New zircon U-Pb and Hf isotopic constraints on the crustal evolution of the Skjoldungen region, South-East Greenland

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We report new zircon U-Pb and Hf isotopic data from the Skjoldungen region between *c.* 62°30′ and 63°40′N in South-East Greenland. The work was carried out under the South-East Greenland Mineral Endowment Task (SEGMENT); a joint project between the Geological Survey of Denmark and Greenland (GEUS) and the Ministry of Mineral Resources (MMR) in Greenland to assess the mineral endowment and update the geological knowledge of the region using modern petrological, geochemical and geochronological tools. This paper presents new zircon U-Pb and Hf isotopic data from a range of different Archaean rocks in the Skjoldungen region, which greatly improve the understanding of the history of crustal growth.

Regional geology

The Skjoldungen region in South-East Greenland as defined here covers the ice-free area between Mogens Heinesen Fjord in the south and Bernstorff Isfjord in the north (Fig. 1). The region exposes a mid- to lower-crustal section of the Archaean North Atlantic craton (Kolb *et al.* 2013 and references therein). The dominant rock type is granodiorite with lesser amounts of monzogranite and rare tonalite, commonly with nebulitic to agmatitic textures, and with abundant mafic and ultramafic inclusions. The northern part of the region includes grey orthogneiss that is interleaved with the agmatitic gneiss. The southern part is structurally highly complex containing abundant migmatitic rocks, generally recording lower crustal conditions. Remnants of older supracrustal rocks forming kilometre-sized lensoidal belts of mafic granulite, ultramafic rocks and paragneiss are found in the northern and southernmost parts of the region (Fig. 1). These rocks are commonly invaded by felsic partial melts, dismembering their border zones into smaller units that also account for the agmatitic texture of the surrounding gneiss.

Kolb *et al.* (2013) and Bagas *et al.* (2013) proposed that the region was deformed during both the > *c.* 2800 Ma Timmiarmiut and the *c.* 2790–2700 Ma Skjoldungen orogenies. The Timmiarmiut orogeny is only weakly defined based on deformation events in the southern part of the area that are overprinted by the Skjoldungen orogeny. Skjoldungen island and its surroundings reached granulite facies peak conditions at *c.* 2760–2740 Ma. Subsequent orogenic collapse characterised by fast exhumation rates (Berger *et al.*

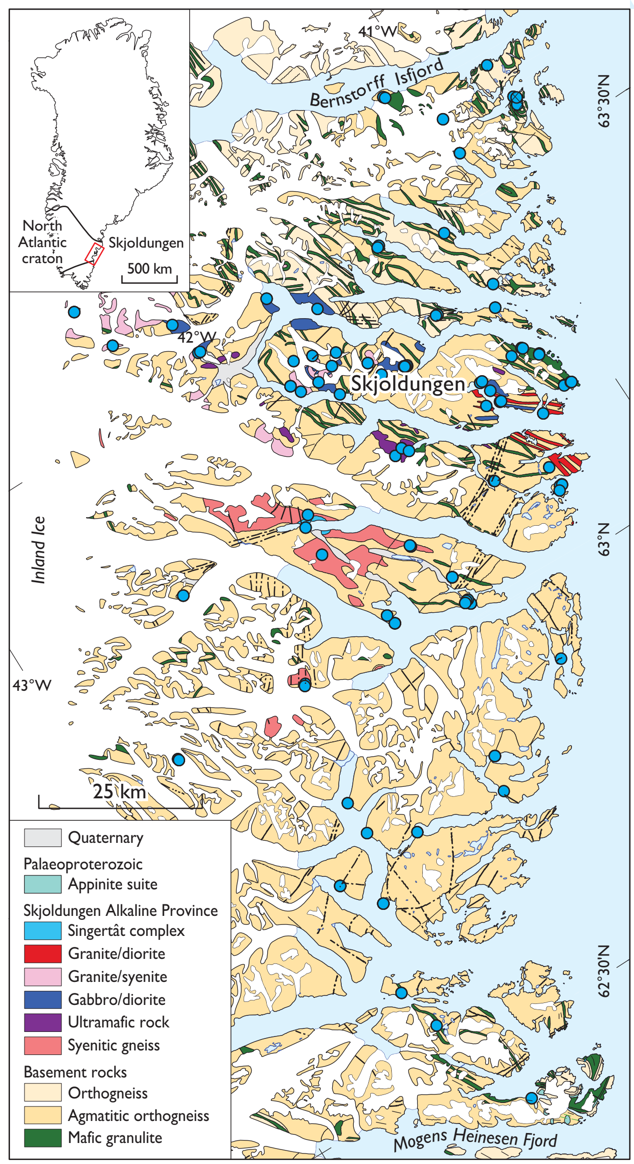

Fig. 1. Geological map of the Skjoldungen region, South-East Greenland, showing locations of samples (blue circles) selected for zircon U-Pb geochronology and zircon Hf isotope analysis.

