 10% concordant and have $^{206}Pb/^{204}Pb > 1000$).*

Quartz syenite (535925)

Locality: Anarnitsoq island, South-east of Yrsa Fjord
Ganfeld station: 12TFK051
Coordinates: N 63.19343, W 41.24039
Collector: TFK, ABO
Collection date: 06-08-2012
Description: Coarse-grained quartz syenite, weakly foliated (Figure 41).
Purpose: Date the intrusion age of the granite. The granite is weakly foliated (130/82˚NE) with a strike parallel to the overall NW-SE trending bands that dominate the south-eastern part of the SAP, from the inner part of Halvdans Fjord over Anarnitsoq island to Kong Skjolds Halvø.

Figure 41. *535925: Coarse-grained felsic granite showing moderate foliation as defined by general alignment of alkali feldspars. The granite is presumed to be intruded syntectonically. Hammer head for scale is 12 cm long.*

Data interpretation:
Zircon grains vary in size, shape and texture, but are generally 50-150 µm in the longest dimension, sub- to anhedral and with aspect ratios of 1:2 – 1:4 (Figure 42). Most grains have faint magmatic zoning. In the Concordia diagram (Figure 42), the majority of data points cluster around the Concordia line with a few grains being distinctly discordant, some also reversely discordant. Based on the 90-110% concordant grains a well-defined age of 2699 ± 5.7 Ma (n/N = 36/39, MSWD = 0.85), interpreted as the intrusion age of the granite. Two grains yield an imprecise age of 2848 ± 31 Ma interpreted as inherited from the gneiss basement.

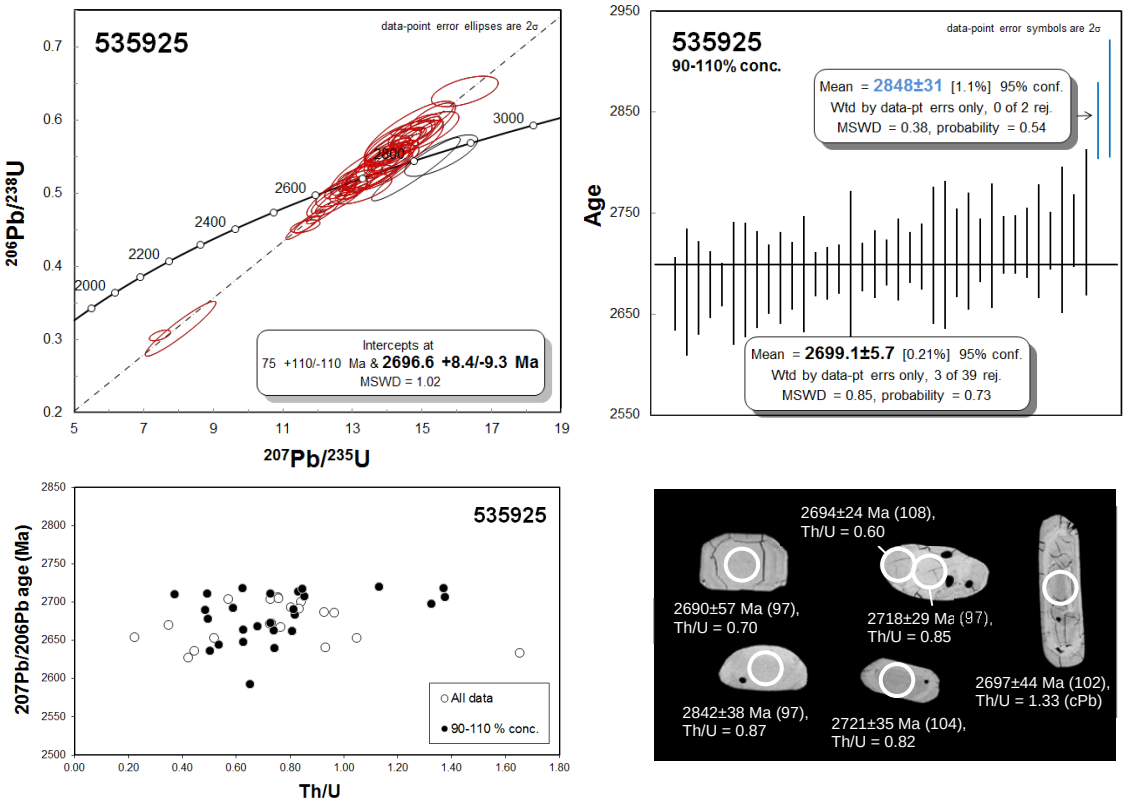

Figure 42. *U-Pb data for sample 535925: Majority of data define a single age population with a well-defined upper Concordia intercept age of 2697 +8/-9 Ma (MSWD = 1.02). Based on the 100 ± 10 % concordant grains a weighted average age of 2699 ± 5.7 Ma (MSWD = 0.85; n/N = 36/39) is derived. Two grains give an age of 2848 ± 31 Ma interpreted as inherited age from the basement gneisses.*

Medium-grained granite (509345)

Locality: Bikuben, Kong Skjold Halvø (845 m.a.s.l.)
Ganfeld station: Helicopter reco stop with rotors running
Coordinates: N 63.12758, W 41.31439
Collector: TFK, CT, ABO, BPM, LT
Collection date: 16/08/2012
Description: The Bikuben mountain, located on the eastern part of Kong Skjold Halvø, was visited while hovering/landing during a transit helicopter flight from Iglermiut Island and back to base camp in central Skjoldungen. Bikuben and the peaks east of it all have characteristic steep, spiky appearances (Figure 43, top), typical for the felsic intrusions of the Skjoldungen area. The Bikuben summit consists of frost-shattered, medium-grained, weakly foliated granite (Figure 43, bottom), and not agmatitic gneiss as otherwise indicated on the 1:500 000 scale geological map. A grab sample (of certain local origin) was taken for U-Pb dating and whole rock geochemistry.
Purpose: Date the age of the granite intrusion from Bikuben and compare this to other granites from the granitic units dissecting the basement gneisses as bands in the south-eastern part of the SAP from Kong Skjold Halvø and onto the Halvdans Fjord area.

Figure 43. *Sample 309345: Grab-sampling of granite on top of Bikuben (845 m.a.s.l.) during a 'soft landing' (notice hovering helicopter). Top: View towards the south with Bikuben on the right-hand side. Bottom: View towards the north; the peak consists of weakly foliated granite with a rubbly surface due to frost-shattering.*

Data interpretation:

Zircon grains are subhedral, relatively small (generally <100 µm) and elongate, semi-rounded with aspect ratios of 1:3 – 1:4 (Figure 44). The grains often display magmatic zoning often with clear core and rim domains. Some grains have metamict cores surrounded by intensely cracked mantle domain. A total of 112 spots were analysed of which only 40 returned acceptable data without any influence from common Pb; 50 spots had common clear influence of common Pb (not included). The data are generally concordant with only seven analyses falling outside the 100 ± 10% concordancy interval. In the Concordia diagram (Figure 44), the analyses constitute two broad age groups, a large age group at c. 2700 Ma and a loosely defined, smaller age group at 2826 ± 23 Ma (MSWD = 0.16; n = 4). In more detail the younger age group may be divided into two groups based on Th/U; one sub-group with Th/U < 0.3 (average U = 1374 ppm) yields an age of 2676 ± 11 Ma (MSWD = 0.40; n = 12), another sub-group with Th/U = 0.30 – 0.50 (average U = 732 ppm) gives an older age 2720 ± 15 Ma (MSWD = 1.6; n = 16). An upper Concordia intercept age for the latter group gives 2711 ± 16 Ma (MSWD = 0.56; n = 20). One interpretation is that age of 2720 Ma reflects the intrusion age of the granite, and the older 2820 Ma age reflects inheritance. The younger age group of 2676 Ma is uncertain but could reflect a late overprinting

event that produced high-U zircons from late- to post-magmatic fluids. Alternatively the intermediate 2720 Ma age group is a mixed age group reflecting insufficient spot resolution.

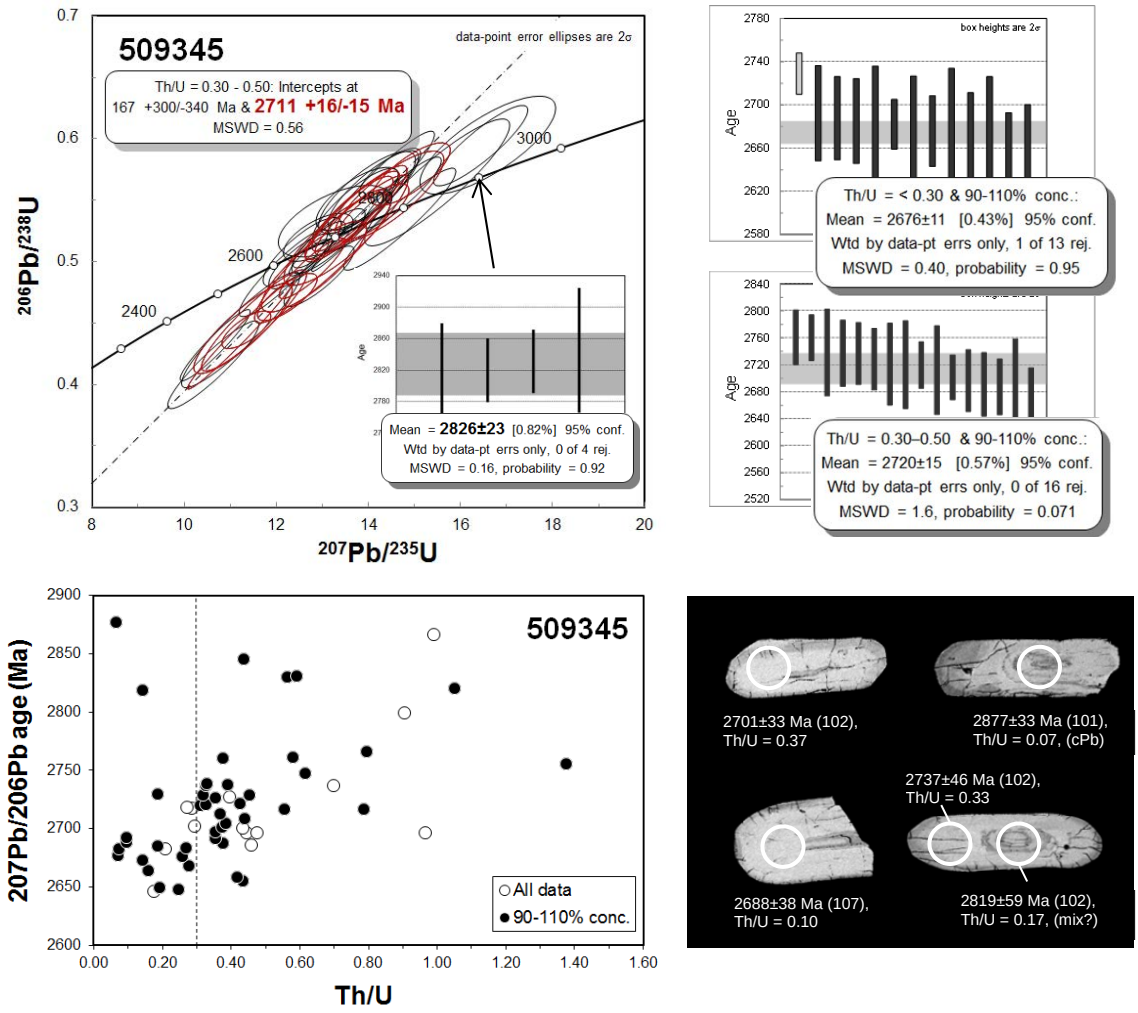

Figure 44. *U-Pb data for sample 309345: The analyses constitute two broad age groups, a large age group at c. 2700 Ma and a loosely defined, smaller age group at 2826 ± 23 Ma (MSWD = 0.16; n = 4). The younger age group may be divided into two groups based on Th/U; one sub-group with Th/U < 0.3 with an age of 2676 ± 11 Ma (MSWD = 0.40; n = 12), and a sub-group with Th/U = 0.30 – 0.50 giving an age 2720 ± 15 Ma (MSWD = 1.6; n = 16).*

Summary

Three granitic intrusions from the NW-SE trending bands have been dated from Halvdans Fjord, Anarnitsoq Island and Kong Skjold Halvø. The two southernmost samples yield consistent ages of 2699 – 2711 Ma (within analytical uncertainty), whereas the granite sample from the eastern side of Halvdans Fjord is slightly older, 2732 Ma (outside analytical error). At face value, this could indicate that the felsic magmatism is oldest in the north, but this is conclusion must be taken cautiously based on the low number of dated granite samples.

An age of a gneissose granite from the contact zone of the Halvdans Fjord gabbro intrusion suggests that the latest tectonism occurred at 2711 ± 5 Ma, as well as provides a likely crystallization age for the large mafic intrusion as the heat from the mafic magmas are thought to have contact metamorphosed the immediately surrounding rocks. Two post-tectonic felsic pegmatites/aplites from Halvdans Fjord give consistent ages of c. 2694 – 2697 Ma, providing the timing of the latest SAP magmatism in this part of the province.

Stærkodder Vig

Geological background

Compared to Halvdan Fjord most of the SAP-related igneous intrusions west of Stærkodder Vig are pervasively sheared and foliated and the area is heavily dissected by brittle faults and thrusts, including an abundance of pseudotachylite breccia veins. The field work in the Stærkodder Vig area included a traverse across a band of variably deformed dioritic-melagabbroic intrusions emplaced into the agmatitic gneiss basement. The large mafic-ultramafic intrusion indicated on the 1 : 500 000 scale map, extending across a large area between Stærkodder Vig and Balders Fjord, was not accessed on the ground. However, judging from inspection from overflying the area in a helicopter, the area seems to consist of mainly gabbroic rocks that are intensely dissected by felsic pegmatites, and thereby resemble the upper part of the mafic intrusion in Halvdans Fjord. The precise relationship between the studied outcrops of gabbro and diorite at the inner parts of Stærkodder Vig and the larger Stærkodder Vig intrusion is uncertain. It seems unlikely however that they are directly related (i.e. part of the same intrusive body) and that Stærkodder Vig probably represents a fault zone along which rocks north and south of the fjord have been displaced relative to each other (see also Klausen & Kokfelt 2014).

Three samples have been dated from the Stærkodder Vig area: (1) a gneissose felsic rock that constitutes the tectonized host lithology in the area, (2) a foliated, monzonite belonging to the syntectonic stage of the SAP magmatism, and (3) a late felsic pegmatite vein that provides a minimum age for the diorite that it intersects, and a maximum age for a cross-cutting deformed dyke.

Gneissose granodiorite (527560)

Locality: Stærkodder Vig
Ganfeld station: 11TFK061
Coordinates: N 63.25567; W 41.68811
Collector: TFK, MBK
Collection date: 28/07/2011
Description: Tectonised, medium-grained, gneissose granitoid with a sugary, massive appearance, intersected by mesocratic veins and dykelets (Figure 45). The E-W orientated glacial valley defines a major fault zone as evidenced by the occurrence of tectonized rocks. Numerous pseudotachylites found in the area could be related to movements along this fault, or along a thrust that is observed in the northern valley side (see Klausen & Kokfelt, 2014).
Purpose: Date the basement rocks in the Stærkodder Vig area. If possible, to date tectonism associated with the E-W trending fault zone.

Figure 45. *Sample 527560: Tectonised gneissose granitoid with a sugary, massive appearance, here cut by a 30 cm wide mafic dyke that is slightly discordant to the foliation of the granitoid. The granitoid is exposed on the northern side of the E-W trending glacial valley (note glacier ice rim at lower left corner) that also hides a major fault zone.*

Data interpretation:

Zircons are typically anhedral of variable size (50 – 200 µm), and with aspect ratios of 1:2 – 1:4 (Figure 46). Some grains show complex zoning with alternating dark (U-poor) and bright (U-rich) zones in core domains resembling relict magmatic zoning, others are more homogeneous. In the Concordia diagram (Figure 46) the data generally smear out along the Concordia line enclosing ages between c. 2700 and 3200 Ma, but with a tendency towards the lower ages showing increasing amount of discordancy, presumably reflecting recent Pb loss effects in these grains. Of the 57 analysed spots, the majority have $^{206}Pb/^{204}Pb$ <1000, and 44 analyses were cPb corrected adding to the uncertainty of the quality of these spots. Of the remainder 13 data points for which cPb was not present, ten are 100 ± 10% concordant. From a filtered subset of data, and disregarding the intermediate ages (they could reflect mixed ages?), two seemingly robust age groups can be extracted: (1) An older group at 3157 ± 22 Ma (N = 6, MSWD = 2.0) made up from core analysis of complexly zoned grains, and (2) a younger and somewhat better defined age group at 2702 ± 8 Ma (MSWD = 0.73; N = 6) consisted by texturally homogeneous grains. The older age is interpreted as the intrusion age of the gneiss protolith, whereas the younger age likely reflects the timing of SAP magmatism in this area. As expected, it is not readily possible to discern an age related to the pervasive tectonic activity associated with either an inferred fault zone or observed thrusts in the area.

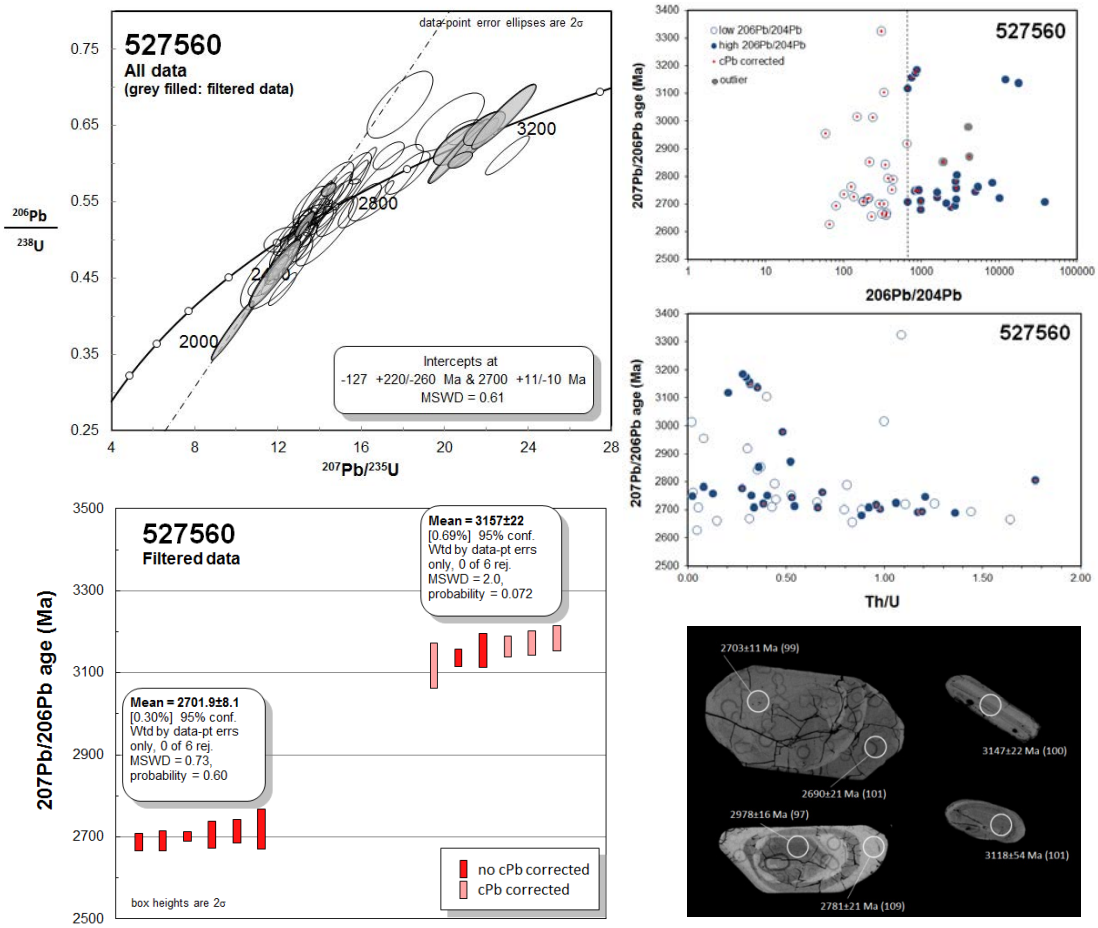

Figure 46. *Sample 527560: The U-Pb data generally smear out along Concordia enclosing ages between c. 2700 and 3200 Ma. Two age groups can be extracted from the data by assuming intermediate ages reflect mixed ages; an older group made up from core ages of complex grains yields an imprecise age of 3157 ± 22 Ma (N = 6, MSWD = 2.0), and a younger age group consisted by texturally homogeneous grains yields an age of 2702 ± 8 Ma (N = 6, MSWD = 0.73).*

Gneissose quartz monzonite (527557)

Locality: Stærkodder Vig
Ganfeld station: 11TFK059
Coordinates: N 63.25413; W 41.66134
Collector: TFK, MBK
Collection date: 27/07/2011
Description: Medium to coarse-grained gneissose quartz monzonite near contact to diorite /gabbro (Figure 47).
Purpose: Age dating will constrain the timing of the syntectonic granitoid SAP magmatism in the Stærkodder Vig area.

Figure 47. *527557: Medium – coarse-grained gneissose quartz monzonite near contact to diorite /gabbro in the Stærkodder Vig area. Sample label tape is 1 cm wide.*

Data interpretation: Zircons are of variable size (30-200 µm) and are generally subhedral with aspect ratios of 1:2 – 1:3. Zircon grains are often faintly zoned with internal darker (U-poor) cores that are variably cracked surrounded by brighter (U-rich) rims (Figure 48). Majority of data are obtained from cores. In the Concordia diagram (Figure 48), the majority of grains are highly concordant and constitute a fairly tight cluster around the Concordia with a main age of 2741 ± 7 Ma (N = 45, MSWD = 1.8) based on the 100 ± 5% concordant grains. This age is interpreted to reflect the intrusion age of the monzonite. A smaller group of grains with low Th/U < 0.3 scatter around c. 2700 Ma, which either reflects rim growth during a thermal event, or alternatively the effects of ancient Pb loss.

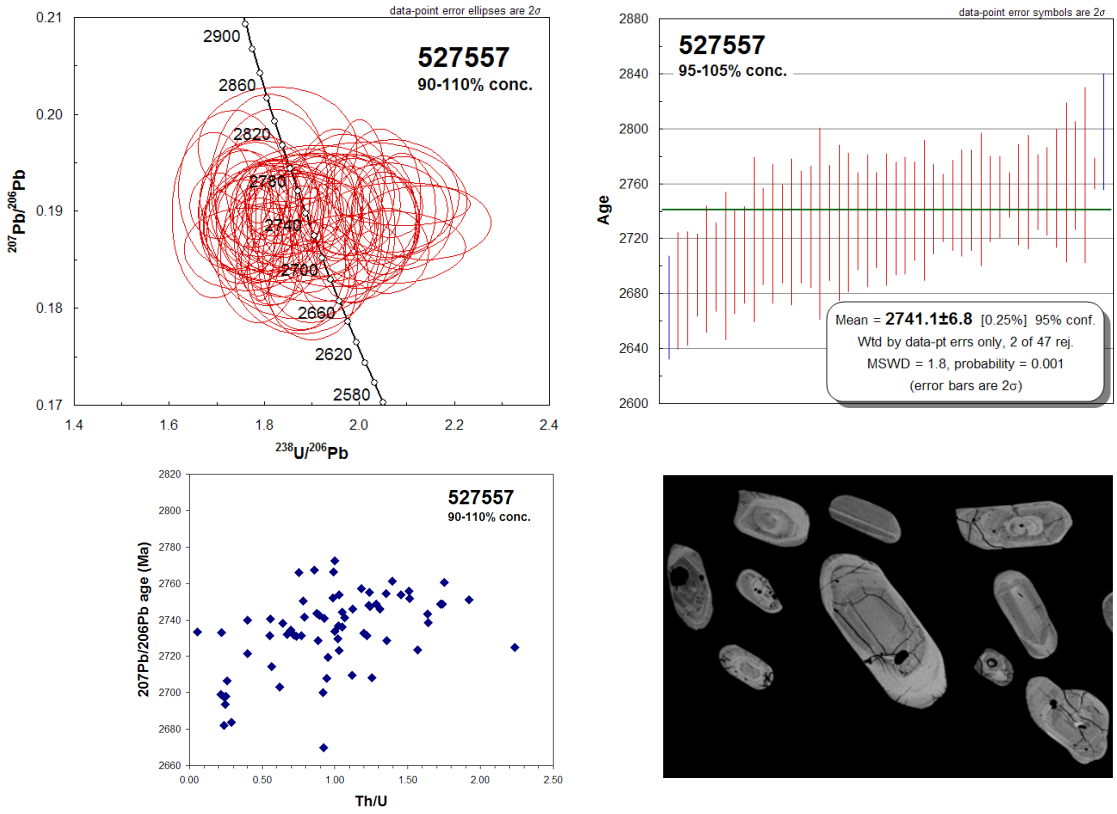

Figure 48. *Sample 527557: The majority of grains are highly concordant and constitute a fairly tight cluster around a Concordia with a main age of 2741 ± 7 Ma (n/N = 45/47, MSWD = 1.8) based on the 100 ± 5% concordant grains. This age is interpreted to reflect the intrusion age of the monzonite. A smaller group of grains with low Th/U < 0.3 scatter around c. 2700 Ma, which could reflect rim growth during a thermal event, or effects of ancient Pb loss.*

Results

Felsic pegmatite vein (527551)

Locality: Stærkodder Vig
Ganfeld station: 11TFK052
Coordinates: N 63.25975; W 41.65996
Collector: TFK, MBK
Collection date: 27/07/2011
Description: Felsic pegmatite sharply cutting a fault bounded mafic (dioritic) intrusion that is oriented WNW-ESE in the western continuation of the Stærkodder Vig. The felsic vein is obliquely cut by two deformed mesocratic dykes of presumed intermediate composition (Figure 49).
Purpose: To date the intrusion age of the aplite that also will provide a minimum age of the diorite and a maximum age of the cross-cutting deformed SAP related dykes.

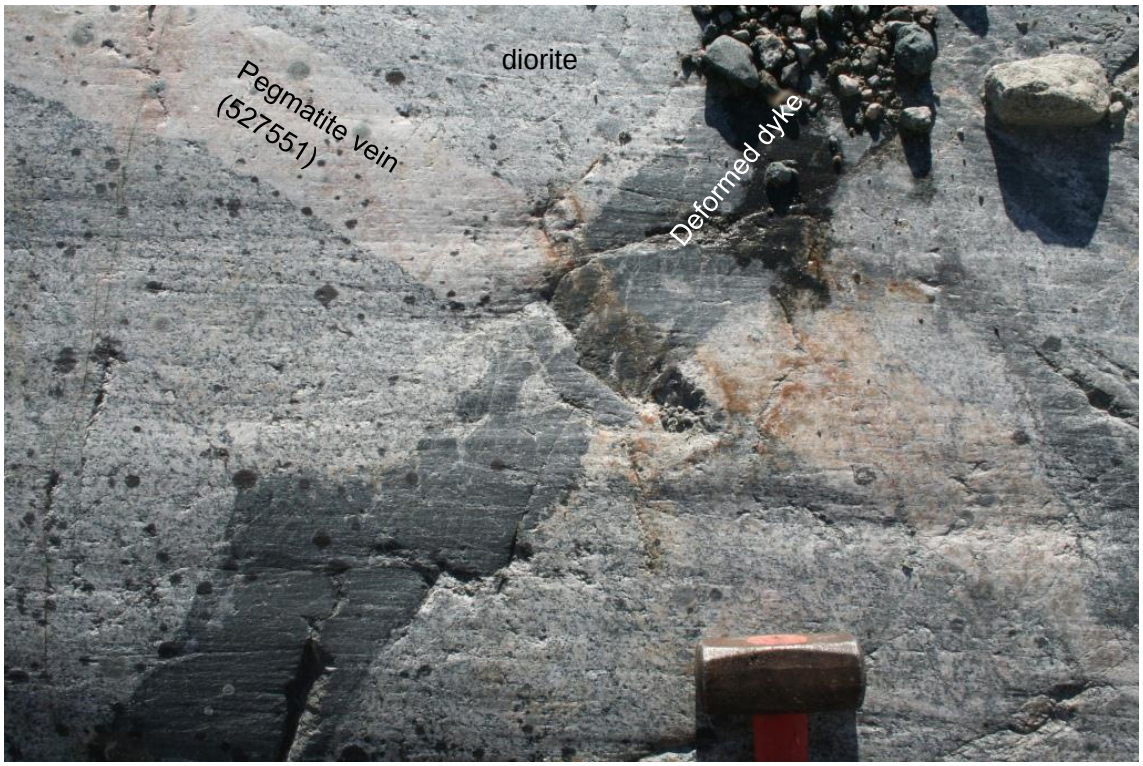

Figure 49. *Sample 527551: Field relations for sample 527551 showing cross-cutting relationship to the host diorite. The felsic pegmatite is cut by a later deformed dyke (or 'meta-dyke').*

Data interpretation: Zircon grains are generally sub- to euhedral, box-shaped to semi-rounded with aspect ratios of 1:2 – 1:4 (Figure 50). Some grains have diffuse zoning patterns often with a darker (U-poor) core surrounded by a brighter (U-rich) rim. In the Tera-Wasserburg diagram (Figure 50), the main group of data plot on the Concordia with a group of spots scattering off to the right hand side with similar $^{207}Pb/^{206}Pb$, suggesting variable effects of recent Pb loss or down hole fractionation. A calculated age of 2695 ±7 Ma (MSWD = 1.4; n = 43) is based on the weighted mean of the most concordant grains (90-106 %). This is interpreted as the intrusion age of the felsic vein and represents a minimum age of the diorite, which it intrudes, as well as a maximum age of the cross-cutting deformed dykes. A single discordant (86 %) grain yields an imprecise age of 2860 Ma, which then could be interpreted as inherited from the basement gneissic rocks.

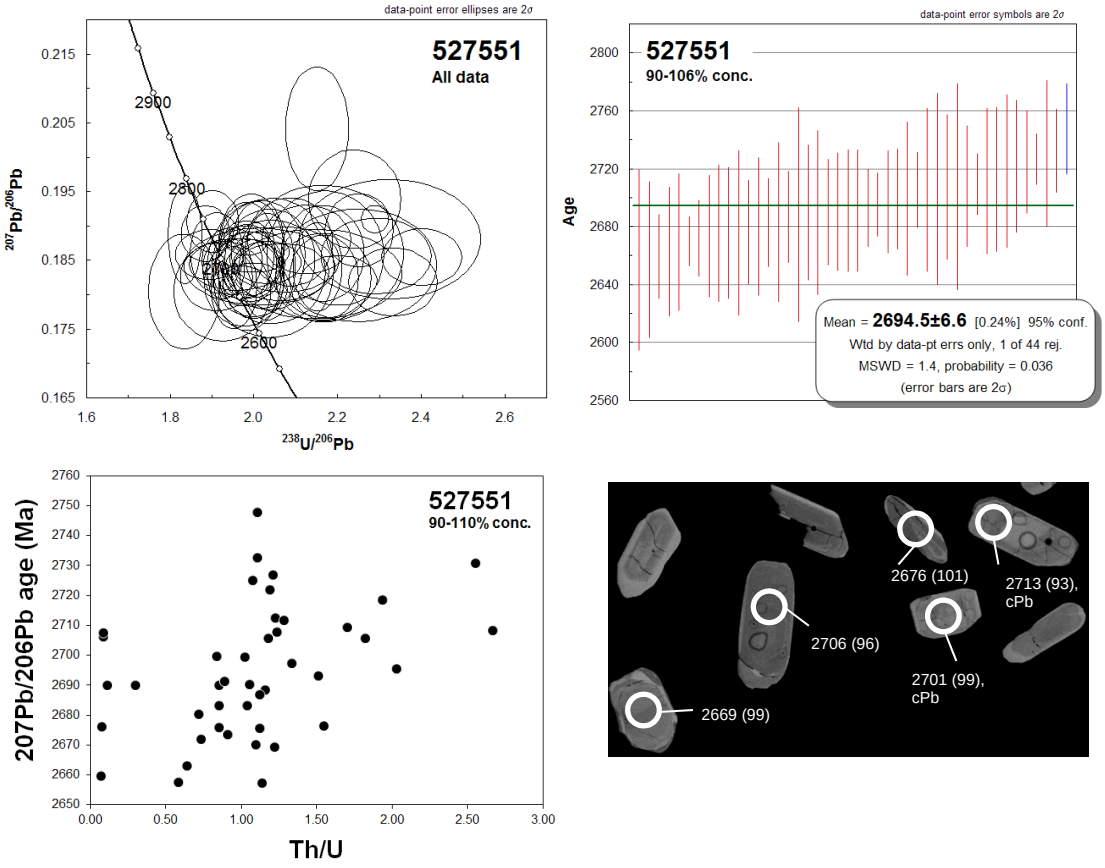

Figure 50. *527551: The zircon data represent a single age population with a weighted $^{207}Pb/^{206}Pb$ age of 2695 ±7 Ma (MSWD = 1.4; N = 43; for the 90-106 % concordant grains). This age represents the intrusion age of the felsic pegmatite vein and also provides a minimum age of the diorite, which it intersects. A single zircon grain with a discordant age of c. 2860 Ma is interpreted as inherited from the basement gneisses.*

Summary

An intrusion age of 2741 ± 7 Ma is established for a foliated monzonite, providing the timing of the syntectonic magmatic stage within this part of the SAP. The exact field relationship between the mafic intrusions and the monzonite is uncertain, but based on the foliated nature of the monzonite, the mafic intrusion most likely post-date the monzonite (i.e. are younger than 2741 Ma). A cross-cutting felsic pegmatite vein is dated at 2695 ± 7 Ma providing a minimum age for the diorite. A deformed dyke cuts the felsic pegmatite and therefore postdates this, but is probably close in time based on the blurred contacts. The gneissose granodioritic wall rock includes two age populations: (1) an inherited population at 3157 ± 22 Ma, which represents some of the oldest dated basement found so far in the Skjoldungen region, and (2) a young population at 2702 ± 8 Ma which is synchronous to the felsic pegmatite intrusion age (within error) and likely reflects a late stage of felsic magmatism that yet pre-dates the local fault activity in the Stærkodder Vig area.

Central Skjoldungen Island

Geological background

The central part of Skjoldungen Island, between Sfinksen and Hermods Vig, is characterised by agmatitic gneisses of unknown origin and should according to the geological map not host any discernible SAP intrusions. In order to verify this, three reco stops were made at various places in this mountainous part of Skjoldungen, targeting possible SAP intrusives for age dating.

Results

Medium-grained granite (509387)

Locality: Central northern Skjoldungen Island, Reco stop
Ganfeld station: 12TFK183
Coordinates: N 63.41935, W 41.66803
Collector: TFK, CT, ABO, BPM, LT
Collection date: 20/08/2012
Description: The outcrop is dominated by agmatitic gneiss basement, which is intruded by granite as irregular sheets (Figure 51). The granite partially engulfs the gneiss and its components and displays a weak and variable foliation, possibly related to feldspars that were flow orientated during emplacement rather than regional deformation.
Purpose: To date the SAP related granitic magmatism in the central part of Skjoldungen Island, and to evaluate the extent of interaction between granite and host gneiss.

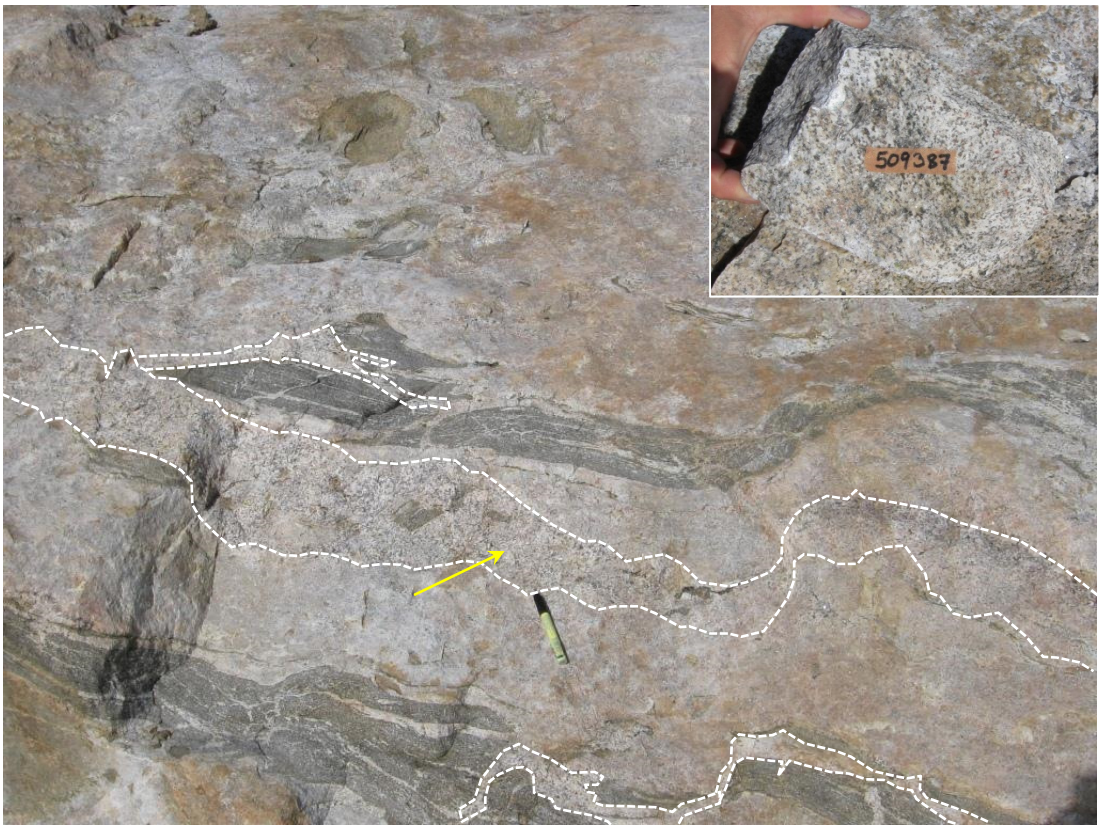

Figure 51. *Field photo of 509387: The SAP-related granite intrudes the agmatitic basement in as irregular, relatively coarse-grained sheets (approximated by white stippled outline), and partly entrains mafic components of the gneiss. Insert photo shows the collected hand specimen for dating; note the granite appears coarser-grained than the surrounding gneiss basement.*

Data interpretation:

105 spots only produced 38 good analyses without common Pb, and of these, 33 fall within the 100 ± 10% concordancy range. These data span a wide age range from c. 2200 to 3200 Ma with two fairly well-defined age plateaus at c. 2715 and 3100 Ma, respectively. In the Concordia diagram (Figure 52), a main age population intersects the Concordia at 2716 ± 15 Ma (MSWD = 1.3) that are interpreted as the intrusion age of the granite. A similar age of 2714 ± 13 Ma (n = 18, MSWD = 1.10) may be deduced based on the 90-110% concordant grains. In addition, four grains constitute an age group with an imprecise age of 3103 ± 60 Ma, which is interpreted as an inherited population from the gneiss basement.

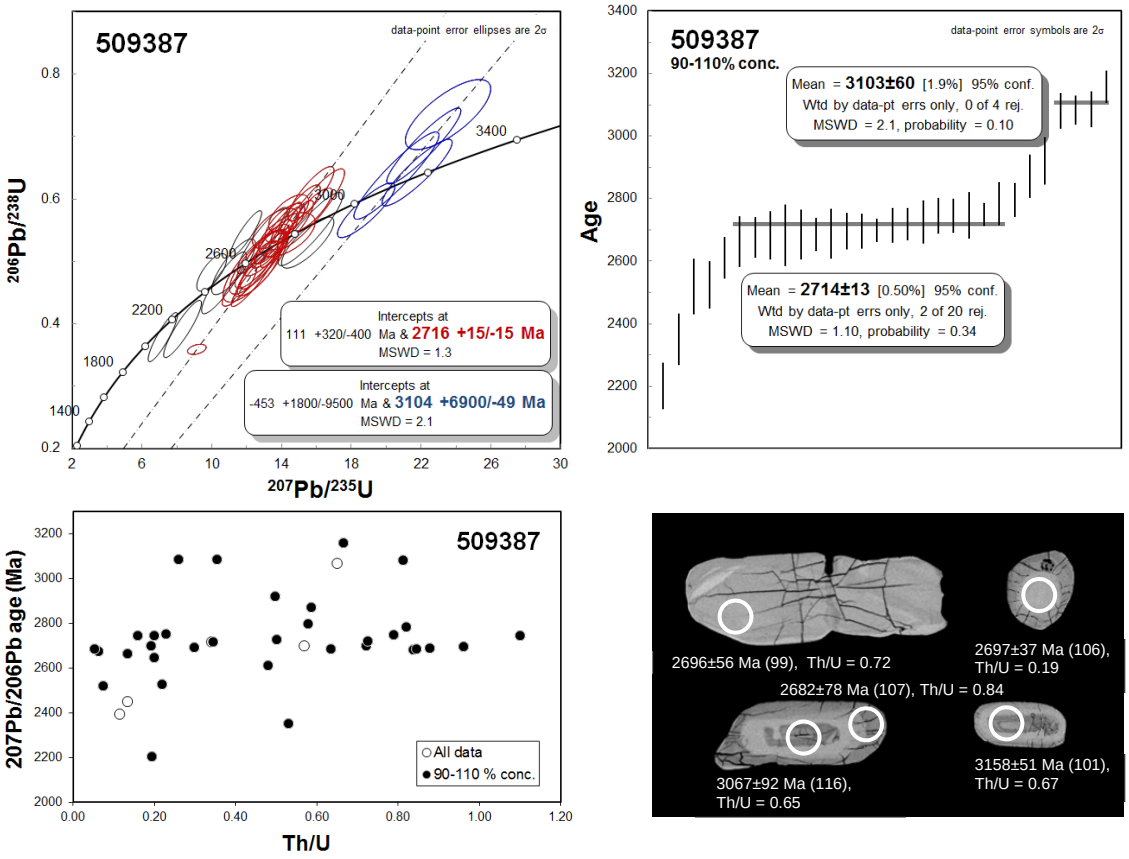

Figure 52. *U-Pb data for sample 509387: The zircon data define two age groups at c. 2715 and 3100 Ma, respectively, with transitional or lower age grains reflecting effects of ancient Pb-loss. The younger group is interpreted as the intrusion age of the SAP granite. The older group consists four grains and reflects an inherited population from the gneiss basement.*

Medium-grained granite, weakly foliated (542068)

Locality: Central NE Skjoldungen, Reco stop 3 (rotors running)
Ganfeld station: 12TFK187
Coordinates: N 63.38345, W 41.60497
Collector: TFK, CT, ABO, BPM, LT
Collection date: 20/08-2012
Description: Medium-grained granite, weakly foliated. This grab sample was collected from a frost-shattered surface next to the helicopter's landing site, and our understanding of the exact field relationships are therefore highly limited (no photographs were taken).
Purpose: Date the granite intrusion in the central part of Skjoldungen Island.

Data interpretation:
The zircon grains are generally small (30-150 µm, average ~60 µm), an- or subhedral, prismatic with highly variable aspect ratios from 1:1 – 1:5. Many of the grains are severely cracked and some also contain patchy alteration zones and are thus from visual grounds suspect. A few grains have zoned cores with overgrowth rims, but this zoning is generally diffuse when present. Out of the 117 analysed spots the majority (71) contained variable

amounts of common Pb; however 10 of these are considered robust enough (all have $^{206}Pb/^{204}Pb > 1000$) to be included in the age calculations.

The sample is characterised by a broad age distribution pattern from which three possible peaks may be discerned: (1) 2697 ± 8.8 Ma (54 % of total), (2) 2748 ± 11 Ma (31 %), and (3) 2801 ± 7.4 Ma (9 %) (Figure 53). The main peak at 2700 Ma constitutes low Th/U (< 0.3) grains, most of which are heavily cracked and without any zoning. This peak could reflect newly grown zircon at the time of intrusion, or alternatively the complete resetting older grains caused by an unknown thermal event. The second largest peak at 2747 ± 11 Ma constitutes relatively homogeneous and less cracked grains with Th/U = 0.7-1.0. This age group is interpreted as the intrusion age of the granite. In the Th/U vs. Pb-Pb age diagram (Figure 53) some data extend towards higher Th/U (~0.5) and older age (~2750 Ma) forming a scattered array (red stippled double arrow) that could reflect a partial resetting of the main ~2750 Ma magmatic zircon population. Alternatively, these grains reflect mixed analyses due to insufficient resolution of the laser. Four inherited grains yield an age of ~2800 Ma. A fourth mini-peak at ~2590 Ma is made up from two concordant grains (5 %) that unfortunately are highly suspect because of their cracked and altered appearance. Thus, we attribute the younger peak to reflect the effects of ancient Pb loss.

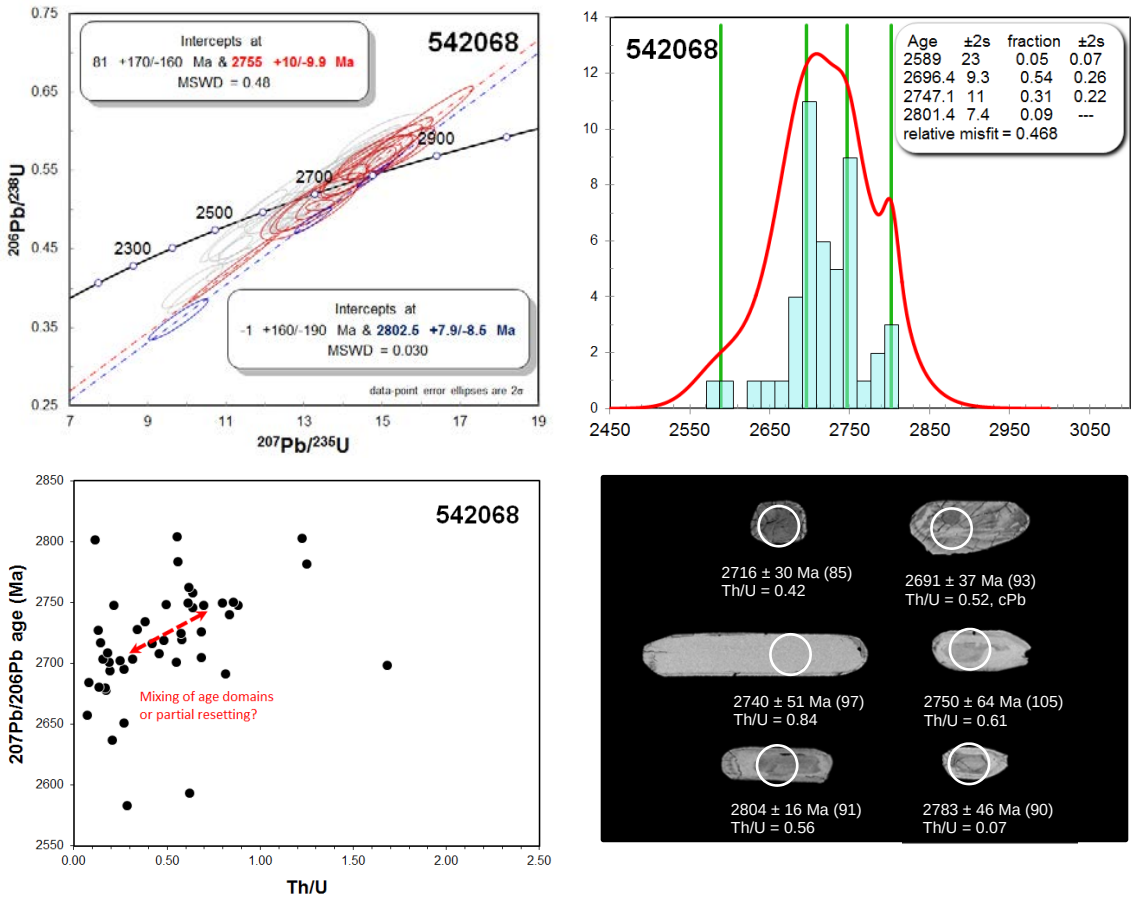

Figure 53. *U-Pb data for sample 542068: Three main peaks are identified: Age 1: 2697 ± 8.8 Ma (54 %); Age 2: 2748 ± 11 Ma (31 %); Age 3: 2801 ± 7.4 Ma (9 %) (see text). Red double arrow in Th/U vs. Pb-Pb age diagram indicates the effect (analytical artefact) of mixing of 2700 and 2750 Ma age domains.*

Agmatitic gneiss (542074)

Locality: Central Skjoldungen, Reco stop 4
Ganfeld station: 12TFK188
Coordinates: 63.35965 N, 41.58764 W
Collector: TFK, CT, ABO, BPM, LT
Collection date: 20/08-2012
Description: Agmatitic gneiss basement with inclusions of mafic and ultramafic rocks (Figure 54).
Purpose: Date the agmatitic gneiss basement and test for any evidence for younger SAP intrusions in this area.
Data interpretation:
The zircons constitute a wide age range from 2700 to 3200 Ma with several age populations. This complex age pattern is also reflected in several textural and morphological types of zircons. Using the unmixing function of Isoplot, four age groups are identified with some confidence (Figure 55): Age group 1 (constitutes 39 %) and age group 2 (22 %) both represent zircon core ages that are 3161 ± 5 Ma and 3015 ± 8 Ma, respectively. Both groups are interpreted as inherited from earlier gneissic protolith intrusions. Age group 3 (24 %) of zircon cores gives an age of 2883 ± 11 Ma that reflects an addition from the youngest gneiss protolith intrusions. Age group 4 (15 %) gives an age of 2744 ± 13 Ma and is mainly based on zircon rim analyses. This age corresponds broadly to the earliest stage of the SAP, suggesting it represents an overprinting by surrounding SAP magmatism.