2014) resulted in extensive crustal remelting and continued emplacement of mildly alkaline plutons forming the Skjoldungen Alkaline Province, which constitutes a globally rare occurrence of Archaean alkaline magmatism (Blichert-Toft *et al.* 1996). The province comprises a large number of mafic and ultramafic to differentiated intrusions within a large area of *c.* 2400 km^2 centered at the WNW-trending Skjoldungen island (Blichert-Toft *et al.* 1995). The magmatism comprises a slightly alkaline, *c.* 2750–2690 Ma, stage followed by a highly alkaline, *c.* 2680-2664 Ma Singertât stage, which includes nephelinitic and carbonatitic rocks (Nielsen & Rosing 1990; Nutman & Rosing 1994; Kolb *et al.* 2013).

Samples and methods

A total of 109 samples of orthogneiss, migmatite, granitic rocks, pegmatite and aplite were collected for U-Pb zircon geochronology. As seen in Fig. 1 the geographical sample distribution is uneven, with most samples collected in the northern part of the region. Similarly, coastal areas are more densely sampled than remote and less accessible areas near the ice sheet.

Most U-Pb data were acquired using laser ablation-single collector-magnetic sector field-inductively coupled plasma-mass spectrometry (LA-SF-ICP-MS) at GEUS, employing a Thermo Finnigan Element2 mass spectrometer coupled to a New Wave Research UP213 frequency-quintupled solid state Nd:YAG laser system. The analytical procedures followed Frei & Gerdes (2009) and Dziggel *et al.* (2014). A few samples were analysed at the Nordsim facility at the Natural History Museum in Stockholm using standard procedures in Whitehouse *et al.* (1999), and at the SHRIMP facility at Curtin University using standard procedures in Compston *et al.* (1984). Different textural domains of the zircon grains such as cores and rims were documented using scanning electron microscopy and targeted during analysis. Hf isotope data by LA-ICPMS were obtained on a subset of samples, targeting the same textural domains as were analysed for U-Pb. The Hf isotope data were analysed at the University of Frankfurt following the methods in Gerdes & Zeh (2006).

Results: *U-Pb data*

More than 7000 analytical spots on zircon grains from the 109 samples resulted in 178 interpreted U-Pb ages, reflecting that some samples contained more than one age population. Intrusion ages were calculated from analyses that were 90–110% concordant, or from upper concordia intercepts. Single spot ages interpreted as inherited should be treated as minimum ages due to potential ancient Pb-loss. The U-Pb age data are summarised in a density distribution diagram (Fig. 2A) where the data define two age groups: a group (shown in red) of granitic veins, sheets and plutons, pegmatite and aplite dykes contemporaneous with the Skjoldungen orogeny, and a group (shown in blue) of pre-Skjoldungen ages related to both grey orthogneiss samples and inherited zircon grains. Grains that are older than the main intrusive age are interpreted as inherited. In the southern area such grains are thought to represent older, reworked gneiss protoliths. In the Skjoldungen Alkaline Province inherited zircons are likely to reflect crustal contamination of juvenile melts. Overall, the dataset spans about 1.3 Ga of Earth history from *c.* 3880 to 2600 Ma, but with the overwhelming majority of ages between *c.* 3250 and 2690 Ma. A major age peak between *c.* 2750 and 2690 Ma reflects that about one third of the analysed samples were collected from the Skjoldungen Alkaline Province. At closer inspection, this relatively narrow age range may be divided into several distinct age peaks at *c.* 2750, 2740, 2710 and 2695 Ma (Fig. 2A).