Figure 54. *Field photo of 542074. The agmatitic gneiss basement with its characteristic mafic meta-inclusions is here seen to be diffusively infiltrated by later SAP-related granitic melts. Folded knife for scale is about 13 cm long.*

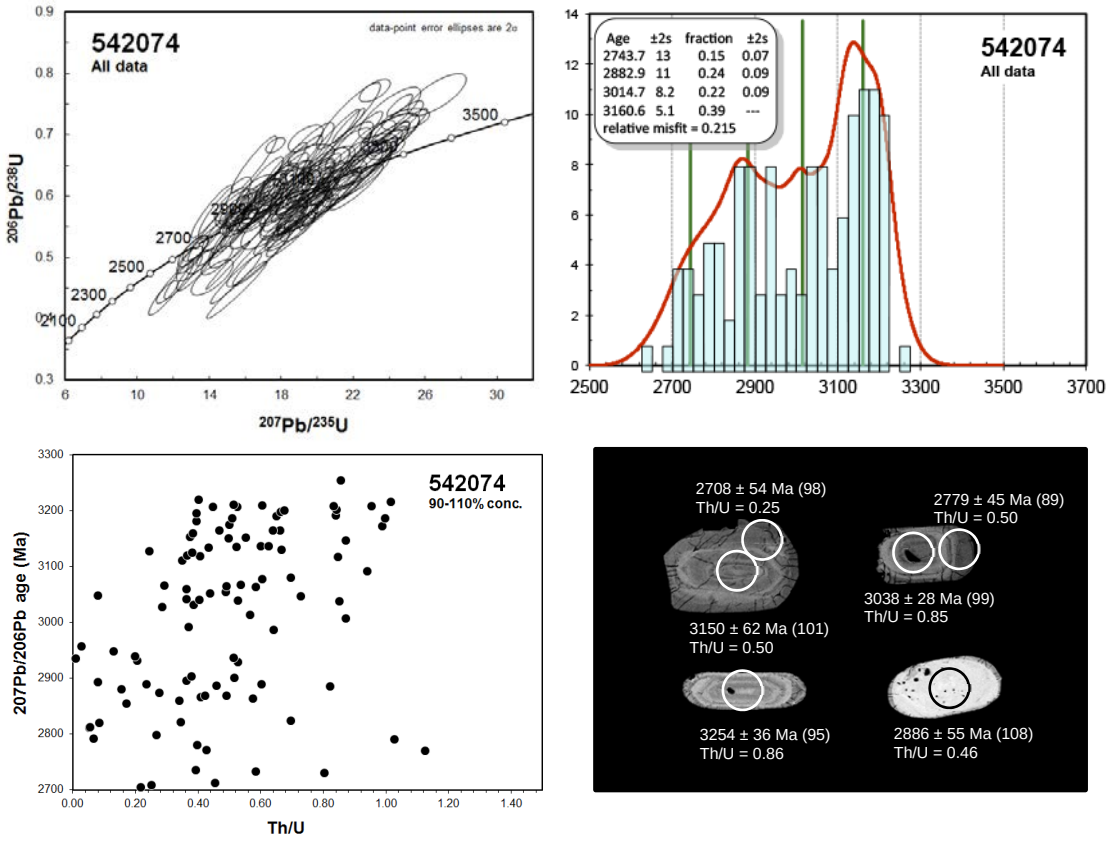

Figure 55. *U-Pb data for sample 542074. Highly complex age pattern reflecting a multi-stage growth and/or inheritance of zircon in the agmatitic gneiss followed by overprinting by SAP intrusion.*

Summary

Despite the lack of larger SAP intrusions in the central Skjoldungen area, it is evident from the zircon ages that overprinting by SAP magmas was ubiquitous throughout much of the province. Thus, the three samples collected for dating all possess sub-populations that are coeval with granitic magma emplacement during a period of 2750 – 2700 Ma, covering the main time span of the SAP magmatism. Most of these SAP intrusions are diffusive and pervasive, intruding as sheets rather than larger discrete magma bodies, and incorporated many generations of older zircon cores inherited from gneissic hosts with a range of zircon ages clustering around 3161 ± 5 Ma, 3103 ± 60 Ma, 3015 ± 8, 2883 ± 11 Ma and 2801 ± 7.4 Ma. Altogether, these observations suggest that agmatite with ages as old as c. 3200 Ma probably was much more widespread in the Skjoldungen area prior to the emplacement of SAP.

The Sfinksen area

Geological background

The Sfinksen area is situated in the northern part of Skjoldungen Island and exposes several fairly well confined intrusions ranging from mafic to felsic compositions, referred to as the Sfinksen Diorite, the Sfinksen Syenite Complex, and the Sfinksen Granite (Nielsen & Rosing, 1990). The Sfinksen syenite complex appears to have a fairly undisturbed circular (ovoid) outline where its central part is eroded down and covered by glaciers; only the more marginal parts of the intrusion are therefore exposed as relatively steep-sided mountains. The south-eastern part of the Syenite Complex appears to be cut by the Sfinksen Diorite, which was visited and sampled for chemistry and dating work.

The Sfinksen Syenite Complex is here represented by three samples collected from the western, northern and eastern margins of the complex, respectively. The ages should provide the intrusion age of the complex. A minimum age of the Sfinksen Diorite is provided by dating of two felsic pegmatite dykes that cross-cut these more mafic rocks of the Sfinksen Diorite.

In addition a magmatically layered syenite was sampled along the north-eastern shore line of the Søndre Skjoldungensund, below the elevated plateau hosting the Sfinksen Diorite. The relationship between this layered syenite and the Sfinksen Diorite is unestablished, but the syenite could belong to this system, or more likely in view of the different composition, be a separate intrusion altogether. Another and perhaps more likely possibility is that the syenite is related to the 'Blåbærskrænt' intrusion of Blichert-Toft et al. (1995); although their sketch map seems to be placing this centre slightly further to the northwest compared to our sample locality, both the description and chemistry reported by Blichert-Toft et al. (1995) match quite well.

It should also be mentioned that 'Blåbærskrænt' seems to be correlative to 'Sfinksen Granite' of Nielsen & Rosing (1990), but the difference seems to reflect that observations were made at low and high altitude, respectively. The Sfinksen Granite was never accessed at the top of the plateau during the recent fieldwork, because it lies in an inaccessible and mountainous area. Thus, its relationship to the syenites and diorites of the rest of the Sfinksen area therefore remains uncertain.

Results

Medium-grained quartz syenite (527678)

Locality: Sfinksen Intrusion
Ganfeld station: 11TFK144, helicopter reco stop
Coordinates: N 63.40676, W 41.70211
Collector: TFK, MBK, BMST, TFN, KHA

Collection date: 07/08/2011
Description: Quartz syenite outcropping on a narrow ledge at the presumed margins of the Sfinksen Syenite Complex (Figure 56). The rock is medium-grained and weakly deformed (syn-tectonic magmatism).
Purpose: Establish the intrusion age of the Sfinksen Syenite Complex which also constrains the syntectonic stage of magmatism in Northern Skjoldungen Island.

Figure 56. *527678: Quartz syenite sampled at the easternmost periphery of the Sfinksen Syenite Complex. The syenite is here cut by one of the many intermediate dykes that are characteristic for the area – a so-called 'deformed dyke' (lower right part of picture).*

Data interpretation:
The main zircon population yields an upper Concordia intercept age of 2739.2 ± 6.6 Ma (Figure 57), which is interpreted as the crystallisation age of the quartz syenite. Two or three older inherited zircons give ages of up to ~3.0 Ga, indicating some degree of interaction between the SAP syenite and the surrounding agmatitic basement gneisses.

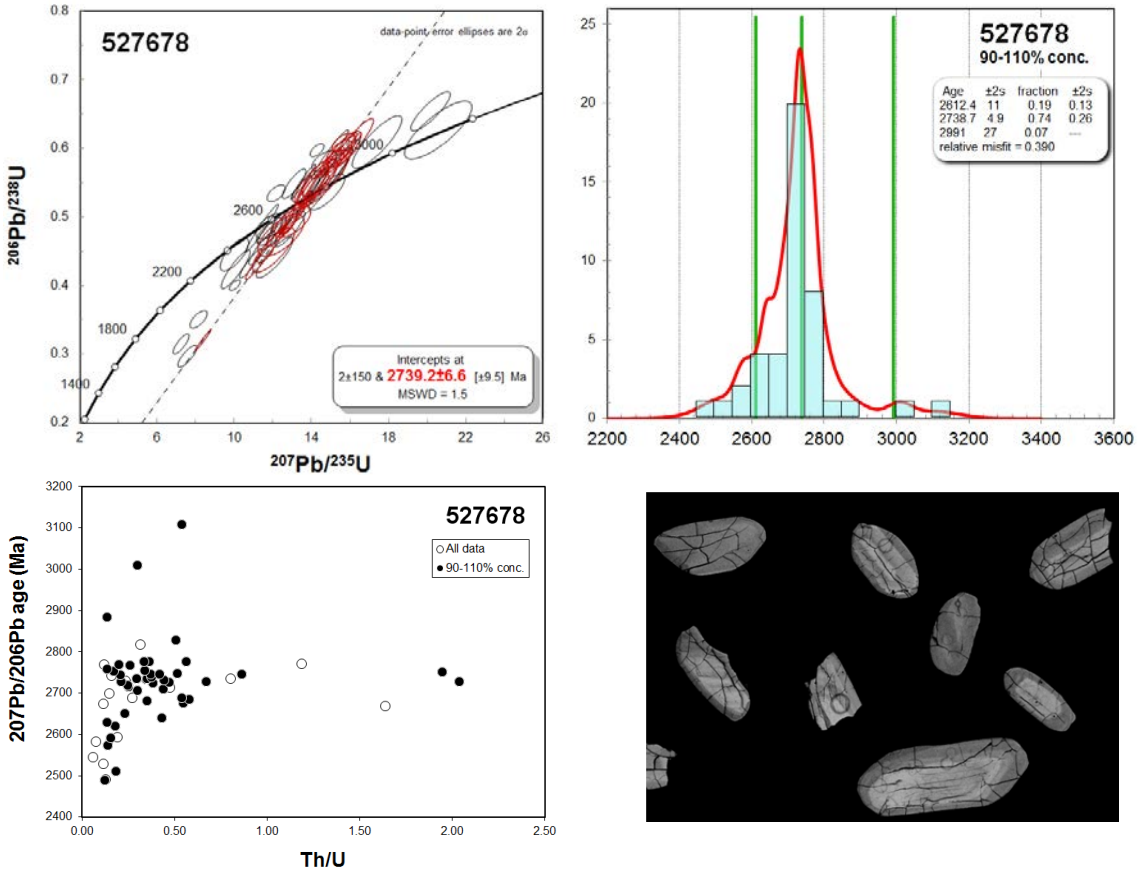

Figure 57. *527678: The main zircon population yields an upper Concordia intercept age of 2739.2 ± 6.6 Ma, which we interpret as the intrusion age of the quartz syenite. Two or three older inherited zircons give ages of up to ~3.0 Ga.*

Quartz syenite (527679)

Locality: Sfinksen Intrusion
Ganfeld station: 11TFK145, helicopter reco stop
Coordinates: N 63.440737, W 41.79188
Collector: TFK, MBK, BMS, TFN, KHA
Collection date: 07/08/2011
Description: Quartz syenite with some sense of foliation to the fabric from the western marginal zone of the Sfinksen Syenite Complex. The marginal zone is locally pervasively red-coloured along fracture planes and joints, reflecting the effect of hydrothermal circulation of fluids along this contact zone (Figure 58). Locally the syenite contains sheared out mafic enclaves and distorted streaky schliren, which along with the foliated fabric of the syenite suggest that it was a syntectonic intrusion.
Purpose: Date the Sfinksen Syenite Complex, which constitutes the main intrusion on the northern part of Skjoldungen Island.

Figure 58. *Sample 527679: Coarse-grained quartz syenite at the northern contact zone of the Sfinksen Syenite Complex. The otherwise whitish pale syenite is pervasively red-coloured along joints and fracture planes, reflecting circulation of fluids along this contact zone.*

Data interpretation:

The zircon grains are generally sub- to euhedral, mostly prismatic to box shaped with sizes of 70 – 200 µm and aspect ratios of 1:2 – 1:4 (Figure 59). Most grains are clearly magmatically zoned.

A total of 104 spots were analysed of which 94 produced acceptable data without any common Pb. The data are generally highly concordant with only 13 analyses falling outside the 100 ± 10 % concordancy interval. In the Concordia diagram (Figure 59), the main zircon population yields a Concordia intercept age of 2740.2 ± 4.9 Ma (MSWD = 1.4). A similar age of 2739.3 ± 6.1 Ma (n = 19, MSWD = 1.12) can be derived based on the 98-102 % concordant grains. This age is interpreted as the intrusion age of the syenite. A few older grains may arguably(?) define an intercept age of c. 2800 Ma, which then could reflect inherited grains from the basement gneisses.

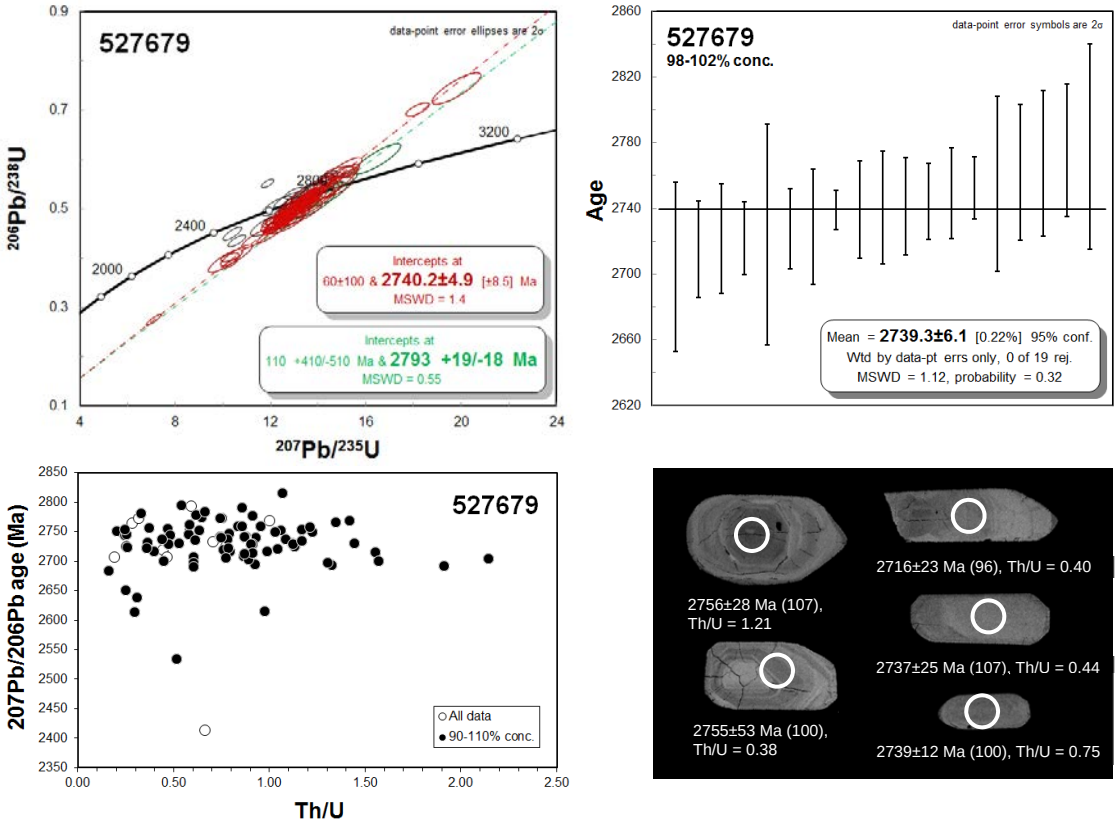

Figure 59. *U-Pb data for sample 527679: The main zircon population yields an upper Concordia intercept age of 2740.2 ± 4.9 Ma, which we interpret as the intrusion age of the quartz syenite. No older inherited grains are found.*

Granite (527685)

Locality: Sfinksen Syenite Complex
Ganfeld station: 11TFK146, helicopter reco stop
Coordinates: N 63.43314, W 41.73435
Collector: TFK, MBK, BMST, TFN, KHA
Collection date: 07/08/2011

Description: Quartz syenite (or granite?) showing evidence of syn-magmatic deformation. The syenite was intruded by a mafic vein that was sheared and disrupted, likely reflecting syn-tectonic magmatism (Figure 60).
Purpose: Date the intrusion age of the Sfinksen Syenite Complex, which corresponds to the syn-tectonic stage of SAP magmatism in the Sfinksen area.

Figure 60. *527685: Medium – coarse-grained quartz syenite with distorted mafic schliren. The outcrop indicates that mafic melts intruded into the syenite during a stage of deformation, presumably under semi-ductile conditions. Shoe size 46 for scale!*

Data interpretation:
Zircon grains are generally sub- or euhedrale, varying somewhat in size but are generally about 150x 50 µm and with an average aspect ratio of 1:3 – 1:2 (Figure 61). Most grains are magmatically zoned with distinctly alternating bright and dark bands down to c. 10µm in thickness.
In the Concordia diagram (Figure 61), the data display a main zircon population with a Concordia intercept age of 2728.7 +4.6/-5.3 Ma (n = 55, MSWD = 0.79). This is similar (within analytical error) to a weighted age of 2732.1 ±5.1 Ma (n = 52, MSWD = 1.10) based on the 90-110 % concordant grains. This is interpreted as the intrusion age of the syenite, and thereby of the Sfinksen Syenite Complex as a whole. Two concordant grains give an age of 3051 ± 28 Ma, interpreted as an inherited age of the basement.

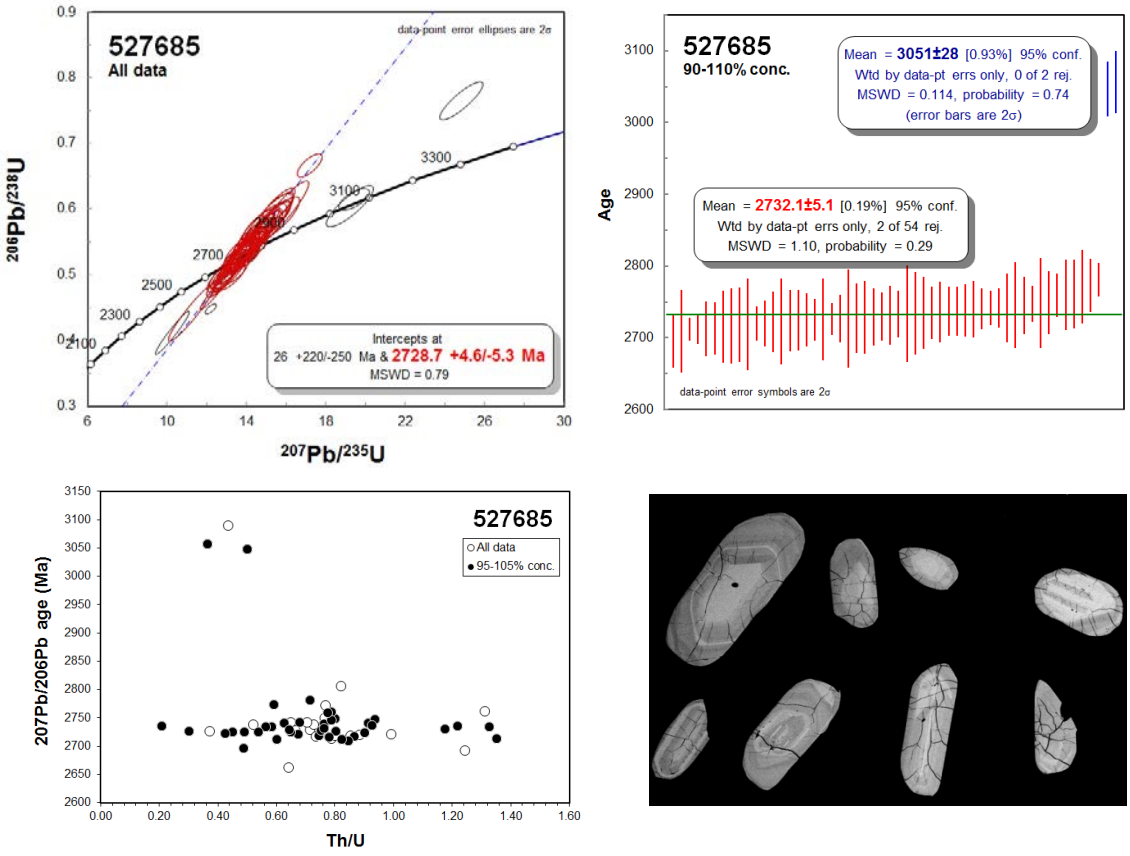

Figure 61. *U-Pb data for sample 527685. A main zircon population gives a Concordia intercept age of 2728.7 +4.6/-5.3 Ma (n = 55, MSWD = 0.79). A similar (within error of the uncertainty) age of 2732.1 ± 5.1 Ma (n = 52, MSWD = 1.10) is calculated based on the 90-110 % concordant grains. Two inherited grains give a concordant age of 3051 ± 28 Ma.*

Magnetite-zircon-rich pegmatite (542059)

Locality: Sfinksen Diorite
Ganfeld station: 12TFK177, Helicopter reco stop on 'Sfinksen Shelf' (cf. TFN)
Coordinates: N 63.39797, W 41.76308
Collector: TFK, ABO, TU, CT, BPM
Collection date: 20/08/2012
Description: Felsic pegmatite with interstitial aggregates rich in magnetite, green amphibole and zircon (Figure 62). The pegmatite intrudes into gabbroic rocks of the Sfinksen Diorite as irregular veins with diffuse contacts. The pegmatite is zoned as the mafic components are concentrated towards the centre of the pegmatite and feldspars dominate the marginal and distal parts.
Purpose: Constrain the age of the Sfinksen Diorite. The zircon material constitutes large crystals (up to c. 10 mm) and is potentially suitable as in house standard material.

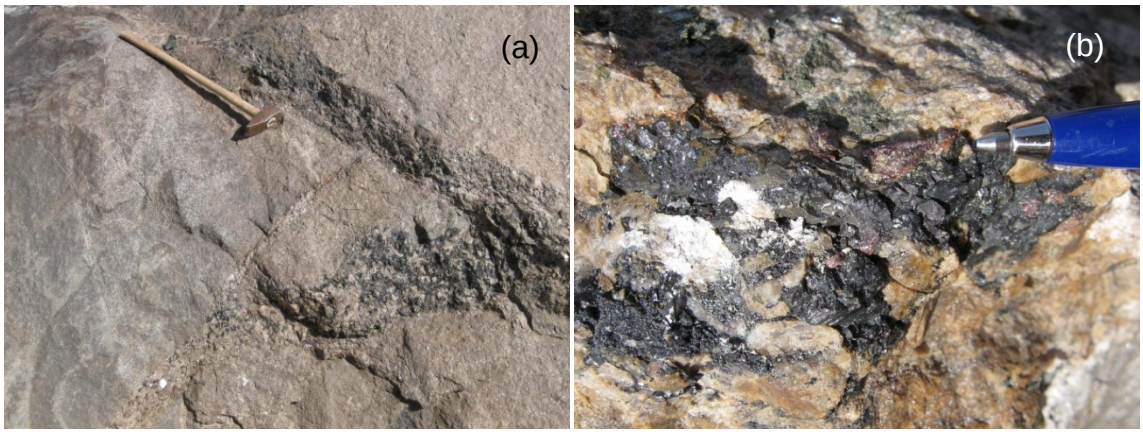

Figure 62. *Sample 542059: (a) Irregular pegmatite vein rich in magnetite cutting the Sfinksen Diorite. (b) Close-up of pegmatite showing an interstitial mineral aggregate of magnetite (black), amphibole (dark green) and zircon (deep purple), surrounded by feldspar. Its large purple zircon grains are candidates for in house standard material.*

Data interpretation:

Two sets of zircons were separated out: (1) Large crystals (>0.5 cm) potential as standard material were gently liberated from the rock material by means of gentle crushing in a mortar. (2) Another set of zircons was separated following the normal procedures including crushing, sieving and washing on the Wilfley table (not reported here). The large zircon grains are faintly magmatically zoned on a large scale, with individual homogeneous bands of up to >100 µm width (Figure 63). In the Concordia diagram (Figure 63), the analyses from single large crystals are mostly highly concordant and yield a Concordia intersection age of 2694 +12/-11 Ma (MSWD = 0.98), interpreted as the intrusion age of the pegmatite. A similar age of 2696 +12 Ma (MSDW = 1.16) is derived from a weighted average of the 95-105 % concordant analyses. This age also provides a minimum age of the Sfinksen Diorite. The relatively large error reflects the low U concentrations in the zircons, average U = 60 ± 18 ppm (1 std. dev.).

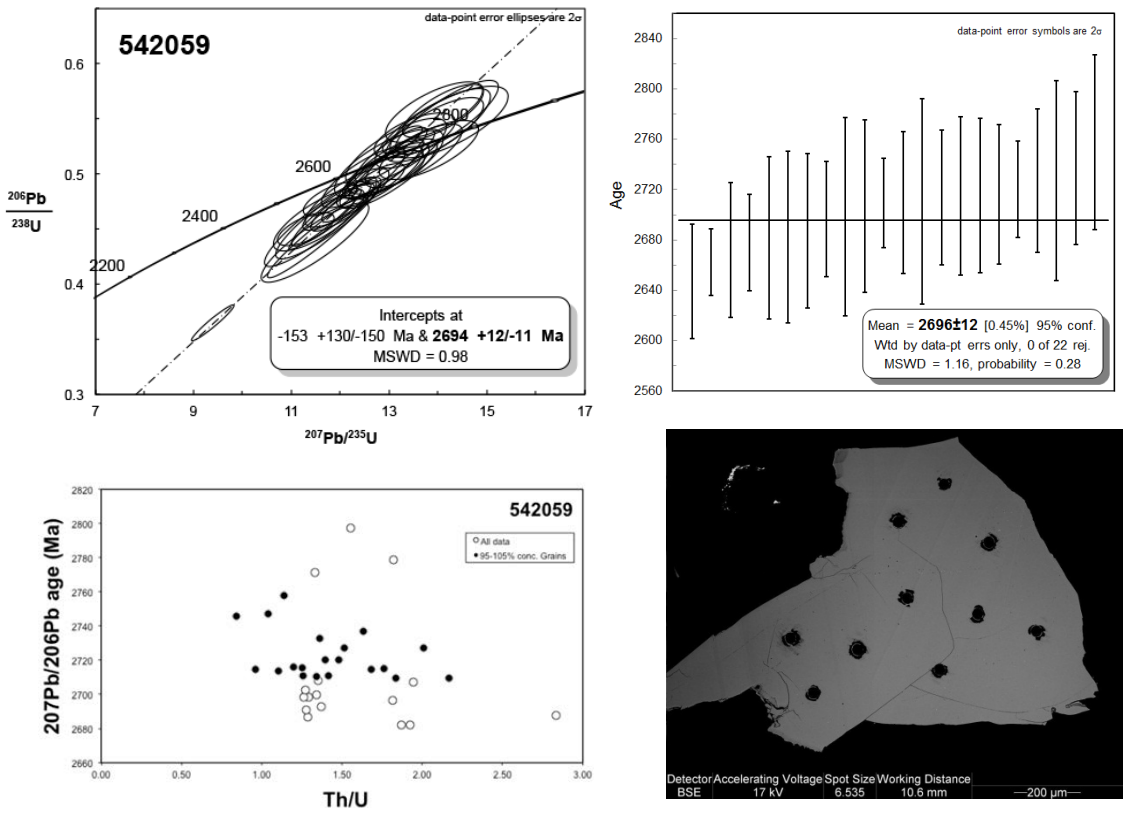

Figure 63. *U-Pb data for sample 542059: The data constitute a single age population with a Concordia intercept age of 2694 +12/-11 Ma (MSWD = 0.98). A similar age of 2696 +12 Ma (MSDW = 1.16) is derived from a weighted average of the 95-105 % concordant analyses. The relatively large error reflects the low U concentrations in the zircons, average U = 60 ± 18 ppm (1 std. dev.).*

Coarse-grained syenite (509369)

Locality: North-western part of Søndre Skjoldungensund (Blåbærskrænt?)
Ganfeld station: 12TFK174
Coordinates: N 63.40033º, W 41.82410º
Collector: TFK, CT
Collection date: 19/08/2012
Description: Coarse-grained syenite with well-developed, steeply dipping magmatic layering that can be followed for several tens of meters (orientation of planar layering: 170/80˚N) (Figure 64). The rock contains ternary feldspar with Schiller-effect (exsolution phenomenon resulting in a bluish luster). The rock's relationship to the Sfinksen syenite complex is uncertain. As mentioned in the introduction to this section, the locality is likely corresponding to 'Blåbærskrænt' following the naming of Blichert-Toft et al. (1995).
Purpose: Date the intrusion age of the syenite and from this possibly establish a relationship to the Sfinksen Syenite Complex.

Figure 64. *Sample 509369: Coarse-grained syenite at the north-western coast of Søndre Skjoldungensund. The syenite exhibits modal layering consisting in various proportions between paler feldspars and darker pyroxene(s) + oxides.*

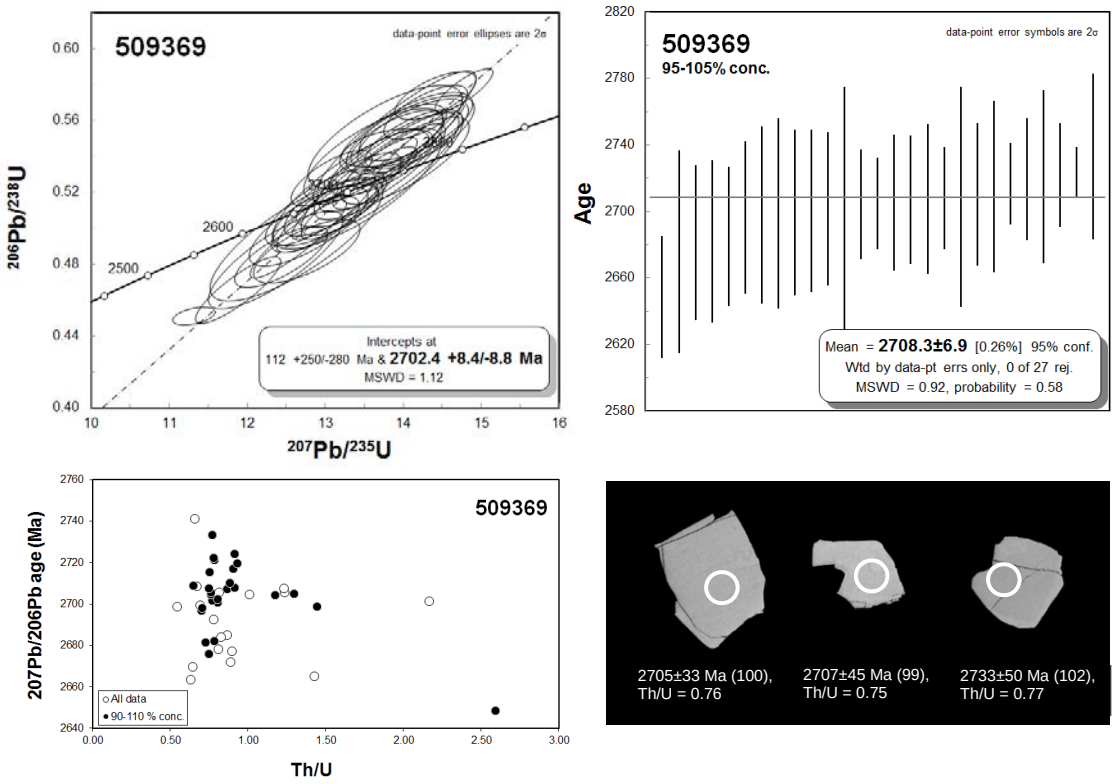

Figure 65. *U-Pb data for sample 509369: A main zircon population gives a Concordia intercept age of 2702.4 +8.4/-8.8 Ma (MSWD = 1.12). A slightly better defined age (similar within error of uncertainty) of 2708.3 ± 6.9 Ma (n = 27, MSWD = 0.92) is calculated based on the 90-110 % concordant grains, interpreted as the intrusion age.*

Data interpretation:
Zircons are mostly anhedral and irregularly shaped, suggesting late stage growth in interstitial pore spaces. The grains are homogeneous without obvious magmatic zoning (Figure 65). A main zircon population gives a Concordia intercept age of 2702.4 +8.4/-8.8 Ma (MSWD = 1.12). A slightly better defined age (similar within error of uncertainty) of 2708.3 ± 6.9 Ma (n = 27, MSWD = 0.92) is calculated based on 90-110 % concordant grains, and is interpreted as the crystallisation age of the syenite.

Very coarse-grained quartz syenitic pegmatite (542036)

Locality: Søndre Skjoldungensund, northern part
Ganfeld station: 12TFK148
Coordinates: N 63.36818, W 41.72770
Collector: TFK, ABO
Collection date: 16/08/2012
Description: Very coarse-grained quartz syenitic pegmatite dyke intruding melagabbroic rocks along the northern shoreline of the Søndre Skjoldungensund (Figure 66).
Purpose: Date late stage, post-tectonic felsic magmatism in the northern part of the Skjoldungen Island.

Figure 66. *Sample 542036: Very coarse-grained syenitic pegmatite dyke intruding melagabbroic rocks along the northern shoreline of the Søndre Skjoldungensund.*

Data interpretation: Zircon grains are often large (up to c. 250 µm), subhedral and weakly zoned (Figure 67). In the Concordia diagram (Figure 67), the zircon data constitute a homogeneous age population with an upper Concordia intercept age of 2694 +9.2 / -8.7 Ma, which is similar to the age obtained based on a weighted average of the 100 ± 5% concordant grains, giving an age of 2694 ± 7 Ma. This is interpreted as the intrusion age of the felsic pegmatite, and also provides a minimum age for the melagabbro host that it intruded.

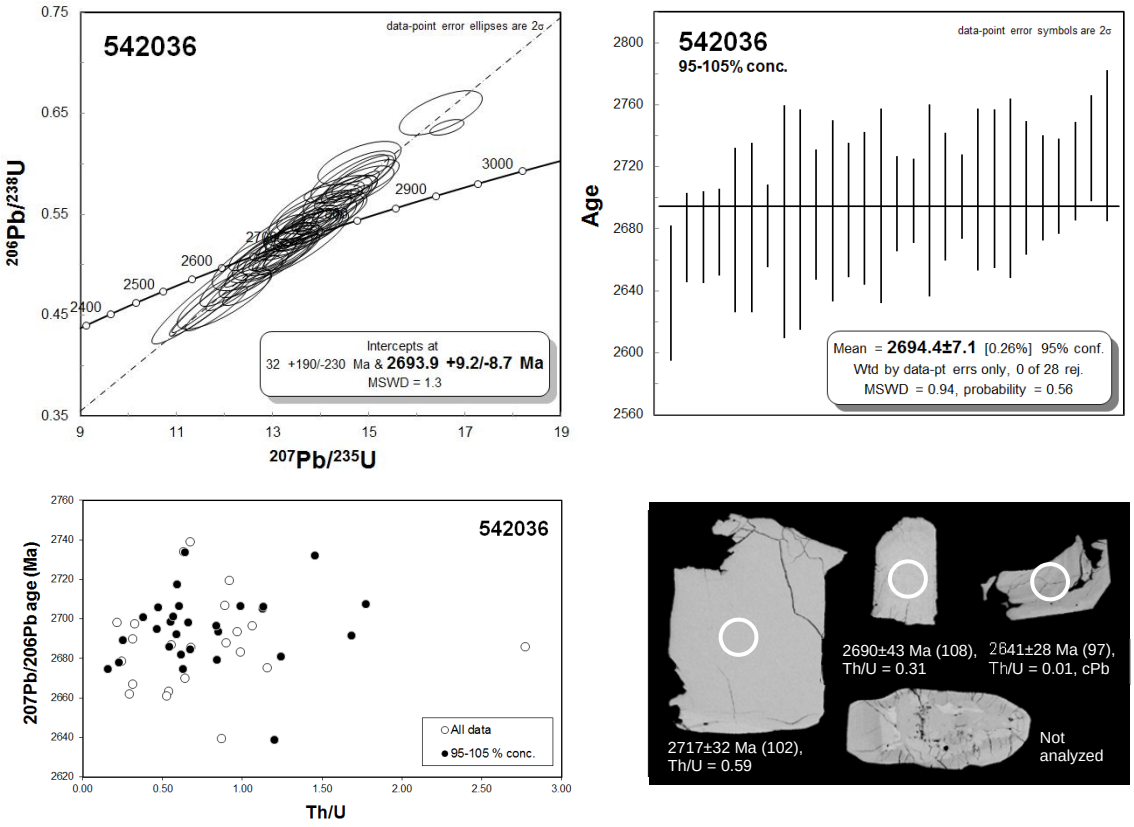

Figure 67. *U-Pb data for sample 542036: The zircon data constitute a homogeneous age population with an upper Concordia intercept age of 2694 +9.2 / -8.7 Ma, which is similar to the age obtained based on a weighted average of the 100 ± 5% concordant grains, giving an age of 2694 ± 7 Ma.*

Summary

Three samples from along the western, northern and eastern margins of the Sfinksen syenite complex yield consistent ages of around 2735 Ma (2732-2739 Ma), supporting the proposed circular outlined extent of the complex.

The Sfinksen Diorite was not dated directly but dating of a cross-cutting pegmatite containing interstitial aggregates of magnetite-amphibole-zircon from the 'Sfinksen Shelf' give a minimum age of 2700 Ma. Another pegmatite, cutting the diorite at sea level in the Søndre Skjoldungensund, likewise gives an age of around 2694 ± 7 Ma, and thereby reinforces this to be the timing of latest stage of magmatism within the Sfinksen area.

A magmatically modal layered syenite (509369), outcropping at sea level below Sfinksen Syenite Complex (likely corresponding to 'Blåbærskrænt' by Blichert-Toft et al. (1995)), gives an intrusion age of 2708 ± 7 Ma. Based on this age, it is unlikely to be related to the Sfinksen Syenite Complex, but rather represents a later separate magmatic event.

The Sfinksen Granite was unfortunately never sampled or dated.

Ruinnæsset Intrusion

Geological background

The Ruinnæsset intrusion is the largest and best investigated of the SAP intrusions (Blichert-Toft et al 1995). It has a rhomb-shaped outline measuring c. 3×3 km, outcropping along the shore lines of the junction between Nordre Skjoldungen Sund and Mørkesund. The intrusion is dominated by coarse-grained rocks ranging widely in composition from gabbro and diorite to monzonite and syenite, minor ultramafic rocks and granite. The main lithology is constituted by coarse-grained monzogabbro, monzonite or syenite that commonly shows rhythmic modal layering as defined by c. 5-20 cm thick layers rich in hornblende, pyroxene and Fe-Ti oxides alternating with layers of ternary feldspar dominated rocks. The contact to the surrounding gneisses is in places demonstrably intrusive, in other places it is tectonic. The intrusion is also cut by multiple generations of late sheets and dykes of granitic or syenitic composition. The irregular outlines of some of these intrusions suggest that these intruded at a late magmatic stage into semi-ductile host rock. Similarly, mafic bands and veins rich in magnetite and apatite (nelsonites) are observed to intrude the bulk lithologies in an irregular fashion, suggesting that these also intruded under semi-crystallised conditions. The presence of apatite and ilmenite-rich nelsonite was also noted by previous workers who considered a process of liquid immiscibility at a late stage during the magmatic evolution (Blichert-Toft et al 1995).

The dating work concentrates on cross-cutting sheets, some of which are interpreted from the field relations to be synchronously emplaced as the crystallization of the host rock, whereas others clearly post-date the main magmatic event. Direct dating of the main monzogabbro – monzonite - syenite host rocks was unsuccessful because no zircon could be found in these rock types despite several attempts to extract these were made.

Results

Pegmatitic quartz syenite (527569)

Locality: Ruinnæsset, North-western contact
Ganfeld station: 11TFK072
Coordinates: N 63.53300º; W 41.75764º
Collector: TFK, MBK, AB, TU
Collection date: 31/07/2011
Description: Coarse-grained quartz syenite with miarolitic cavities intruded at the contact of the northern part of the Ruinnæsset intrusion (Figure 68).
Purpose: Dating the late stage magmatism of the Ruinnæsset Intrusion. The presence of miarolitic cavities in the pegmatitic sample gives an additional constraint on the time at which the intrusion was emplaced at a relatively shallow crustal level (< 4-5 km depth).
Reference: Berger et al. (2014)

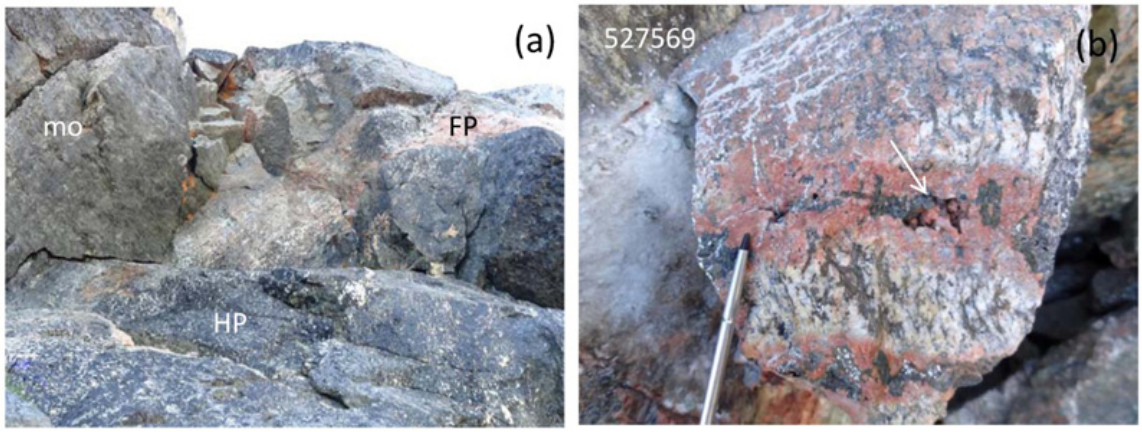

Figure 68. *Sample 527569: (a) Field photograph showing the northern contact between monzonite (mo) and the gneiss basement (outside view, to the right). The contact zone contains felsic pegmatite (FP) and a marginal hornblende pegmatite (HP). (b) Sample 527569 of felsic pegmatite contains mineral-filled miarolitic cavities (white arrow).*

Data interpretation:

The zircon grains are generally large (up to 250 µm), sub- to euhedral and exhibit distinct magmatic zoning (Figure 69). The majority of the U-Pb data form a tight cluster around the Concordia with an approximate age of c. 2700 Ma, with some analyses scattering off to the right-hand side in the Tera-Wasserburg diagram suggesting recent Pb loss effects. A single slightly discordant grain yields an age of c. 2820 Ma (inherited?). Among the 100 ± 10% concordant grains the analyses with Th/U > 1.3 form a well defined age of 2694 ± 5 Ma (N = 22, MSWD = 0.99) (Figure 69), which is also interpreted to represent the intrusion age of the syenite. In contrast, the analyses with lower Th/U < 1.3 define a subtle positive trend when plotting Pb-Pb age as function of Th/U, making these data suspect of reflecting mixed ages (mixing towards a lower age component with an age of c. 2650 Ma and Th/U ≈ 0.1).

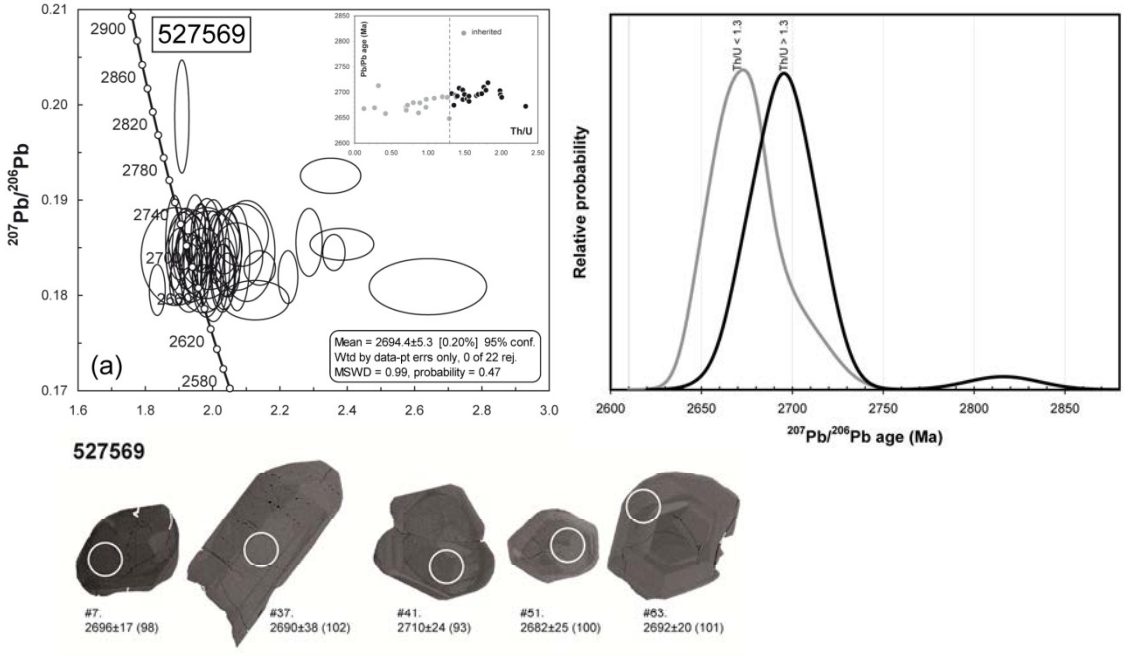

Figure 69. *527569: The 100 ± 10% concordant grains with Th/U > 1.3 form a well defined age of 2694 ± 5 Ma (N = 22, MSWD = 0.99), interpreted as the intrusion age of the syenite.*

Fine-grained syenitic sheet (527585)

Locality: Ruinnæsset Intrusion, Southern part.
Ganfeld station: 11TFK087
Coordinates: N 63.48689, W 41.71250
Collector: TFK, MBK
Collection date: 01/08/2011
Description: Fine-grained syenitic thin sheet (ca 20 cm thick) with a well-developed schistosity (Figure 70). The fine-grained, irregular flat-lying syenitic sheet appears to cut all other lithologies.
Purpose: Date the presumed youngest of the magmatic events exposed at the outcrop.