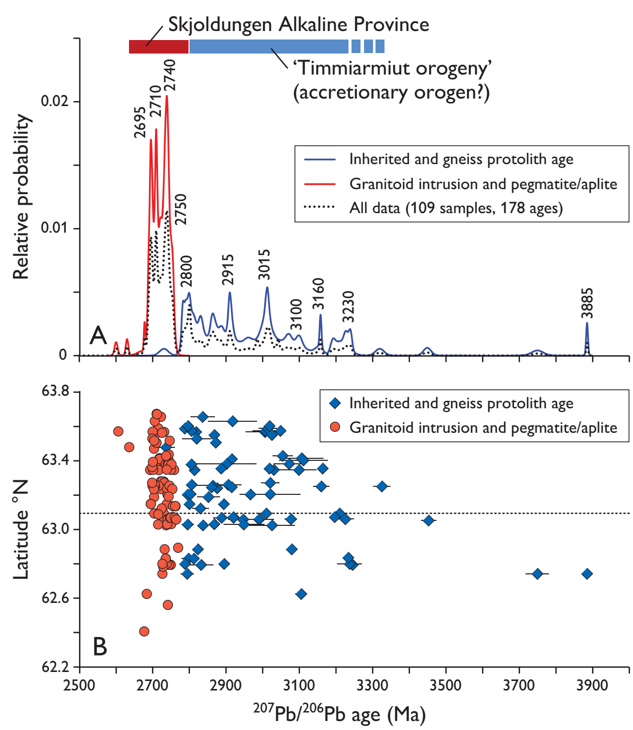

Fig. 2. **A**: ^{207}Pb/^{206}Pb age distribution diagram for the Skjoldungen region, based on 109 samples that provide 178 distinct ages. The black dashed curve indicates the relative probability of all age data. **B**: ^{207}Pb/^{206}Pb ages plotted against geographical latitude. The rare, detected oldest age components are restricted to the southern part of the region, whereas the dominant ≤3100 Ma age components are equally distributed.

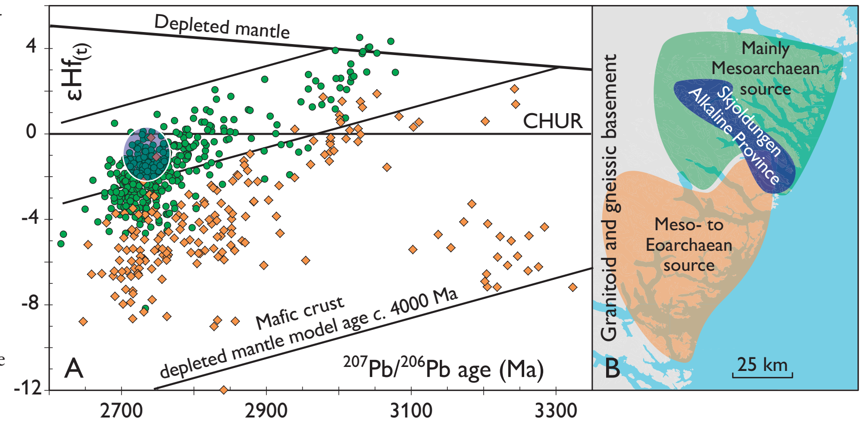

Fig. 3. Geographical distribution of zircon analytical data. **A**: Zircon εHf plotted against $^{207}Pb/^{206}Pb$ ages. Samples collected north and south of 63°10′ shown in green and brown. The compositional range of the Skjoldungen Alkaline Province (blue field; Næraa *et al.* 2015) corresponds to a near-chondritic signature and overlaps with the data from the northern part of the region. **CHUR**: Chondritic uniform reservoir. **B**: Division of the Skjoldungen region into geographical areas based on zircon Hf isotopic compositions. The northern part is derived from a mainly Mesoarchaean source (2950–3100 Ma), and the southern part from a mainly Meso- and Eoarchaean source (≥3200 Ma).

The zircon ages are plotted against geographical latitude in Fig. 2B. The diagram displays a systematic difference in the age distribution of inherited zircons north and south of 63°10´N, despite the above-mentioned uneven sampling density. The southern and northern areas share a significant inherited population with ages spanning from *c.* 3100 to 2800 Ma, but whereas the northern area has few zircon grains older than *c.* 3100 Ma, the southern area contains several inherited grains with ages between *c.* 3880 and 3100 Ma. The diagram also arguably reveals a broad trend of northwards decreasing maximum ages. A similar, albeit less pronounced and more local, trend is seen for the younger intrusions of Skjoldungen Alkaline Province, where the oldest ages of *c.* 2750 Ma are found in the south (syenitic gneiss in the Skirner Bjerge and Kassertoq areas), and the ages decrease down to *c.* 2720 Ma in the north (Figs 1, 2B). These age trends reflect regional differences in the crust at depth and have implications for the interpretation of the regional geodynamic evolution.