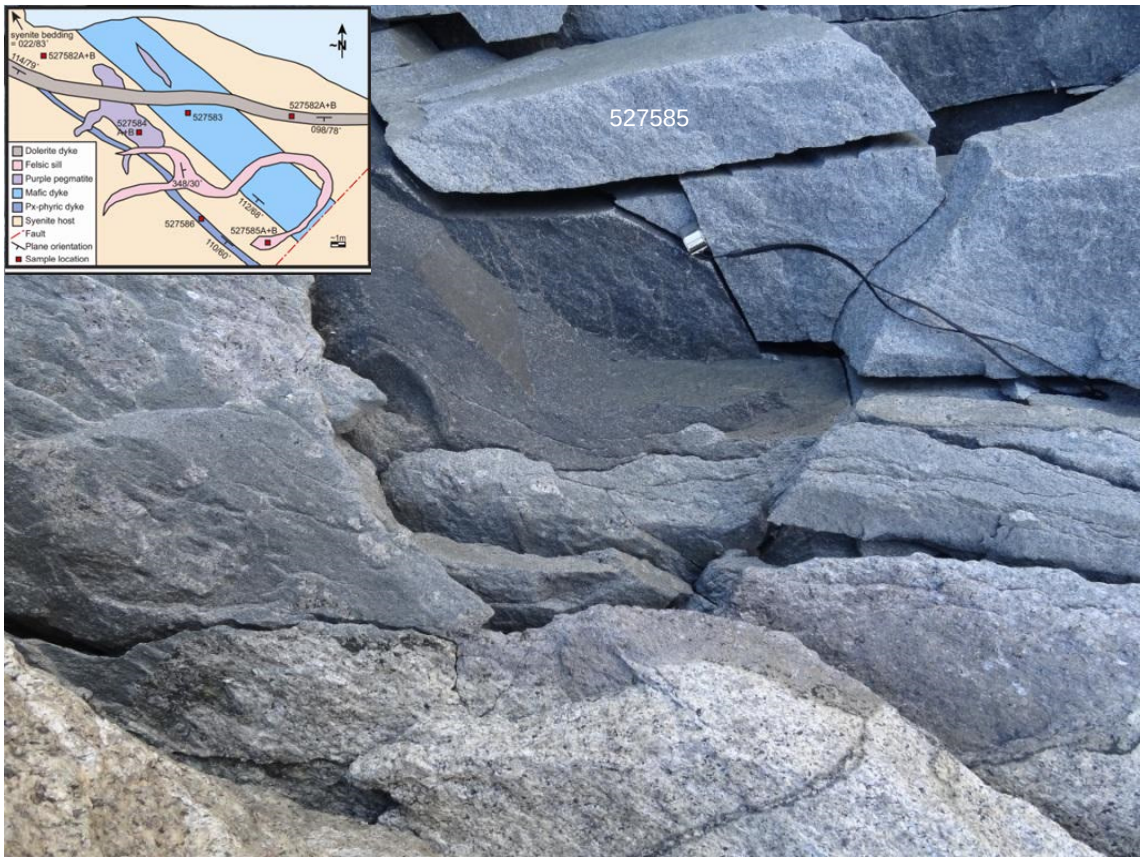

Figure 70. *Sample 527585: Locality 11TFK087 where the normal monzonite/syenite of the Ruinnæsset Intrusion (in foreground) is cut by several generations of magmatic sheets and dykes. Note a hand lens for scale. Insert sketch is a drawing of the outcrop (Figure 54a in Klausen & Kokfelt, 2014).*

Data interpretation: The zircons are often anhedral with irregular morphologies characterised by embayments and lobate boundaries (Figure 70), suggesting a late growth controlled by the pre-exisiting mineral phases (mainly feldspars) in the rock. A total of 97 acceptable data points have been analysed; of these 93 are concordant at 100 ± 10 % and none contain any significant common Pb. Based on the 93 data points, an upper Concordia intercept age of 2709 ± 5 Ma (MSWD = 1.8) is derived (Figure 71). This age is similar to a weighted mean age based on only the highly concordant grains (100 ± 5%). The main age is interpreted as the intrusion age of the syenitic sheet.

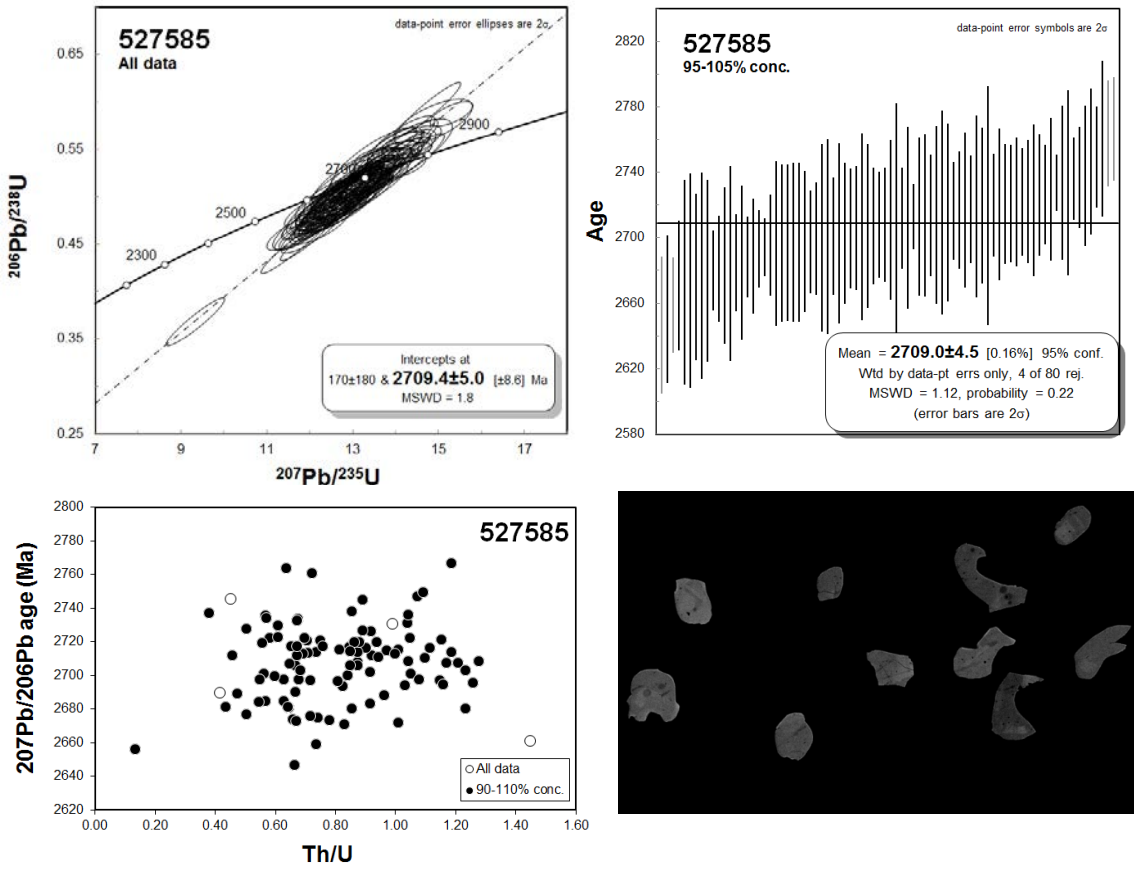

Figure 71. *527585: A single zircon population extracted from the syenitic sheet yields a Concordia interception age of 2709 ± 5 Ma, interpreted as the intrusion age. Zircons are anhedral reflecting a late crystallization (grain morphologies being controlled by pre-existing phases).*

Purple pegmatitic syenite (527598)

Locality: Ruinnæsset Intrusion, north-eastern part
Ganfeld station: 11TFK092
Coordinates: N 63.48333, W 41.64337
Collector: TFK, MBK
Collection date: 01/08/2011
Description: According to our observations and descriptions by Blichert-Toft (1995), 'purple pegmatite' represents generally the latest intrusive phase within the Ruinnæsset Intrusion. The name "purple pegmatite" refers to its flesh-colour, which reflects a high proportion of coarse-grained alkali feldspar and very little mafic phases and quartz (Figure 72). Often these pegmatites intrude as thin (< 1 m), inclined sheets into all other lithologies of the Ruinnæsset Intrusion. Purple pegmatites of this kind are characteristic for the latest stage of the magmatism within the Ruinnæsset Intrusion, and pegmatites of similar nature and age have not been found outside Ruinnæsset Intrusion.
Purpose: Date the latest stage of magmatism within the Ruinnæsset Intrusion.

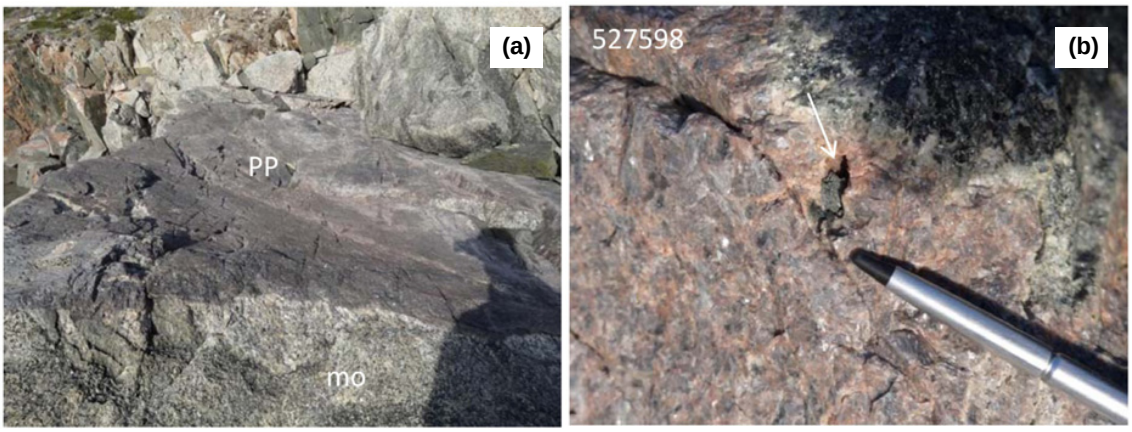

Figure 72. *527598: (a) Outcrop of gently inclined sheet of 'purple pegmatite' (PP) intruded into coarse-grained monzonite (mo). (b) Sample 527598 of 'purple pegmatite' contains crystal filled miarolitic cavities (white arrow). See also Berger et al. (2014).*

Data interpretation:

The zircon grains vary widely in shape and size but are generally an- or subhedral. The irregular grain morphologies suggest that zircon was formed interstitially at a late stage of crystallisation (controlled by earlier formed phases). In the Concordia diagram (Figure 73), the main part of the data cluster close to Concordia with a fairly well defined intercept age of 2630.7 ± 7.3 Ma (MSWD = 1.01), with some grains scattering towards recent Pb loss. Based on the 100 ± 10% concordant grains a similar weighted average $^{207}Pb/^{206}Pb$ age of 2632 ± 7 Ma (MSWD = 0.8, N = 12) is derived. This age post-dates the main magmatic phase of the Ruinnæsset intrusion by ~60 Myr (Blichert-Toft, 1995), suggesting that the actual SAP magmatism lasted longer than hitherto acknowledged (Berger et al. 2014). A single concordant grain gives an unusual age of 1980 ± 48 Ma, i.e much younger than the rocks in the Skjoldungen area, with the possible exception of various Paleoproterozoic doloritic dykes that dissect the area (M. Nilsson, unpublished data). One possibility is that the zircon reflects a thermal resetting due to the intrusion of a doleritic dyke in the relative vicinity. Indeed a c. 30 m wide WNW-ESE s trending dolorite dyke is intruded c. 120 m from the sampling site of 527598 giving some credibility to such a model. Alternatively, the grain reflects contamination in the laboratory during preparation.

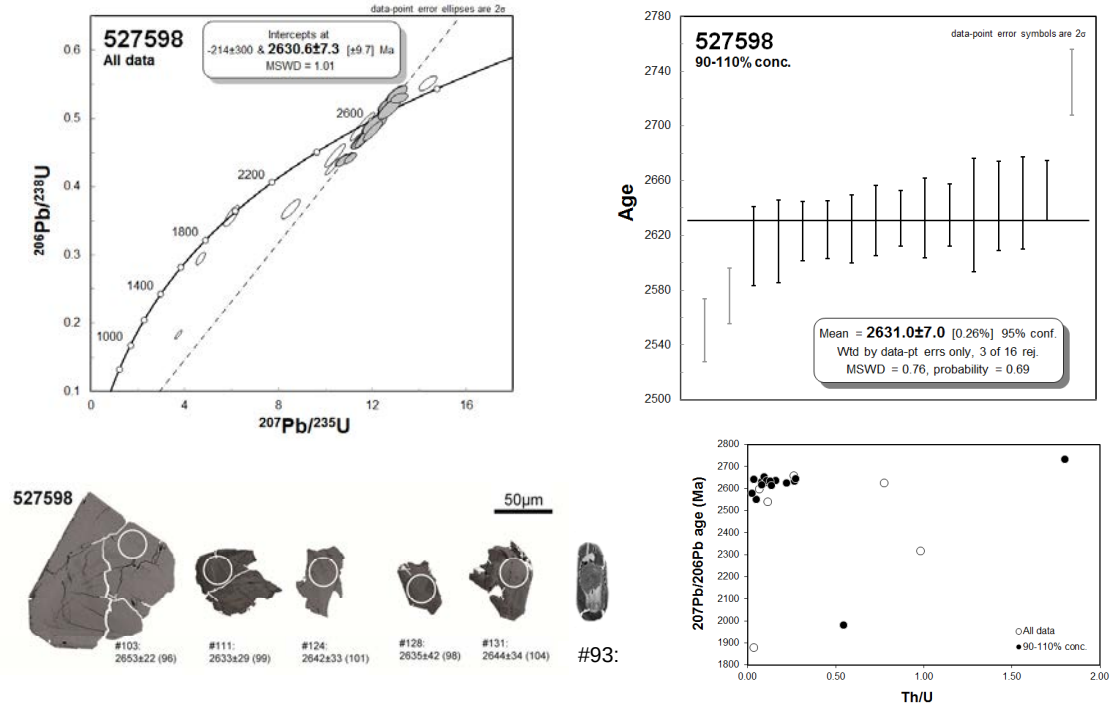

Figure 73. *Sample 527598: A Discordia intersection age gives 2631 ±7 Ma (MSWD = 1.01). This is consistent with a weighted mean age based on the 100 ± 10% concordant grains (MSWD = 0.80; N = 12). A single concordant zircon gives an age of c. 1980 Ma; an age which could reflect thermal resetting in association with the intrusion of a Paleoproterozoic doloritic dyke in the vicinity of the sampling site.*

Summary

The monzogabbros, monzonites and syenites that constitute the main part of the Ruinnæsset Intrusion carry no zircon and have therefore not been directly dated. However, based on the undeformed nature of the Ruinnæsset rocks, they are likely younger than c. 2730 Ma, which mark the timing of post-tectonically affected rocks in the neighboring Sfinksen area. Dating of the late stage felsic sheets and dykes has also provided a minimum age for the intrusion. A late dyke that cuts the main lithologies in the south-western part of the intrusion yields an age of 2709 ± 5 Ma. A felsic pegmatite at the north-western contact is dated at 2694 ± 5 Ma, suggesting an extended period of 10-15 Myr to characterize the late stage of Ruinnæsset magmatism. Finally, a sample of a “purple pegmatite” sheet is dated at 2631 Ma marking the latest so far known age of magmatism within the SAP. From thermal considerations it is however unlikely that the Ruinnæsset intrusion remained continuously active as a magmatic system for about 80 Ma. Instead we propose that the volumetrically insignificant purple pegmatites reflect a late, small-scale heating event that generated small amounts of felsic melts in the crust.

Tværdalen

Geological background

On Esher's (1995) geological map, several SAP-intrusions cut basement rocks in a short hanging valley, north of Dronning Louise's Dal. However, Klausen & Kokfelt (2014) found the extent of an ultramafic intrusion to be greatly exaggerated. In an unsuccessful attempt to climb up the northern ridge of the valley bottom's saddle, to reach the contact of what appears from a distance to resemble a larger gabbroic intrusion, 14 samples were collected from a variety of 28 measured dykes, and one sample from the weakly foliated and sporadically agmatitic granite gneiss host. These vertical to very steeply E-dipping dykes have an average thickness of 0.86 m, trend NNW-SSE (average strike of 169°) and range in appearance from being more or less leucocratic, fine grained (aplitic), as well as occasionally pegmatitic. They therefore appear to constitute the same aplite-pegmatite swarm. The weakly foliated granitic host is locally more deformed along narrow ductile shear zones, one of which indicated dextral shear along 140/80°SE. Rather than representing boudinaged amphibolite remnants within an agmatitic gneiss, these could be mafic enclaves within a granitic intrusion. Finally, a few presumed Paleoproterozoic diabase dykes and more brittle NE-dipping normal faults appear to cut all rocks, and hydrothermal fluids along the latter appear to have imparted a reddish discolouration of the host rock's feldspars.

Results

Felsic aplite (542402)

Locality: Tværdalen (Dronning Louise's Dal)
Ganfeld station: MBK helicopter reco
Coordinates: N 63.52122, W 42.01784
Collector: MBK and LLS
Collection date: 21/08/2012
Description: The sample was collected from a regular WSW-ENE-trending and medium-grained granitic aplite dyke (0.6 m thick) that intruded into a coarser-grained host of syntectonically deformed granitic SAP "basement" (Figure 74). In detail, however, dyke contacts are very irregular and devoid of any chilled margins, suggesting that the dyke was injected while the host granite was relatively hot.
Purpose: Date the late stage magmatism in the area.

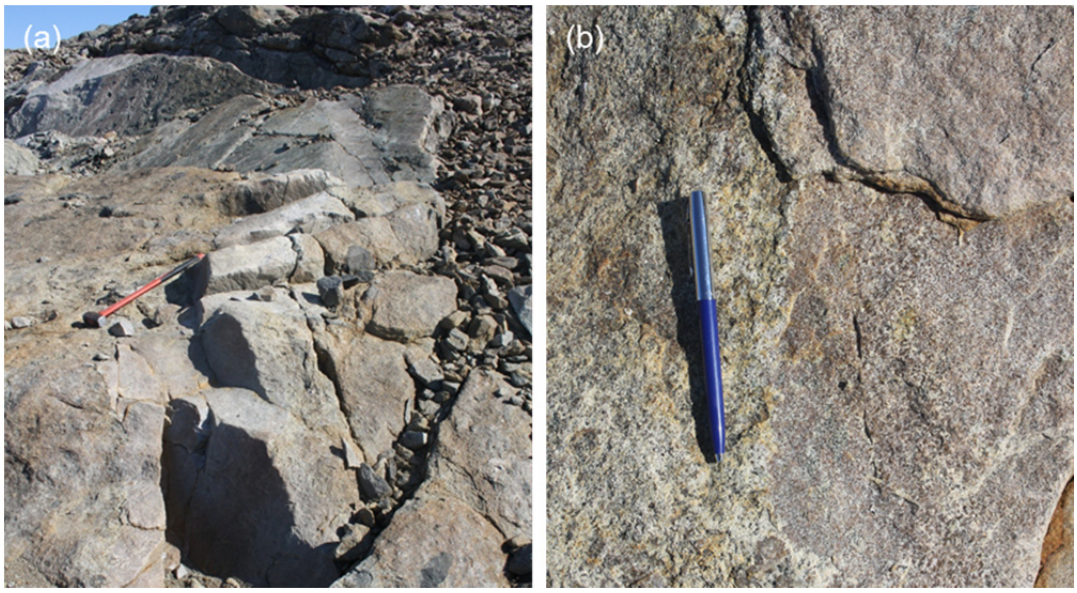

Figure 74. *(a) A 0.6 m-thick felsic aplite dyke (075/90°) cutting agmatitic basement in the Tværdalen area. (b) Note irregular contact between aplite (right) and its granitic host (left).*

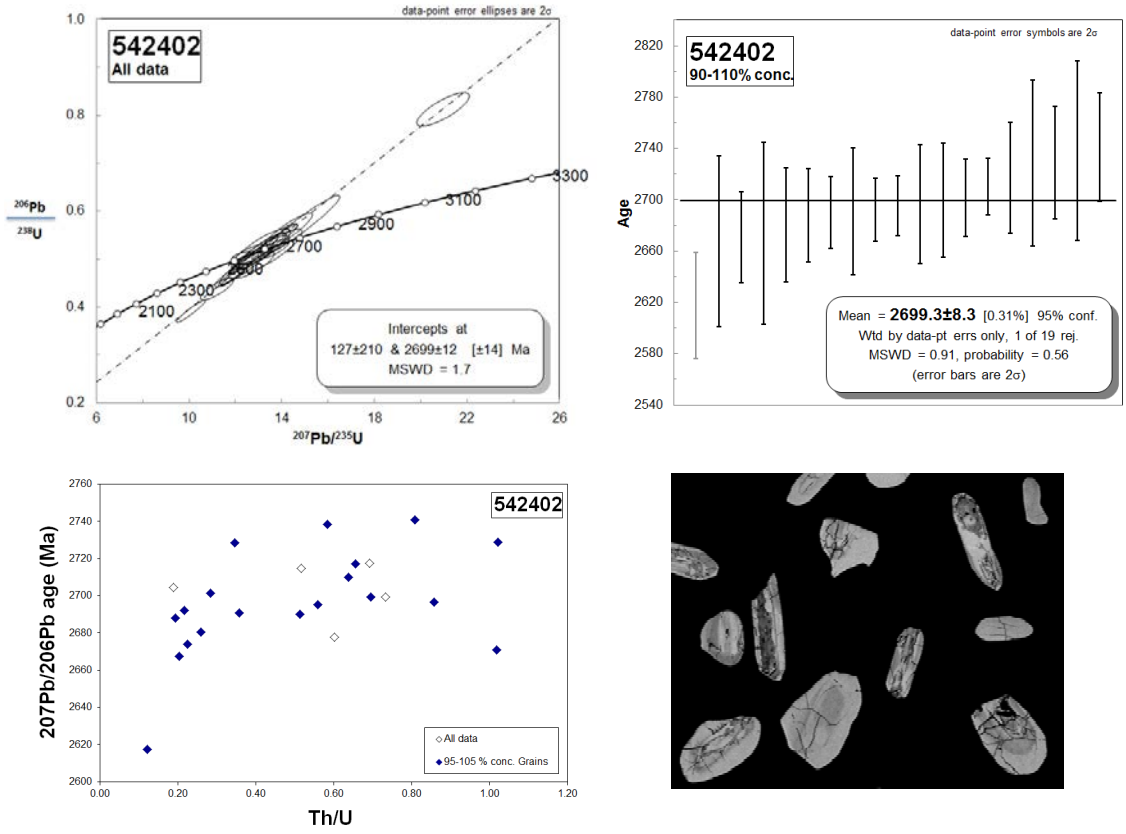

Figure 75. (previous page) *U-Pb data for sample 542402: The zircon data constitute a homogeneous age population with an upper Concordia intercept age of 2699 ± 12 Ma. A similar age of 2699.3 ± 8.3 Ma is derived by taken a weighted average of the 100 ± 10% concordant grains.*

Data interpretation:
The zircon grains show a range of morphologies and sizes, but are often elongate, rounded, sub- to anhedral with faint zoning in darker cores that are surrounded by more homogeneous lighter rim domains (Figure 75). Grains are variably fractured. The U-Pb data are mostly highly concordant and in the Concordia diagram (Figure 75) they define an intersection age with the Concordia of 2699 ± 8 Ma with a MSWD = 0.91 (n = 18). The age is interpreted as the intrusion age of the aplite and is coeval with the timing of the felsic intrusions in the northern part of Skjoldungen Island, namely the Sfinksen and the Ruinnæsset Intrusions.

Mildly foliated, medium-grained granite (542410)

Locality: Tværdalen (Dronning Louise's Dal)
Ganfeld station: MBK and Lars Lund Sørensen, helicopter reco
Coordinates: N 63.5211, W 42.02459
Collector: MBK and LLS
Collection date: 21/08/2012
Description: Sample of a slightly foliated agmatitic granite gneiss basement, which is locally cut by ductile shear zones as well as a swarm of felsic dykes, like the sampled 542402 (Figure 76).
Purpose: Constrain the age of major granitic magmatism in the Tværdalen area.

Figure 76. *Slightly foliated granite gneiss of the north-western part of the Tværdalen area, Skjoldungen.*

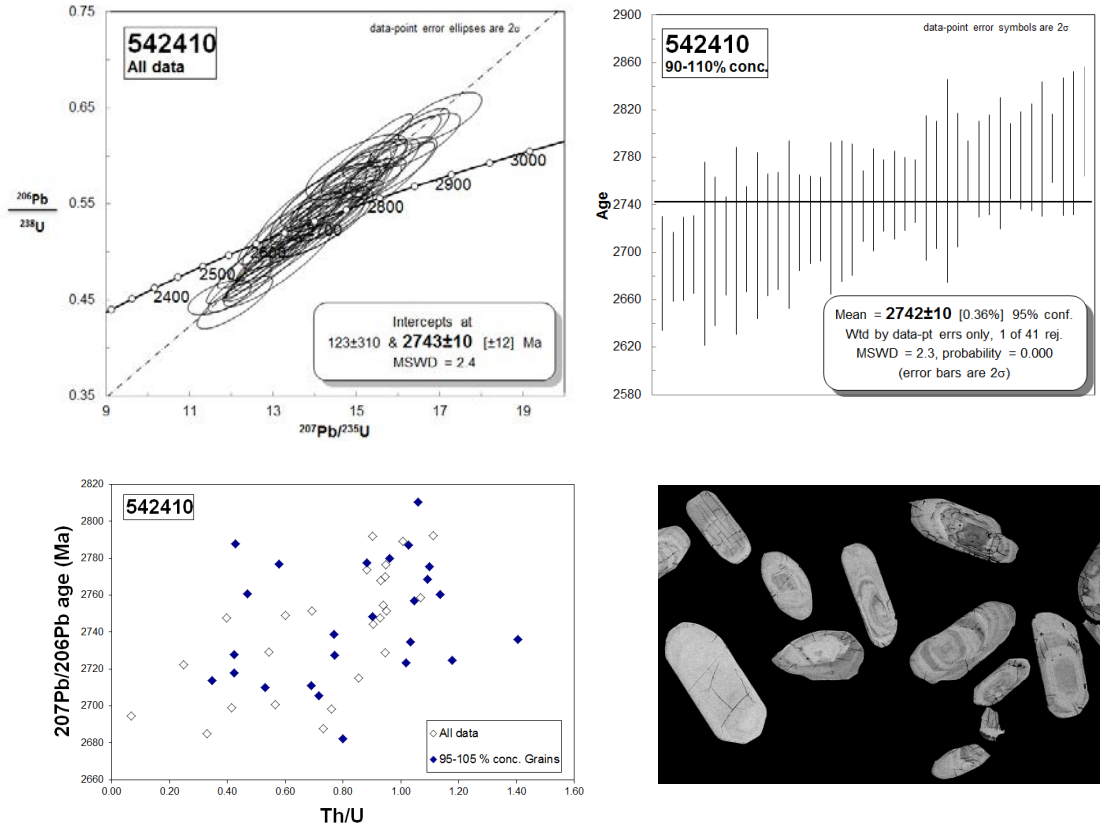

Figure 77. *U-Pb data for sample 542410: The zircon data constitute a homogeneous age population with an upper Concordia intercept age of 2743 ± 10 Ma. A similar age of 2742 ± 10 Ma is derived from a weighted average of the 100 ± 10% concordant grains.*

Data interpretation:
The zircons in sample 542410 constitute a homogeneous age population with an upper Concordia intercept age of 2743 ± 10 Ma (Figure 77). This age is interpreted as the intrusion age of the granite. No inherited older ages are found in the sample.

Summary

Two samples were selected for U-Pb age dating from the Tværdalen region: A weakly foliated granite gneiss host yields and age of 2742 ± 10 Ma, which is overlapping with the syntectonic SAP magmatism found in the Sfinksen area situated close by. A granitic aplite dyke that cuts across this agmatitic gneiss basement gives an age of 2699.3 ± 8.3 Ma, which is contemporaneous to the Ruinnæsset Intrusion and likely represent the latest (post-tectonic) stage of the SAP magmatism in the area. Thus, disproving a shorter duration between emplacements, tentatively deduced from irregular intrusive contacts.

Thrymheim (‘nunatak’) area

Geological background

The Thrymheim ‘nunatak’ area is dominated by extensive sheet-like intrusions of mainly granite and monzonite that are emplaced into the basement of agmatitic gneiss. The exact field relationships are often difficult to establish, partly due to the irregular nature of the SAP intrusions, and partly because of the apparent similarity between SAP intrusions and gneiss basement; both lithologies typically display weak to moderate foliation as defined by the alignment of feldspars and both often contain mafic blocks, either as xenoliths or mafic enclaves. A distinguishing feature in the field, however, seems to be rock colour, as the agmatitic gneisses typically possess a rusty brown colour which is characteristic of retro-graded granulite facies rocks (due to a rusty weathering of orthopyroxene), whereas the SAP intrusives that did not experience granulite facies conditions are often more pinkish. These characteristics have previously been used to map this large inland area of nunataks, primarily from helicopter and short accessible stops, which was repeated during a reco-day flight in 2011. Age dating has been undertaken for three SAP samples representing the syntectonic (two samples) and the post-tectonic magmatic stages (one sample) of the Thrymheim area.

Results

Syntectonic quartz monzonite (527654)

Locality: Thrymheim (nunatak area)
Ganfeld station: 11TFK137, helicopter reco stop
Coordinates: N 63.59285, W 42.23498
Collector: TFK, MBK, AB, TU
Collection date: 06/07/2011
Description: Coarse-grained, feldspar porphyric weakly foliated quartz monzonite (Figure 78).
Purpose: Date the monzonitic intrusion and assess the main syn-tectonic magmatic phase in the Thrymheim area.

Figure 78. *527654: Feldspar porphyritic (akin macro-trachytic texture) and syntectonic quartz monzonite from the Thrymheim area showing alignment of large feldspar crystals in an undulating fashion.*

Data interpretation:

Zircons are generally subhedral ranging in size between 80-150 µm and with aspect ratios of 1:2 – 1:3 (Figure 79). Many grains show a faint zoning sometimes with a small bright (U-rich) resorbed core surrounded by a darker (U-poor) mantle and a thin (< 10 µm) outer bright rim. A total of 85 zircon grains were analysed and none of the analyses were affected by common Pb. The far majority of the data points (82) are highly concordant within 100 ± 10 % and these data constitute a single age population at 2710.5 ± 3.4 Ma (MSWD = 0.89, n/N = 79/83) based on a weighted mean of the $^{207}Pb/^{206}Pb$ ages (Figure 79). A similar age can be derived from the upper intercept with Concordia: 2713 ±4 Ma (MSWD = 1.4) based on all data. The age is interpreted as the intrusion age of the monzonite. No inherited zircons were found.

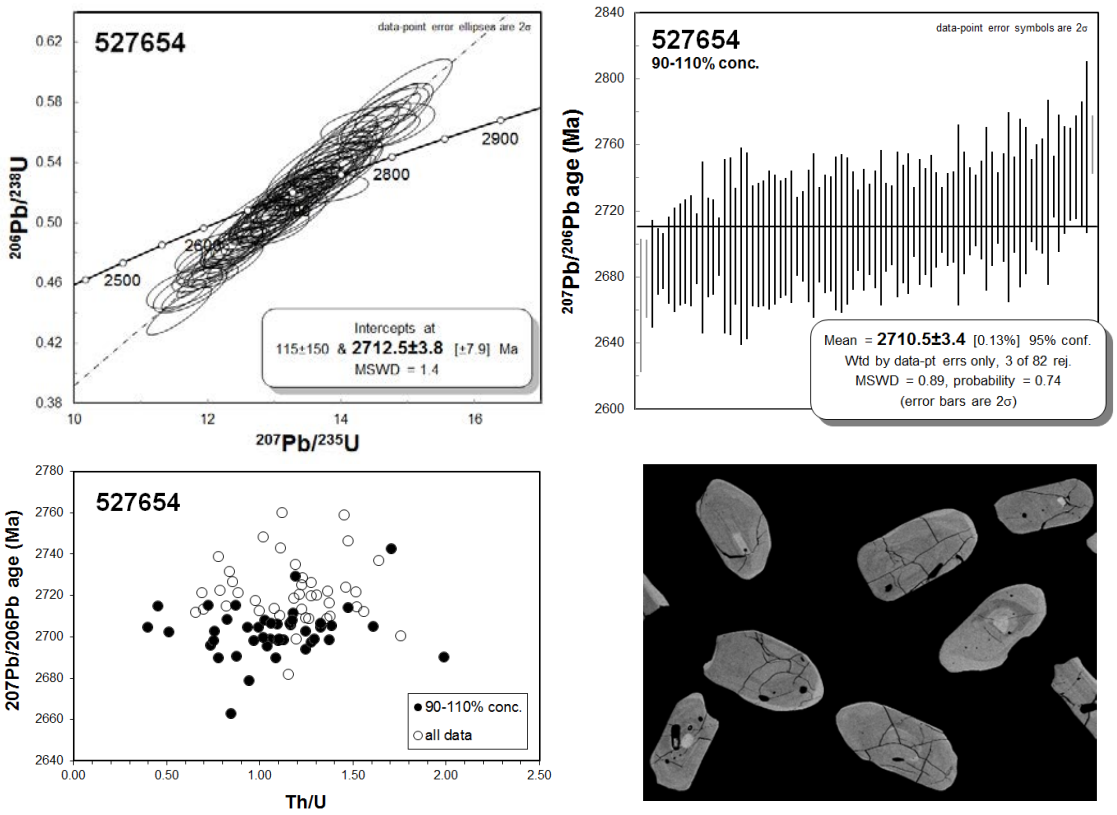

Figure 79. *Sample 527654: The U-Pb data are highly concordant and constitute a single age population with an age of 2710.5 ± 3.4 Ma based on a weighted average of the 90-110% concordant grains. This is interpreted as the intrusion age of the monzonite.*

Fine-grained granite (527659)

Locality: Thrymheim (nunatak area)
Ganfeld station: 11TFK139, helicopter reco stop
Coordinates: N 63.66014, W 42.27941
Collector: TFK, MBK, AB, TU
Collection date: 06/07/2011
Description: Fine-grained granite intruding into an area of agmatitic gneisses that are cut but numerous granitic and quartz monzonitic intrusions and sheets (Figure 80). The fine-grained granitic sheets generally represent the latest phase of magmatism in the area because these cut the coarser-grained syenitic to monzonitic SAP intrusions.
Purpose: Date the late tectonic to post-tectonic phase of SAP magmatism in the eastern-most exposed parts of the Skjoldungen Alkaline Province.

Figure 80. *Sample 527659: Fine-grained granitic sheets represent the latest phase of magmatism in the Thrymheim area. Here the granitic sheet contains a mafic enclave that has been deformed during flow and emplacement.*

Data interpretation:

The zircon grains show variable morphologies and internal textures, including larger sub-hedral grains with high aspect ratios of 1:4 – 1:5 and smaller more rounded grains with

aspect ratios of 1:2 – 1:3 (Figure 81). Several grains have distinct internal textures of zones or bands of baddeleyite, presumably of late magmatic (see below), if not of secondary origin.

A total of 69 spots were analysed and of these 49 returned good data without any significant contribution from common Pb. The majority of data are concordant at the 100 ± 10 % level, 11 analyses lie outside this range and mainly below. Grains containing baddeleyite seem to have suffered Pb loss as these analyses generally are less than 90% concordant. In the Concordia diagram (Figure 81), the main group of analyses intersects Concordia at around 2.70 Ga with some scatter around a regression line. By focussing on the analyses with Th/U > 0.80 a well defined upper intersect age of 2711 ± 10 Ma (MSWD = 2.0) is derived. A similar (within error), though slightly older age of 2718 ± 10 Ma (MSWD = 2.6; n = 12) is calculated based on the 100 ± 10 % concordant grains with Th/U > 0.8. This age is taken as the intrusion age of the granite and thus a best estimate of the latest magmatic activity in the Thrymheim area. A single inherited grain gives an age of c. 2830 Ma.

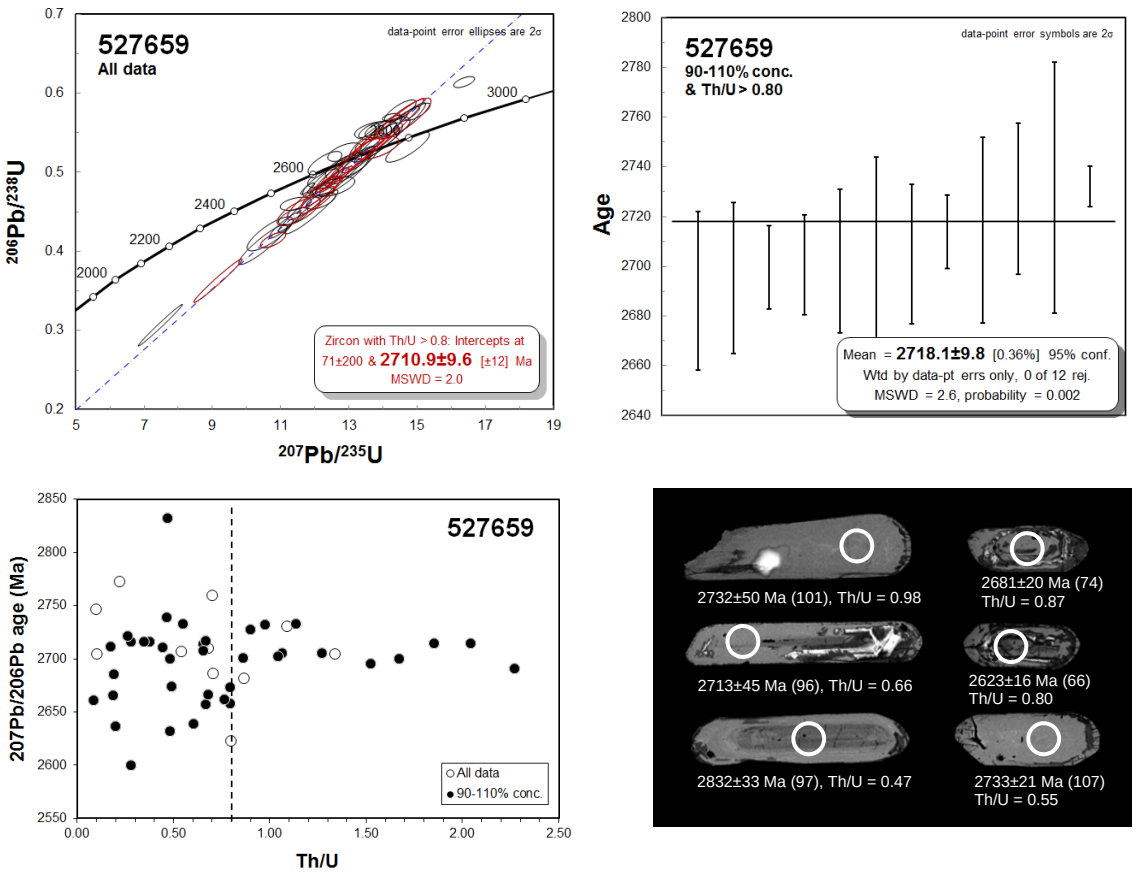

Figure 81. *U-Pb data for sample 527659: The analyses with Th/U > 0.80 define an upper intersection age of 2711 ± 10 Ma (MSWD = 2.0); rather similar to the mean weighted age of 2718 ± 10 Ma (MSWD = 2.6; n = 12) based on the 100 ± 10 % concordant grains with Th/U > 0.8. Note the occurrence of zircon grains with secondary baddeleyite zones characterised by relatively severe Pb loss (not included in the age calculation).*

Quartz syenite (527675)

Locality: Thrymheim (nunatak area)
Ganfeld station: 11TFK142, helicopter reco stop
Coordinates: N 63.57303, W 42.04634
Collector: TFK, MBK, AB, TU
Collection date: 06/07/2011
Description: Medium-grained grey quartz syenite cut by joints with a reddish staining, possibly reflecting late-stage fluid-rock interaction (Figure 82).
Purpose: Date the latest stage of the SAP magmatism in the Thrymheim area.

Figure 82. *527675: Medium-grained grey quartz syenite cut by joints of reddish staining, possibly related to late-stage fluid-rock interaction.*

Data interpretation:
Zircon grains are sub- to anhedral with a range of sizes (50 - 200 µm) and morphologies (Figure 83). Some grains have bright homogenous domains that could reflect recrystallization in presence of (late magmatic?) fluids. These grains have irregular lobate grain morphologies that seem to suggest disequilibrium features and resorption. Darker (U-poor) outer domains are variably cracked and most grains have very thin (<10 µm) outer rims that are relatively bright (U-rich).

A total of 73 spots were analysed of which 67 are unaffected by common Pb. The data are generally highly concordant with only seven analyses outside the 100 ± 10% concordancy interval. Analyses from recrystallized bright domains generally provide lower ages around c. 2660 Ma, suggesting that fluids at that time probably induced a partial overprinting of the original magmatic textures. The overprinted grains are generally as concordant

as the remaining data spots meaning that a filtering is not possible based on a concordancy criteria. However, as the overprinted grains generally (but not always) have lower Th/U than the magmatic ones, it is proposed that the magmatic zircons can be successfully identified from data with Th/U > 0.80. In the Concordia diagram (Figure 83), an upper Concordia intercept for grains with Th/U > 0.80 gives an age of 2693 ± 7 Ma (MSWD = 1.5; n = 31). A slightly better defined mean weighted age of 2695 ± 4 Ma (MSWD = 1.11; n = 27) is based on the 100 ± 10% concordant grains with Th/U > 0.80. This age is taken as the intrusion age of the granite.

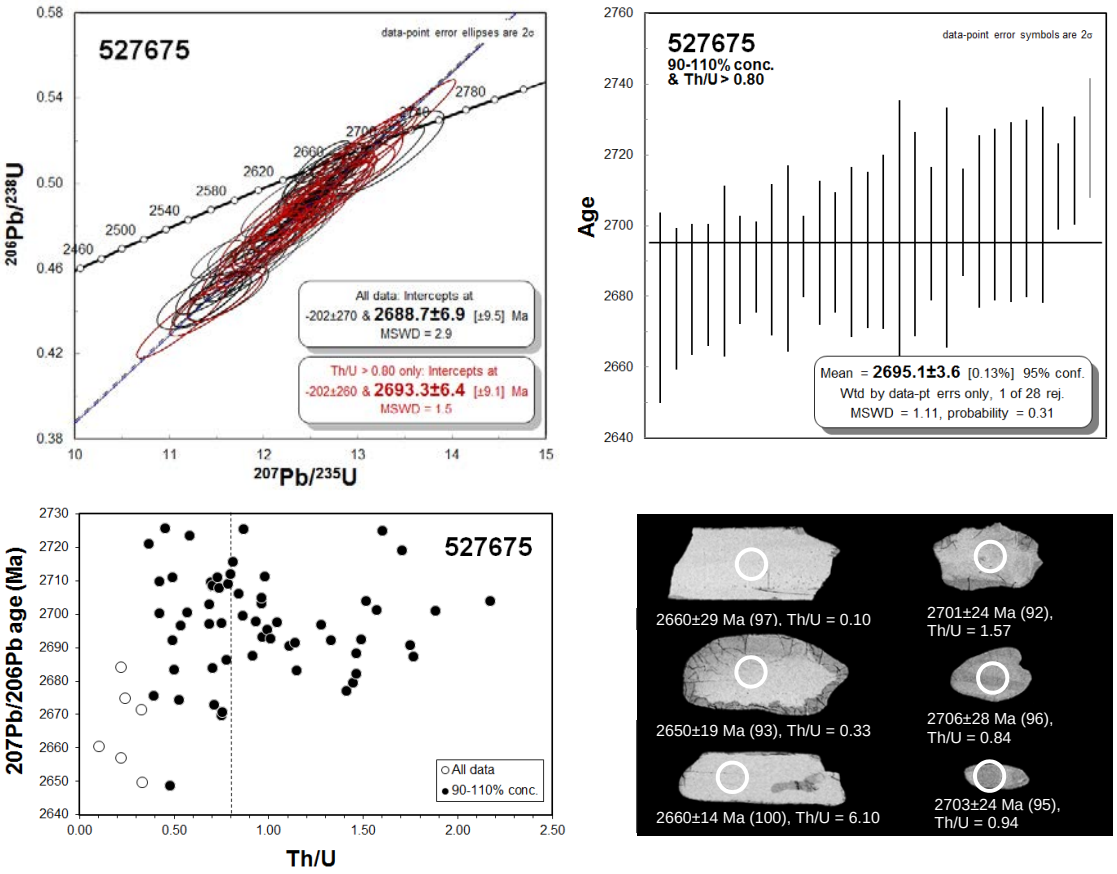

Figure 83. *U-Pb data for sample 527675: The overprinted grains tend to have lower Th/U than the unaffected ones. The magmatic zircons, unaffected by overprinting, are suggested to have Th/U > 0.80; a weighted mean age interpreted as the intrusion age of 2695 ± 4 Ma (MSWD = 1.11; n = 27) is derived from the 100 ± 10 % concordant grains with Th/U > 0.80.*

Summary

Dating of two syn- to late tectonic SAP intrusions from the Thrymheim 'nunatak' area both give consistent ages of ~2711 Ma, whereas a younger quartz syenite is dated at 2695 ± 4 Ma. This time interval of ~16 Myr appears to bracket the timing of magmatism in the westernmost part of the SAP and seems to mark the transition from syn- to post-tectonic magmatism.

Kong Dan Halvø and Skirner Bjerge

Geological background

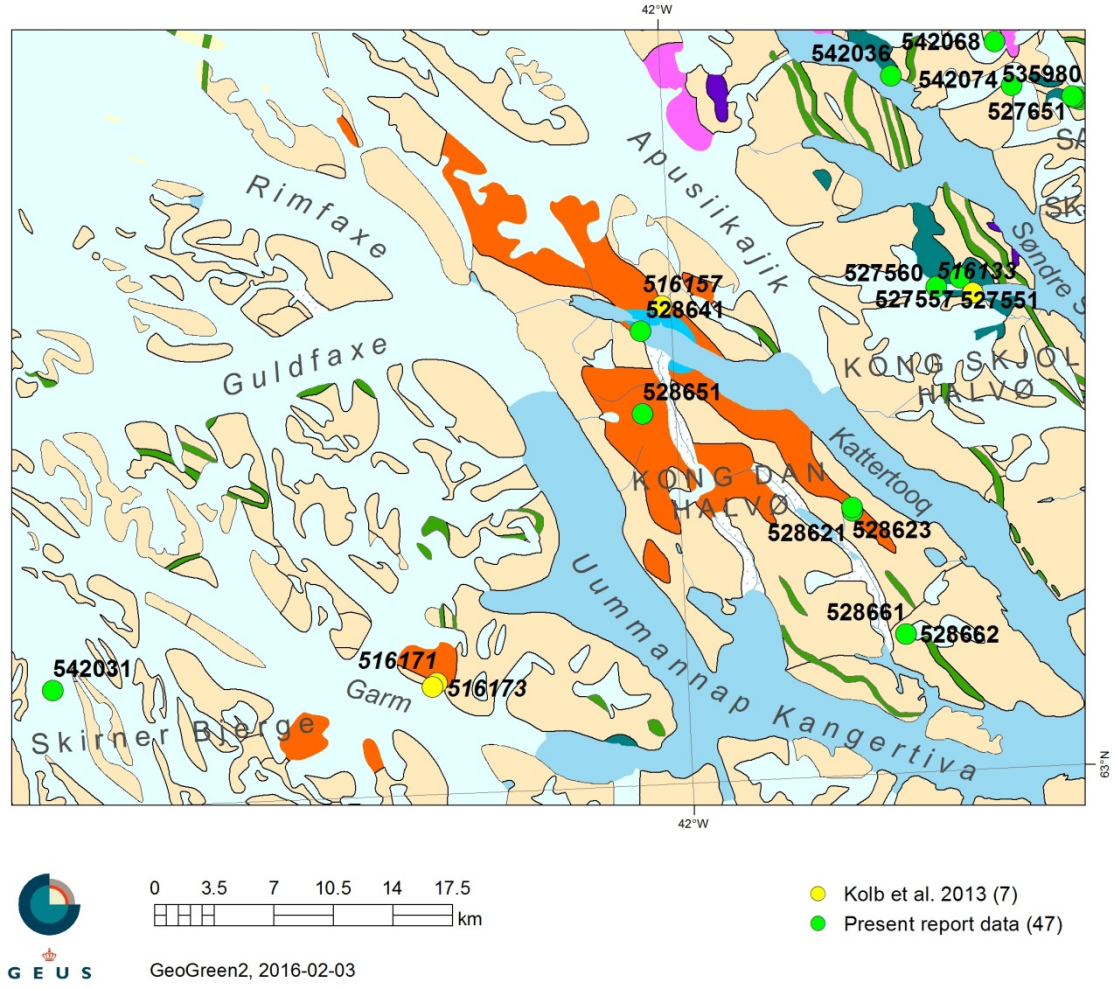

Figure 84. *Geological map of the Kong Dan Halvø and Skirner Bjerge area showing syenitic gneiss (orange unit) surrounded by orthogneiss (beige unit) and enclosing the Singertât nephelinite complex (light blue unit) at the inner part of Kattertooq fjord. Legend as in Figure 1.*

In the Kattertooq fjord area, on Kong Dan Halvø and areas farther north. a rock type is outcropping that was originally described as grey gneiss (Nielsen et al. 1988). The gneiss is recognised by smooth pale grey outcrops, as opposed to the uneven agmatitic gneiss terrain dominating the remaining basement of the NAC. The grey gneiss is described as a medium- to coarse- grained, foliated and quartz-poor amphibole-bearing rock (Nielsen et al., 1988), and occur as regular sheet-like or more rounded bodies up to 10 km in size. The contacts to the surrounding agmatitic gneiss have been described as tectonic. The grey gneiss was later redefined to be a syenitic gneiss (Nielsen & Rosing 1990), dominated by perthitic alkali feldspar, with up to 10 % quartz and containing minor green aegirine-augite and/or green to bluish-green alkali amphibole and biotite. Sphene, opaque minerals and

apatite are common accessory phases. Plagioclase is not a common phase and nepheline is not observed.

The samples on Kong Dan Halvø were collected in 2011. The syenitic gneisses in Skirner Bjerge were visited and sampled during a brief helicopter reco trip in 2012. The quartz-poor and alkali amphibole bearing syenitic gneiss has mineralogical and textural features that altogether distinguish it from the older gneiss basement of South-East Greenland, and suggest that the syenitic gneiss probably is related to the Skjoldungen Alkaline Province.

The purpose of this study was to characterise the syenite gneiss, to see how far it extends and if all syenite occurrences are part of a single large body, or if it is composed of several smaller discernible units. It was very difficult, however, to delimit the syenite in the field, due to limited exposure in the deep valleys that characterise the area. The appearance of these syenitic rocks also changes gradually from almost undeformed to more gneissic, with no clear contacts between these. In some localities we did observe two co- mingling phases of syenites, one slightly coarser-grained and quartz-rich than the other.