Results: *Hf isotope data*

Combined U-Pb and Hf zircon isotope data have been obtained from 29 samples (Fig. 3). The data in Fig. 3A are displayed in Fig. 3B by assigning individual samples to either the northern or southern area by combining intrusive and inherited ages for each area for simplicity. The northern area is characterised by relatively higher initial εHf values and is interpreted as being more juvenile, with a depleted mantle model age of *c.* 3100 Ma. The southern area has somewhat lower initial εHf values and has older model ages of *c.* 4000–3300 Ma (assuming a linear depleted mantle model from εHf = 0 at 4500 Ma to +17 at present), and is interpreted as less juvenile. Although both areas also share an age distribution between 3100 and 2700 Ma, the Hf isotope data indicate that the melts in the northern and southern areas were sourced from different regions, with the northern area tapping a relatively more juvenile and younger crustal reservoir than the southern area.

Discussion and summary

The comprehensive new U-Pb and Hf isotope dataset from the Skjoldungen region sheds new light on the tectono-magmatic evolution of the North Atlantic craton. As illustrated in Figs 2B and 3, the Skjoldungen region can be divided into two crustal terranes with distinct Hf isotopic signatures, albeit with partially overlapping age profiles. Both terranes include U-Pb zircon ages between 3100 and 2700 Ma, but the southern terrane also contains a noticeable component of inherited grains between *c.* 3880 and 3200 Ma (Figs 2, 3). Traces of such old crustal remnants have rarely been found in South-East Greenland but have been recorded from local stream sediments (Thrane & Keulen 2015).

Although the basement throughout the Skjoldungen region records a similar age distribution from *c.* 3100 Ma onwards, the zircon Hf isotopic data define two distinct crustal source terranes, where the zircon Hf isotope data in these rocks display higher initial εHf values in the north than in the south (Fig. 3).

The few inherited zircon ages from *c.* 3880 to 3100 Ma leave the geodynamic setting responsible for the earliest magmatic activity unclear. Still, the U-Pb-Hf isotope data suggest long-lived growth of a terrane or crustal block that includes very old (>4000 Ma) crustal source components. The subsequent period from *c.* 3100 to 2800 Ma records semi-continuous magmatic activity throughout the entire Skjoldungen region with contemporaneous development of rocks of the northern and southern terranes and diminishing juvenile input over time, as reflected by the steady decrease in Hf isotope compositions (Fig. 3A). These signatures could reflect that the northern terrane formed in an accretionary orogeny that was building out from south to north. In this model, south-verging subduction along the northern boundary of the southern terrane would have proceeded for several hundreds of millions of years with progressive accretion of arc systems to form the northern juvenile terrane. Alternatively, the northern terrane with its distinct and younger Hf source signature could have developed as a separate entity prior to the Skjoldungen orogeny, in which case the broad overlap in ages between the southern and northern terranes would be coincidental. The prolonged period of accretion-related magmatism diminished at *c.* 2800 Ma, where the prelude to the Skjoldungen orogeny represents a shift in tectonic setting to that of a continent–continent collision orogeny (Bagas *et al.* 2013; Kolb *et al.* 2013). The orogeny was associated with renewed, intensified magmatism and the development of the Skjoldungen Alkaline Province (Blichert-Toft *et al.* 1995).

The new zircon data from the main magmatic stage of the Skjoldungen Alkaline Province are consistent with formation in a protracted time period from *c.* 2750 to 2690 Ma, overlapping with the late stage of the Skjoldungen orogeny. Whole rock Hf isotope data from mafic intrusions in the province plot with near-primitive mantle signatures (εHf from 0 to –2) and overlap with the Hf zircon isotope composition of the northern area (Næraa *et al.* 2015). The slightly negative Hf isotope values are consistent with derivation from a slightly enriched mantle source, probably coupled with an enrichment in incompatible elements arising from the preceding subduction processes, and by assimilation of crustal material. The new age data from the province also suggest distinct magmatic events at *c.* 2750, 2740, 2710 and 2695 Ma. The reason for such episodic magmatism is currently not understood but might be tectonically controlled.

The new U-Pb-Hf isotopic data dramatically widen the insight into the crustal development of South-East Greenland. The new data indicate that the study region consists of two different domains, a southern one containing source components older than c. 3200 Ma (up to *c.* 4000 Ma), and a northern one entirely younger than *c.* 3100 Ma. These systematics might either be explained by the existence of two distinct crustal terranes that were amalgamated at *c.* 2800 Ma, or as one continuous terrane that was built out by progressive accretion from south to north between *c.* 3100 and 2800 Ma.

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