Results

Syenite (528620)

Locality: Camp 2, Kong Dan Halvø
Ganfeld station: 11KT037
Coordinates N 63.13962; W 41.79938
Collector: KT and JW
Collection date: 29/07/2011
Description: Steep cliffs of white syenite, which looks grey from a distance (Figure 85). In detail, a more quartz-poor syenite (528620) appears to be mingle with another slightly more quartz-rich syenite (528621).
Purpose: To obtain an age of the syenite, and to compare this age to the co-mingling quartz syenite.
Data interpretation: A total of 44 zircons were analysed. A large zircon population of various sizes and shapes was extracted from the sample. All zircons are subhedrally rounded to elongated. Most grains are slightly zoned, whereas some are almost homogeneous. All analyses yield overlapping ages of which only two analyses are more than 10 % discordant (Figure 86). All analyses are included in the calculation of an upper intercept age of 2751 ± 8 Ma (MSWD = 0.93, n = 44), which is interpreted to be the crystallisation age of the syenite.

Figure 85. *Outcrop of 528620 and 528621.*

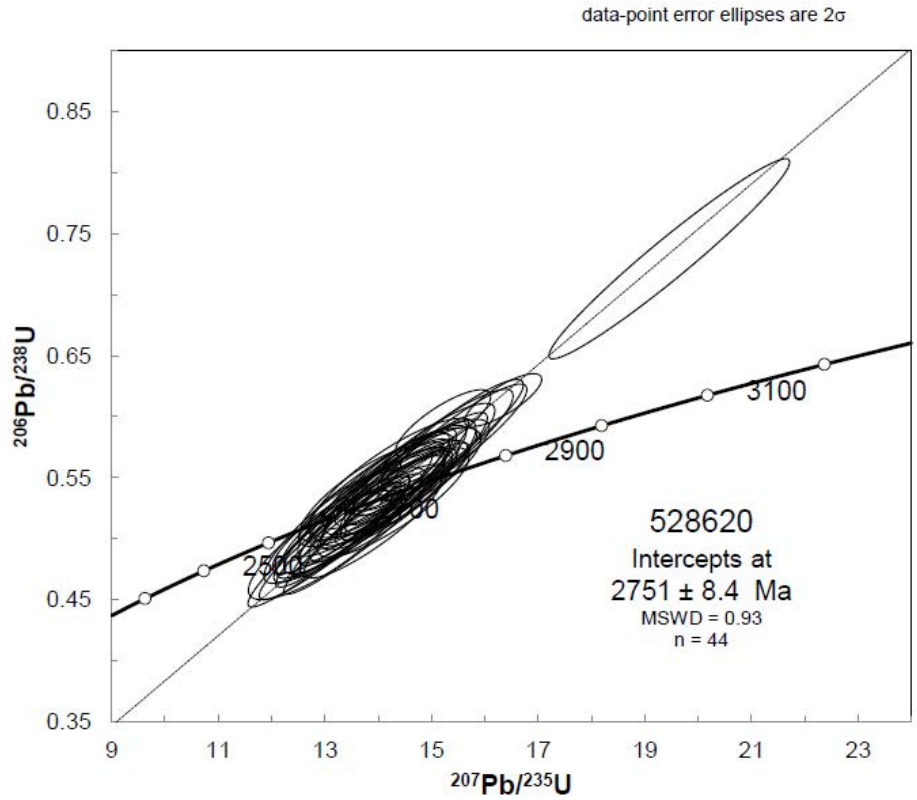

Figure 86. *Sample 528620 presented in a Concordia diagram, showing that the majority of the analyses are concordant and that all of the data represents a single age population.*

Syenite (528621)

Locality: Camp 2, Kong Dan Halvø
Ganfeld station: 11KT039
Coordinates N 63.14155; W 41.79951
Collector: KT and JW
Collection date: 29/07/2011
Description: Coarse grained syenite, slightly more mafic and quartz-rich than 528620 (Figure 85). The gneiss is co-mingling with the more deformed syenitic gneiss (528620).
Purpose: To obtain an age of the gneiss and to unravel the age-relationship between the different gneiss types.
Data interpretation: 72 analyses were carried out. The sample is dominated by large, elongated zircons with rounded tips, but smaller zircons are also present. Many grains show clear core and rims, and both types were analysed, but they yield the same age within the resolution. Several grains are fractured. All analyses yield an upper intercept age of 2758 ± 7 Ma (MSWD = 1.7; n = 72) (Figure 87).

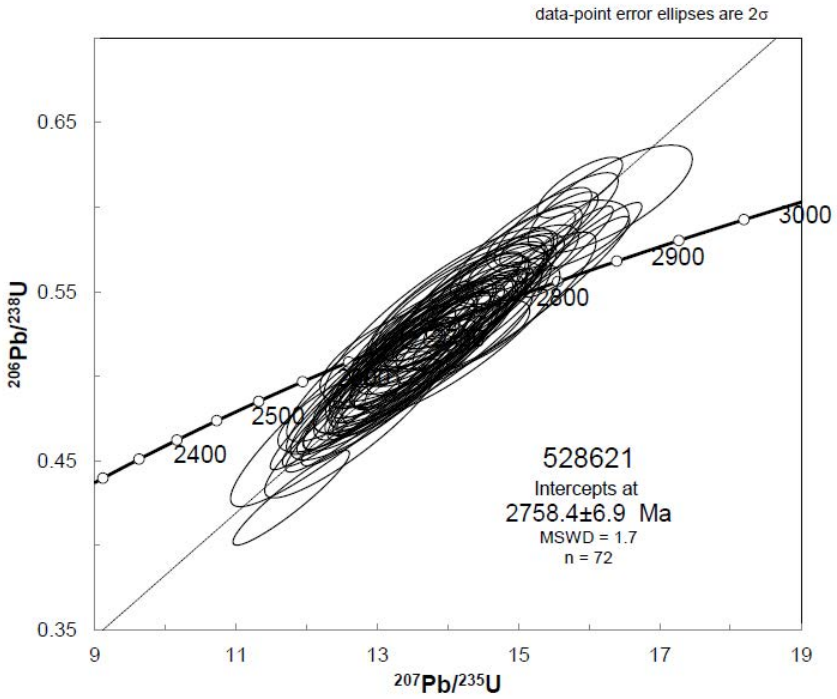

Figure 87. *Sample 528621 presented in a Concordia diagram, showing that the majority of the analyses are concordant and that the data represents one single age population.*

Sample 528620 and 528621 are collected as two different types of syenites. The field relationships showed that the two magmas were mingling and it seemed that 528621 was infiltrating 528620 and therefore assumed to be slightly younger. However, the ages are unresolvable within the analytical errors, so the field relationships are therefore interpreted to reflect mingling of two slightly different magmas of similar age.

Syenite (528623)

Locality: Camp 2, Kong Dan Halvø
Ganfeld station: 11KT039
Coordinates N 63.14155; W 41.79951
Collector: KT and JW
Collection date: 29/07/2011
Description: Syenite slightly gneissic, increasingly deformed towards the east (Figure 88).
Purpose: To date the syenite and unravel the time-relation with the other more gneissic syenites in the area.
Data interpretation: A total of 87 zircons were analysed. The zircons in this sample have similar features as sample 528621, where clear core and rims are present in several grains. However, no age difference is detected between the core and rim and the data yield an upper intercept age of 2757 ± 6 Ma (MSWD = 1.19, n = 87) (Figure 89). The age suggests that the sample belongs to the same syenitic intrusion as sample 528621.

Figure 88. *Outcrop of sample 528623.*

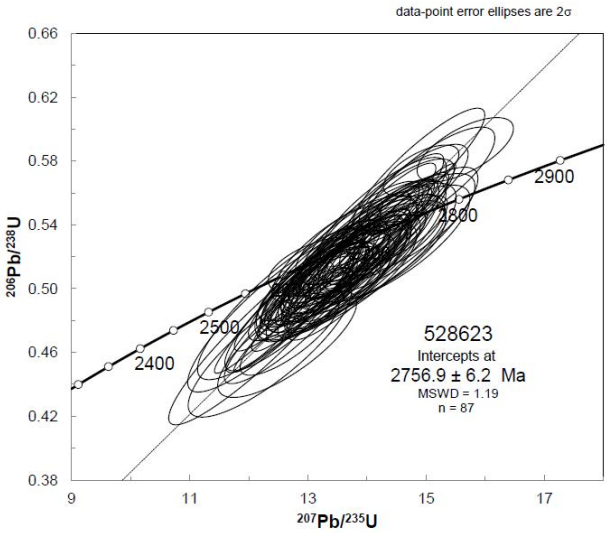

Figure 89. *Sample 528623 presented in a Concordia diagram, showing that the majority of the analyses are concordant and that the data represents one single age population.*

Syenite (528641)

Locality: Singertât Complex
Ganfeld station: 11KT059
Coordinates N 63.23982; W 42.03699
Collector: KT and JW
Collection date: 01/08/2011
Description: Medium-grained syenite, showing little evidence of deformation (Figure 90).
Purpose: To obtain an age of the syenite and see if it belongs to the same body as the other syenites.

Figure 90. *Outcrop of sample 528641. (a) Overview of outcrop with the Kattertoq fjord in the background. (b) Medium-grained weakly deformed syenite.*

Data interpretation: A total of 93 analyses were carried out from this sample. The zircons are subhedrally rounded to elongated. Many grains show cores overgrown by broad rims, and both zones were analysed, yet yielded no age difference. Some grains had thin U-rich rims that were too narrow to analyse. Some grains were fractured and metamict. Only two analyses are more than 10 % discordant, yet all analyses are part of the same age population yielding an upper intercept age of 2749 ± 6 Ma (MSWD = 1.04, n = 93) (Figure 91).

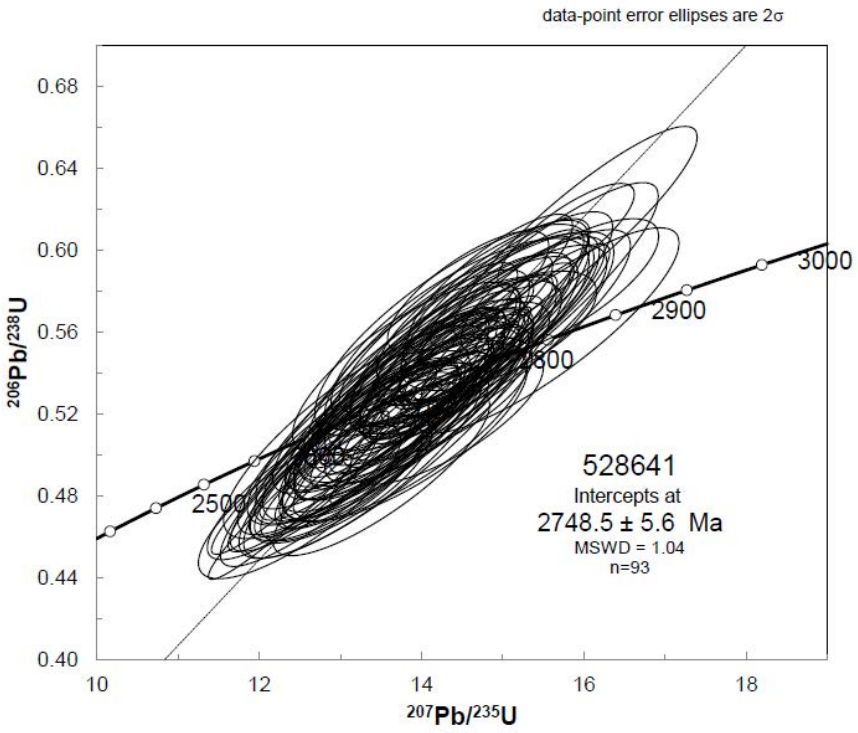

Figure 91. *Sample 528641 presented in a Concordia diagram, showing that the majority of the analyses are concordant and that the data represents one single age population.*

Syenite (528651)

Locality: Singertât Complex, type locality for the Syenite. Reco stop.
Ganfeld station: 11KT068
Coordinates N 63.19607; W 42.03921
Collector: KT and JW
Collection date: 02/08/2011
Description: Type locality for the Syenitic gneiss, within a large boulder field on the top of a mountain, south of Kattertooq fjord (Figure 92). These syenites are very weakly foliated (Figure 93) and do not have a gneissic appearance as suggested by previously investigations. Despite the sampled boulders are not being in-situ, it is obvious, that they have not been transported far, but represent the underlying syenite. The rock is leucocratic and alkali-feldspar-rich, with only a few percent mafic minerals.
Purpose: To obtain an age of the syenite and relate it to the other syenites.

Figure 92. *Type locality of the syenitic gneiss, on top of the mountain, south of Kattertooq fjord and the Singertât complex.*

Figure 93. *Sample 528651. Weakly foliated syenite.*

Data interpretation: A total of 73 analyses were carried out on sample 528651. The sample contains subhedral, elongated zircons with rounded ends. Many grains show clear cores and rims, but as for the previously described sample these yielded the same age withinerrror. Eight analyses were more than 10 % discordant and seem to have suffered Pb-loss. However, only 3 of these are not included in the age calculation, which yield an upper intercept age of 2739 ± 6 Ma (MSWD = 1.3, n = 70) (Figure 94). This age overlaps with the age of 528641, but is slightly younger than the three samples collected at Camp 2.

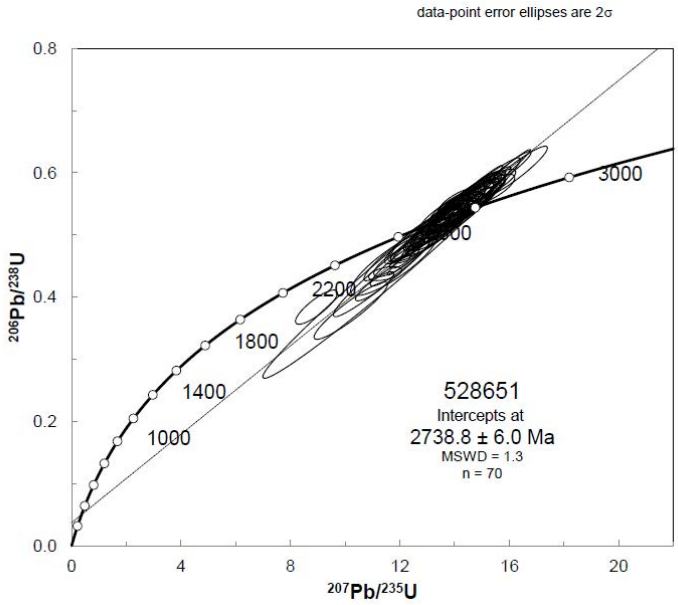

Figure 94. *Sample 528651 presented in a Concordia diagram, showing that the majority of the analyses are concordant and that the data represents one single age population.*

Diorite (528661)

Locality: South-east part of Kong Dan Halvø – Reco stop.
Ganfeld station: 11KT088
Coordinates N 63.07319; W 41.74448
Collector: KT and JW
Collection date: 06/08/2011
Description: Large dioritic xenolith of an older gneiss (528662) (Figure 95).
Purpose: To obtain an age for the diorite inclusion and thereby a metamorphic age of the older gneiss that the syenites intruded into.

Figure 95. *Medium grained diorite, sample 528661.*

Data interpretation: A total of 53 analyses were carried out. The zircons are an- to subhedral, and only a few of these are zoned. Many grains are fractured or broken up to smaller fragments. Despite their poor stat, only very few of the analyses are more than 10 % discordant and all analyses clearly belong to one single age-population. If one analyses is removed, then the rest yields an upper intercept age of 2745 ± 10 Ma (MSWD = 1.8; n = 52). If the 4 largest outliers are removed an upper intercept age of 2744 ± 9 Ma (MSWD = 1.6, n = 49) is obtained (Figure 96). This sample is not part of the syenite intrusions, but yields an age that overlaps with the previously described syenites of the area.

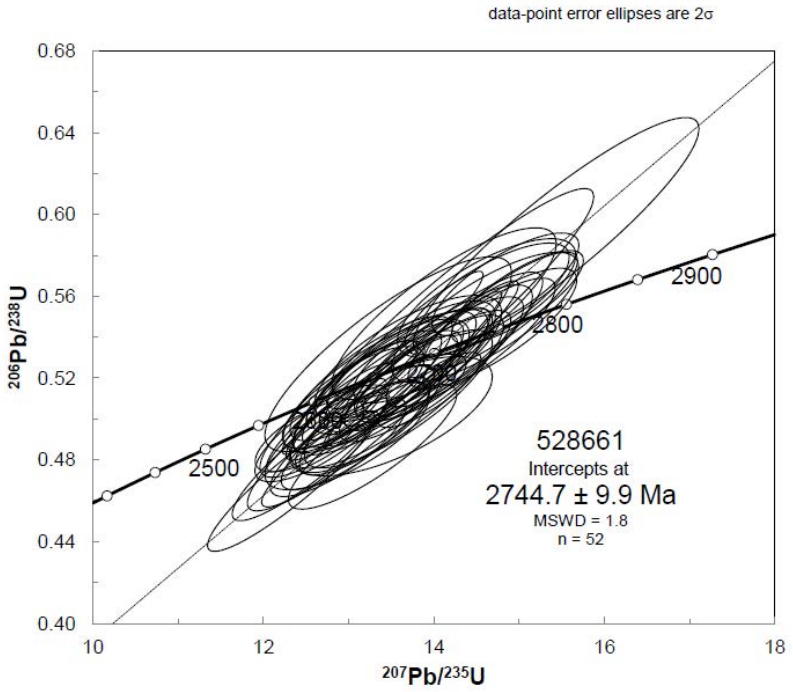

Figure 96. *Sample 528661 presented in a Concordia diagram, showing that the majority of the analyses are concordant and that the data represents a single age population.*

Granodioritic gneiss (528662)

Locality: South-east part of Kong Dan Halvø – Reco stop.
Ganfeld station: 11KT088
Coordinates N 63.07319; W 41.74448
Collector: KT and JW
Collection date: 06/08/2011
Description: The granodioritic gneiss is hosting the diorite inclusion (528661) (Figure 97). The sample represents the leucosome part of the gneiss.
Purpose: To date the leucosome and thereby relate it to the other gneisses.

Figure 97. *Outcrop from which sample 528662 was collected.*

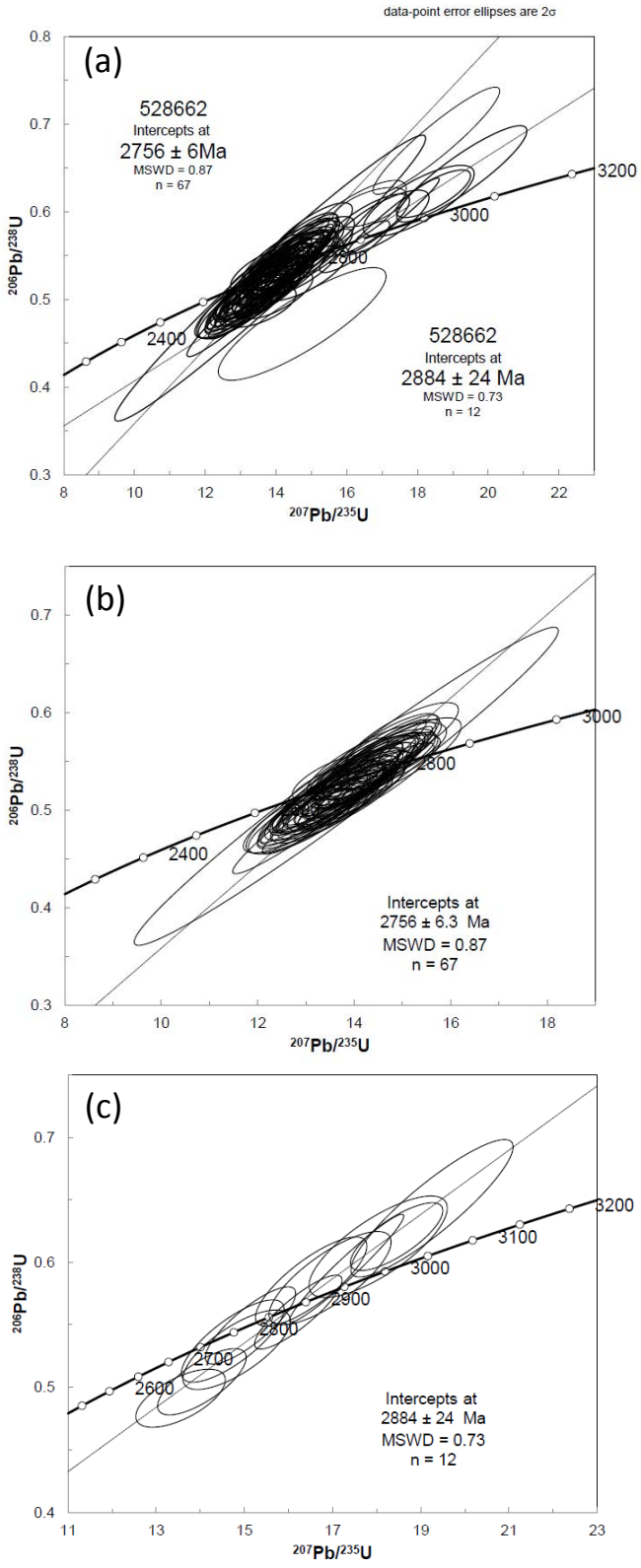

Figure 98. *Sample 528662 presented in a Concordia diagram. The analyses represent two different age populations. A minor population represents the older generation while the majority of the analyses belongs to the younger population of the same age as the syenites.*

Data interpretation: A total of 83 analyses were made on extracted zircon grains. The zircons are an- to subhedrally elongated to rounded grains. Several grains are zoned and most grains are very metamict; especially the rims are full of cracks.
Analyses can be divided into two groups, an older small group yielding an intercept age of 2884 ± 24 Ma (MSWD = 0.73; n = 12), and a younger, dominating population yielding an age of 2756 ± 6 Ma (MSWD = 0.87; n= 67). The older group only determined by cores, whereas the younger population is derived from a mixture of both cores and rims. Most of the zircons are very metamict and especially the rims are full of cracks. The older age is interpreted to represent the protolith age.The younger age overlaps with the majority of syenite ages, and is interpreted to reflect the contact metamorphism that affected the surrounding basement due to these intrusions.

Gneissose syenite with inclusions of banded gneiss (542031)

Locality: Skirner Bjerge – Reco stop
Ganfeld station: 12TFK105
Coordinates N 63.06467; W 42.74056
Collector: TFK, BMST, CT, ST and ABO
Collection date: 12/08/2012
Description: Leucocratic gneissose syenite with inclusions of banded gneiss in dismembered trains (Figure 99).
Purpose: To obtain age information for the southernmost syenitic gneisses that is presumed to be part of the SAP. The banded gneiss inclusions were sampled (542032) for age dating (see Næraa et al. 2016).

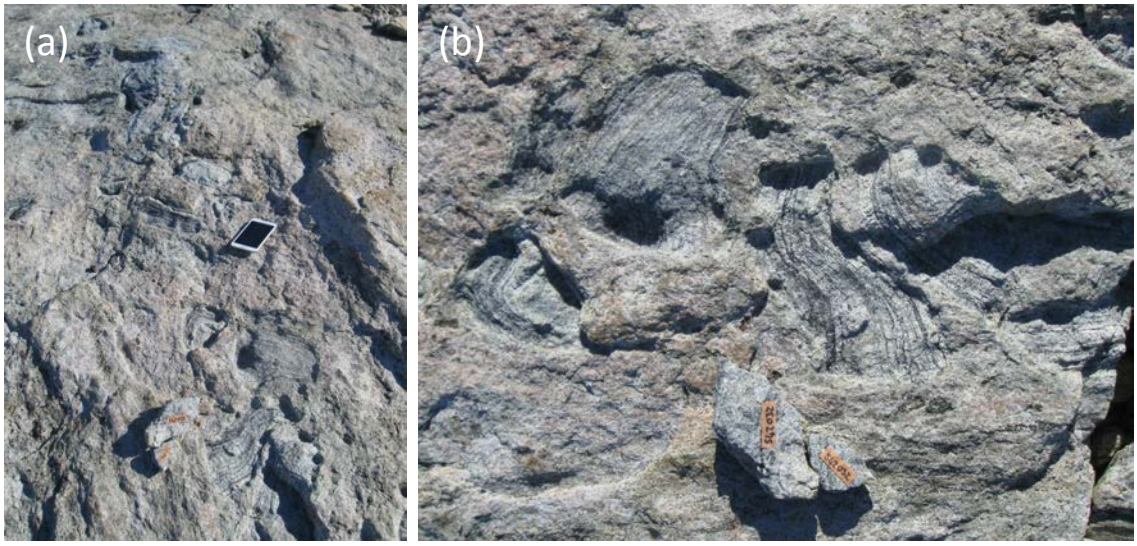

Figure 99. *Sample 542031: (a) Outcrop scale: Gneissose agmatitic syenite (sample 542031) with trains of inclusions of banded gneiss (542032; see Næraa et al. 2016). (b) Close-up photograph of agmatitic textured syenite.*

Data interpretation

The zircons are usually subhedrale and cracked and often show variable degrees of faint zoning patterns with bright centres and darker rims (Figure 100). 105 spots were analysed of which 81 produced acceptable data with no or very minimal effects of common Pb influence. Most analyses are concordant at a 100 +/- 10% level, with some (mainly older) analyses showing reverse discordancy. The main zircon population yields a single concordant age population at 2760 ± 6 Ma, interpreted as the crystallisation and intrusion age of the syenite (Figure 100). A broad age peak consisting inherited zircons gives an imprecise older age of 2959 ± 19 Ma.

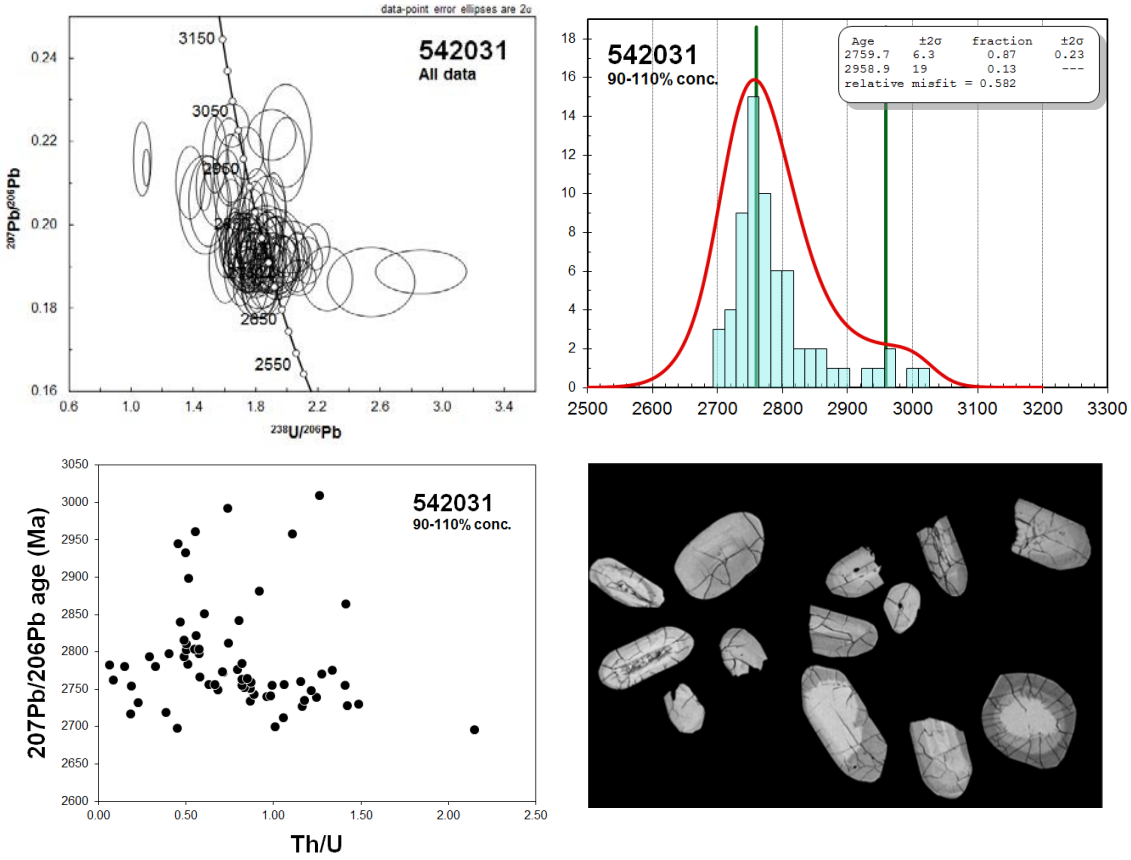

Figure 100. *U-Pb data for 542031: The main zircon population yields a single age population at 2760 ± 6 Ma interpreted as the crystallisation and intrusion age of the syenite. A broad age peak consisting inherited zircons gives an imprecise older age of 2959 ± 19 Ma.*

Summary

Of the seven samples of syenitic gneiss dated from Kong Dan Halvø six are identical within the analytical errors of the analyses, giving an average of 2752 ± 6 Ma. Sample 528651 is 2739 ± 6 Ma and thus significantly younger than three of the oldest samples (528621, 528623 and 528662). Overall the syenitic gneisses from the Kattertooq fjord area predate any of the other samples dated from the SAP, and thus define the earliest development of the Province.

In Skirner Bjerge a single sample of a gneissose syenite containing inclusions of banded gneiss gives an age of 2760 ± 6 Ma, which is interpreted as the earliest and southernmost expression of the SAP magmatism recorded to date.

Consecutive summary

This report presents zircon U-Pb age data by LA-ICPMS measured at GEUS for 47 samples that were sampled during field work in 2011 and 2012 in the Skjoldungen Alkaline Province (Nielsen and Rosing 1990; Blichert-Toft et al. 1995) in South-East Greenland. Of the 47 age dated samples 38 are intrusive granitoids, 14 are pegmatitic or aplitic veins and three are gneisses that are variably overprinted by SAP intrusions (Appendix Table A1). The geology of each sub-area (intrusive centre) is briefly covered, whereas a more detailed account on the field relationships can be found in Klausen and Kokfelt (2014).

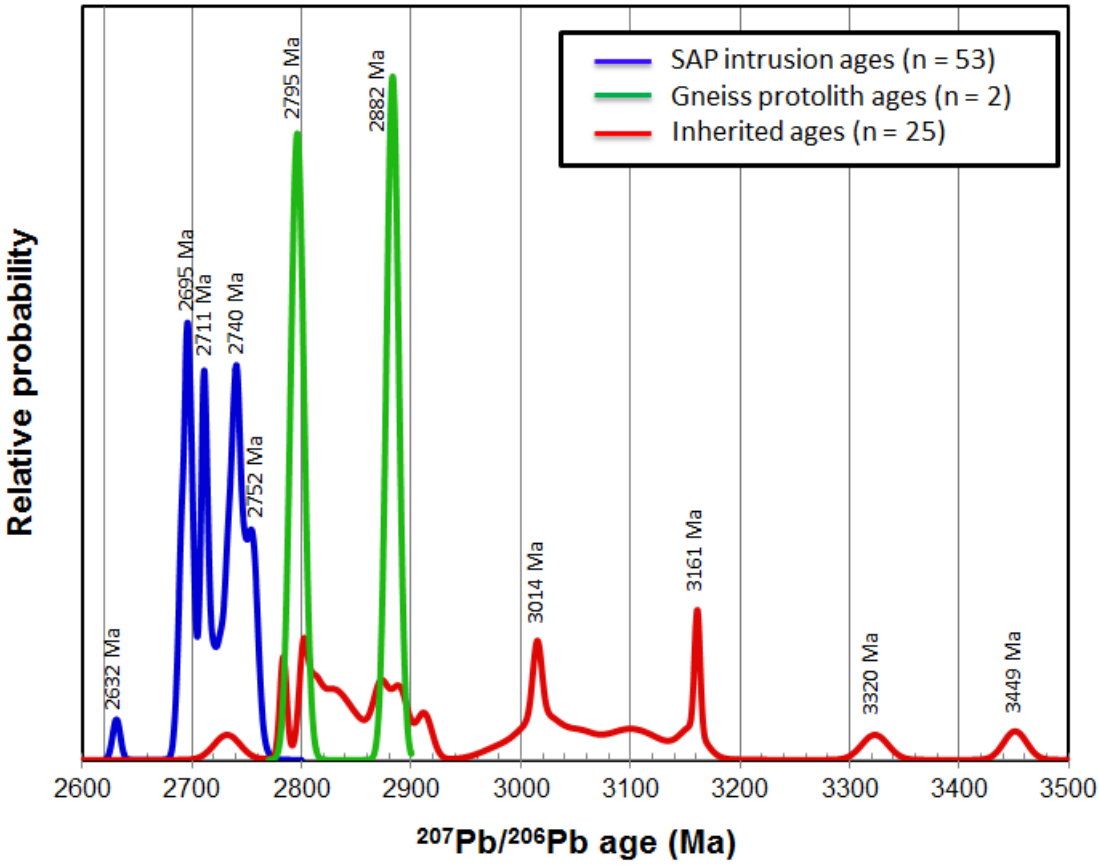

Figure 101. *A summary age distribution diagram showing the 47 age dated samples from the Skjoldungen Alkaline Province plus seven additional SAP samples published by Kolb et al. (2013). The ages are divided into SAP related and older types (gneiss protolith or inherited). Note that 'n' is the number of ages recorded for each group.*

The new age data are summarised in Figure 101 that plots the age distribution for the 47 new samples along with seven SAP samples that were already published by Kolb et al. (2013). In this Figure the SAP intrusions (blue) define a relatively narrow time interval of c. 60 Ma from c. 2750 to c. 2690 Ma (disregarding one younger sample at 2632 Ma, sample 527598). Within this time span four distinct age peaks are apparent at 2695, 2711, 2740 and 2752 Ma (Figure 101) suggesting that SAP can be characterised by different phases of magmatic activity (see below). Inherited zircons constitute 25 age determinations in the

range c. 2800 – 3450 Ma, defining six fairly distinct age peaks at c. 2800, 2880, 3015, 3160, 3320 and 3450 Ma. The two gneiss protolith ages reiterate the existence of the former two youngest age peaks. Taken together, these older ages at 2800 – 3450 Ma indicate that zircons from the gneissic basement were incorporated into the SAP magmas during emplacement, and thus witness crustal contamination processes playing a role in the generation of the felsic to intermediate SAP magmas.

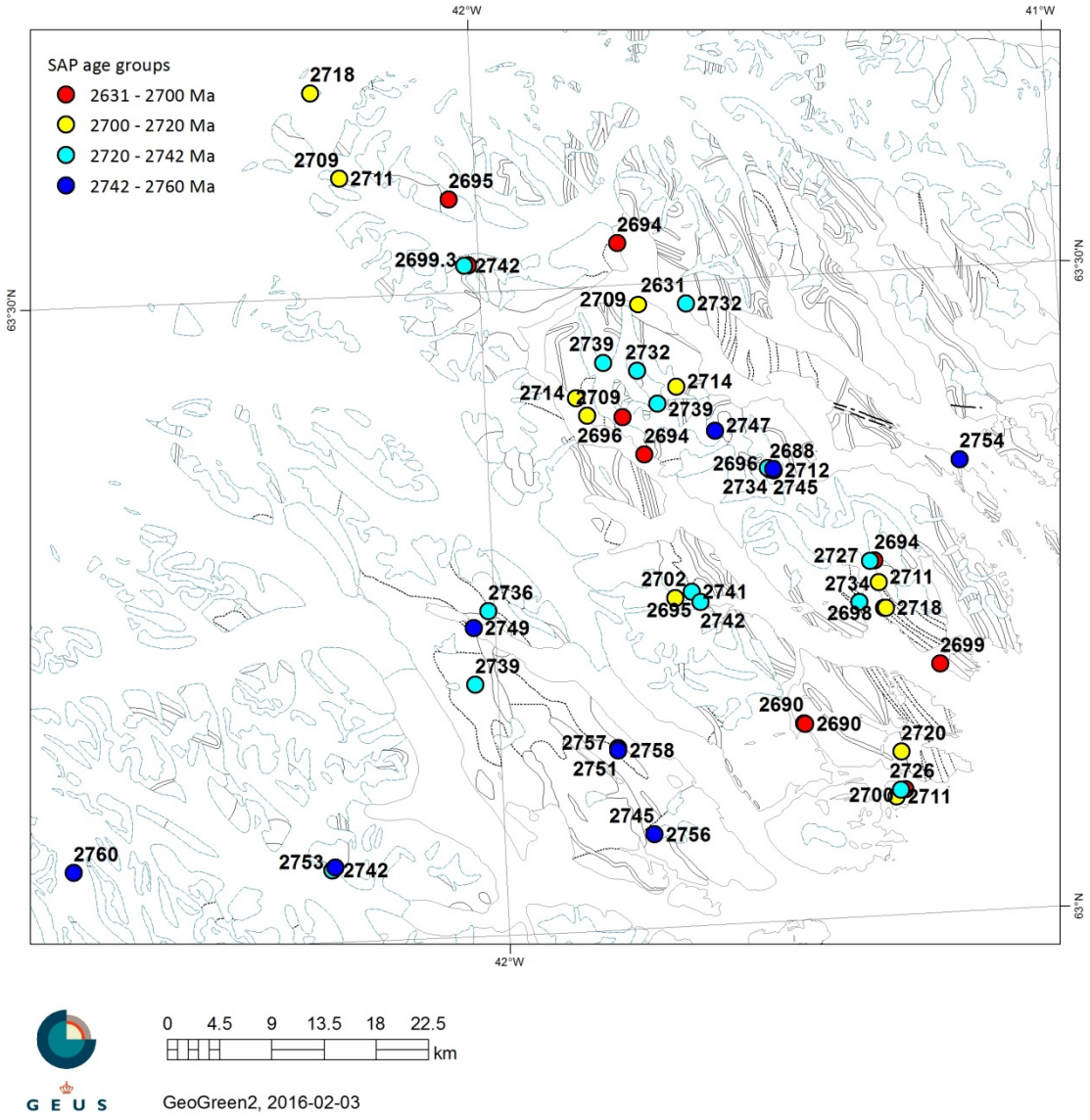

Figure 102. *Map of the Skjoldungen Alkaline Province showing the new age data as four distinct groups based on age interval. The age distribution is broadly systematic with a temporal migration of magmatism from the south to north, but also defines a shift in direction from initially being centred along a NE-SW axis (2760 – 2720 Ma) to being centred along a NW-SE axis at the later stage (2720 – 2695 Ma).*

A more thorough analysis of the temporal evolution of the gneiss basement based on additional zircon U-Pb analysis from the larger Skjoldungen area (i.e. gneisses from the areas

between Bernstoff Isfjord and Mogens Heinesen Fjord) is the focus of the second volume of geochronological data reported from South-East Greenland (Næraa et al. 2016).

In Figure 102 the SAP age data are plotted by color-coding the four identified age groups from above in order to assess how magmatism is distributed through time and space. It appears from this figure that the timing of magmatism defines a general younging from south to north, with the oldest ages of 2760-2742 Ma (dark blue) represented by the syenitic gneisses in Skirner Bjerge and around Kong Dan Halvø. The remaining younger age groups are 2742-2720 Ma (light blue), 2720-2700 Ma (yellow) and 2700-2632 Ma (red); and all occur without any distinct geographical systematics along the NW-SE axis defined by Skjoldungen Island and parts of Kong Skjold Halvø plus the (Thrymheim 'nunatak' area). Thus the earliest phase of SAP magmatism (i.e. 2760 – 2720 Ma) started in the south and was emplaced along a NE-SW axis, whereas the subsequent magmatism (2720 – 2695 Ma) was emplaced along a NW-SE axis, implying an overall shift in the direction during the emplacement of SAP.

In the context of the tectono-metamorphic model proposed for the Skjoldungen area by Kolb et al. (2013), the earliest SAP rocks in the Skirner Bjerge could reflect a juvenile mantle melt input related to subduction processes correlating with the convergent Skjoldungen Orogeny. Our age data have not obtained direct age constrains on the timing of the (presumed) early mafic magmatism, such as the larger mafic intrusions in Stærkodder Vig and Halvdans Fjord mafic, because these rock types simply do not contain zircons. However, their deformed nature (Klausen and Kokfelt, 2014) would certainly argue for them representing an early phase within the SAP. In terms of P-T conditions, this stage corresponds to peak granulite facies metamorphic conditions as recorded by metasediments from Helge Halvø (Berger et al. 2014). The following stage(s) in the evolution of the region was synchronous with the emplacement of the bulk part of the alkaline intrusive rocks forming the SAP in a subduction setting from 2740 to 2700 Ma. This period was characterised by uplift of the area accompanied by retrograde metamorphism under amphibolite facies conditions and regional scale folding. Overall the new U-Pb zircon age data show an evolution from c. 2750 Ma to 2690 Ma with distinct phases of magmatic pulses and metamorphic recrystallisation, suggesting a protracted convergent setting that lasted c. 50 m.yr., which is correlated with the exhumation of the high-grade rocks (Berger et al. 2014).

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Appendices

List of samples dated

Table 1. *Samples selected for zircon U-Pb dating by LA-ICPMS at GEUS*

Sample (GGU#)	Latitude (deg. N)	Longitude (deg. W)	Elevation (m.a.s.l.)	Station ID	Place name	Rock description
509319	63.09765	-41.31193	49	12TFK140	Igdlermiut, E	Syenitic pegmatite at margin of mafic intrusion
509328	63.09769	-41.31964	100	12TFK148	Igdlermiut, E	Fsp porphyric granitic gneiss
509345	63.12758	41.31439	845	-	Bikuben, Kong Skjold Halvø	Mgr granite (frost shattered grab sample)
509369	63.40033	-41.82410	53	12TFK174	Northern Sdr. Skjoldungensund	Cgr monzonite with schiller effect
509387	63.41935	-41.66803	858	12TFK183	NE Skjoldungen	Granite
527505	63.15322	-41.47867	61	11MBK003	Vend Om Gabbro	Leucocratic pegmatite cross cuts mafic gabbro
527506	63.15252	-41.47714	0	11MBK005	Vend Om Gabbro	Leucocratic pegmatite cross cuts mafic gabbro
527509	63.15253	-41.47102	151	11MBK012	Vend Om Gabbro	Migmatitic gneiss
527528	63.27619	-41.35051	54	11TFK005	Halvdans Fjord	Gneissose granite
527534	63.24486	-41.36483		-	Halvdans Fjord	Weakly foliated granite
527540	63.23928	-41.33126		-	Halvdans Fjord	Aplitic part of pegmatite
527547	63.25929	-41.33795	50	11TFK002	Stærkodder Vig	Gneissose granite
527551	63.25398	-41.65996	88	11TFK052	Stærkodder Vig	Leucocratic pegmatite dyke
527557	63.25413	-41.66134	84	11TFK059	Stærkodder Vig	Mgr-cgr granodioritic gneiss near contact to diorite/gabbro
527560	63.25567	-41.68811	357	11TFK061	Stærkodder Vig	Granodioritic gneiss, oriented sample
527569	63.53300	-41.75764	55	11TFK072	Ruinnæsset	Kfsp porphyric syenite with mineral filled miarolithic cavity
527585	63.48689	-41.71250	46	11TFK087	Ruinnæsset	Fine-grained syenitic sheet w/ well developed schistosity
527598	63.48333	-41.64337	45	11TFK092	Ruinnæsset	Purple pegmatite (w/ miarolithic cavities)
527609	63.27644	-41.34316	191	11TFK008	Halvdans Fjord	Migmatised amphibolite
527637	63.35427	-41.44157	47	11TFK103	Hermods Vig	Coarse grained quartz syenite
527650	63.35041	-41.50797	520	11TFK129	Njords Gletcher	Fine grained felsic (syenitic?) intrusion in coarse grained to pegmatitic heterogeneous gabbro
527651	63.35160	-41.50832	493	11TFK131	Njords Gletcher	Coarse grained gabbro w/ contact
527654	63.59285	-42.23498	1298	11TFK137	Thrymheim	Monzonite, cgr weakly fol
527659	63.66014	-42.27941	1845	11TFK139	Thrymheim	Granite fgr, intrudes agmatitic gneiss
527675	63.57303	-42.04634	1535	11TFK142	Thrymheim	Qtz syenite (intrudes 527674)
527678	63.40676	-41.70211	1349	11TFK144	Sfinksen	Qtz syenite, cgr
527679	63.44074	-41.79188	1092	11TFK145	Sfinksen	Qtz syenite
527685	63.43314	-41.73435	1114	11TFK146	Sfinksen	Qtz syenite, cgr
528620	63.13962	-41.79938	-	11KT037	Midt Kong Dan Halvø	syenitic gneiss
528621	63.13962	-41.79938	-	11KT037	Midt Kong Dan Halvø	tonalite
528623	63.141552	-41.79951	-	11KT039	Midt Kong Dan Halvø	tonalite
528641	63.239822	-42.036988	-	11KT059	Singertat Complex	Syenitic gneiss?
528651	63.196073	-42.039208	-	11KT068	Singertat Complex	Syenite boulder field
528661	63.07319	-41.744482	-	11KT088	East part of Kong Dan Halvø	syenitic gneiss
528662	63.07319	-41.744482	-	11KT088	East part of Kong Dan Halvø	tonalitic gneiss
535905	63.09250	-41.32771	172	12TFK024	Igdlermiut, S	Granitic vein (from melting of agmatitic gneiss?)
535925	63.19343	-41.24039	66	12TFK051	Anarnitsoq island	Qtz syenite. Cgr slightly fsp porphyric. Foliated.
535962	63.35124	-41.51390	735	12TFK076	Njords Gletscher Intrusion, upper part	Felsic aplite cuts gabbro.
535968	63.35168	-41.51521	768	12TFK081	Njords Gletscher Intrusion, upper part	Very Cgr pegmatite w bt and mt. Zr dating?
542031	63.06273	-42.73933	1848	12TFK104	Skirner Bjerge	Agmatitic gneiss with train of disrupted banded gneiss.
542036	63.36818	-41.72870	39	12TFK108	Sdr Skjoldungensund, Northern part	Very cgr felsic pegmatite intruding gabbro.
542059	63.39797	-41.76308	725	12TFK177	Sfinksen Shelf	Felsic pegmatite with up to 1 cm reddish zircon (possible zr std?)
542068	63.38345	-41.60497	930	12TFK187	Central NE Skjoldungen	Granite, frost shattered grab sample (local origin)
542074	63.35965	-41.58764	1047	12TFK188	Central Skjoldungen	Agmatitic gneiss
542402	63.52122	-42.01784	-	-	Dronning Maries Dal	Granitic aplite intruded into deformed felsic SAP rocks
542410	63.52110	-42.02459	-	-	Dronning Maries Dal	Mildly foliated granite
527561_B	63.30040	-41.71559	56	11MBK034	Stærkodder Vig	Fsp porphyric moderately foliated granodioritic gneiss w/ mafic and UM xenoliths
Samples published in Kolb et al. (2013)						
516104	63.414247	-41.842005	-	09JKOL005	Skjoldungen Island	Granitic granulite
516117	63.350978	-41.185955	-	09JKOL013	Langenæs Peninsular	Granodioritic gneiss
516133	63.251392	-41.645857	-	09JKOL021	Sønder Skjoldungensund	Granodioritic gneiss
516157	63.252498	-42.010653	-	09JKOL043	Singertat Complex	Quartz syenite
516161	63.2393	-41.327975	-	09JKOL047	Roar Halvø	Granitic dyke
516171	63.058995	-42.292008	-	09JKOL059	Skirner Bjerge	Syenitic gneiss
516173	63.056885	-42.297478	-	09JKOL061	Skirner Bjerge	Granodioritic gneiss

List of field participants and their affiliations

Table 1. *Overview of participants in the fieldwork in the Skjoldungen area 2011 and 2012 (arranged alphabetically).*

Name & initials	Affiliation	2011	2012
Alfons Berger AB	University of Copenhagen	X	
Andries Botha ABO	Stellenbosch University, SA		X
Bjørn Peder Maarupgaard BPM	Aarhus University		X
Christian Tegner CT	Aarhus University		X
Justyna Wiewióra JW	Geological Museum, University of Copenhagen, DK	X	
Karen Hanghøj KHA	Geological Survey of Denmark and Greenland, DK	X	X
Kristine Thrane KT	Geological Survey of Denmark and Greenland, DK	X	X
Lars Lund Sørensen LLS	Geological Survey of Denmark and Greenland, DK	X	X
Leon Bagas LBA	University of Western Australia, AU	X	X
Lærke Thomsen LT	Ministry of Minerals and Resources, Greenland Government		X
Martin Broman Klausen MBK	Stellenbosch University, SA	X	X
Sebastian Tappe ST	University of Johannesburg, SA		X
Troels Nielsen TFN	Geological Survey of Denmark and Greenland, DK	X	
Thomas Find Kokfelt TFK	Geological Survey of Denmark and Greenland, DK	X	X
Thomas Ulrich TU	Aarhus University	X	
Tomas Næraa TN	Geological Survey of Denmark and Greenland, DK	X	X