Using zircon geochronology to resolve the Archaean geology of southern West Greenland

Julie A. Hollis, Dirk Frei, Jeroen A.M. van Gool, Adam A. Garde and Mac Persson

Until recently, *in situ* U-Pb zircon geochronology could be carried out only using ion microprobes, requiring lengthy analysis times of *c.* 20 minutes. However, new developments in laser ablation inductively coupled plasma mass spectrometer technologies have resulted in zircon geochronology techniques that are much faster, simpler, cheaper, and more precise than before (e.g. Frei *et al.* 2006, this volume). Analyses approaching the precision obtained via ion microprobe can now be undertaken in 2–4 minutes using instruments such as the 213 nm laser ablation (LA) system coupled with Element2 sector-field inductively coupled plasma mass spectrometer (SF-ICP-MS) housed at the Geological Survey of Denmark and Greenland (GEUS). The up to tenfold decrease in analytical time means that zircon geochronology can now be used in a much wider range of studies.

The Godthåbsfjord region, southern West Greenland, contains some of the oldest rocks exposed on the Earth's surface reflecting a very complex Archaean geological evolution (Figs 1, 2). Over recent years GEUS has undertaken a range of mapping projects at various scales within the Godthåbsfjord region (see also below). These include the mapping of the 1:100 000 scale Kapisillit geological map sheet (Fig. 1), and regional and local investigations of the environments of formation and geological evolution of supracrustal belts, hosting potentially economic mineral occurrences.

Zircon geochronology is an important tool for investigating a range of geological problems in this region. By breaking down the complex geology into a series of simple problems that can be addressed using this tool, the geological evolution can be unlocked in a stepwise manner. Three examples are presented below: (1) the mapping of regional structures; (2) characterising and correlating supracrustal belts; and (3) dating metamorphism and mineralisation. Although focus is on the application of zircon geochronology to these problems, it is important to note that the resulting data must always be viewed within a wider context incorporating geological mapping and structural, geochemical and petrographic investigations.

Regional geology

The geology of the Godthåbsfjord region is dominated by orthogneiss formed during several distinct episodes of crustal growth during the Archaean (Fig. 2). These different-aged gneisses are thought to represent distinct small continental blocks that were amalgamated during the Neoarchaean (at

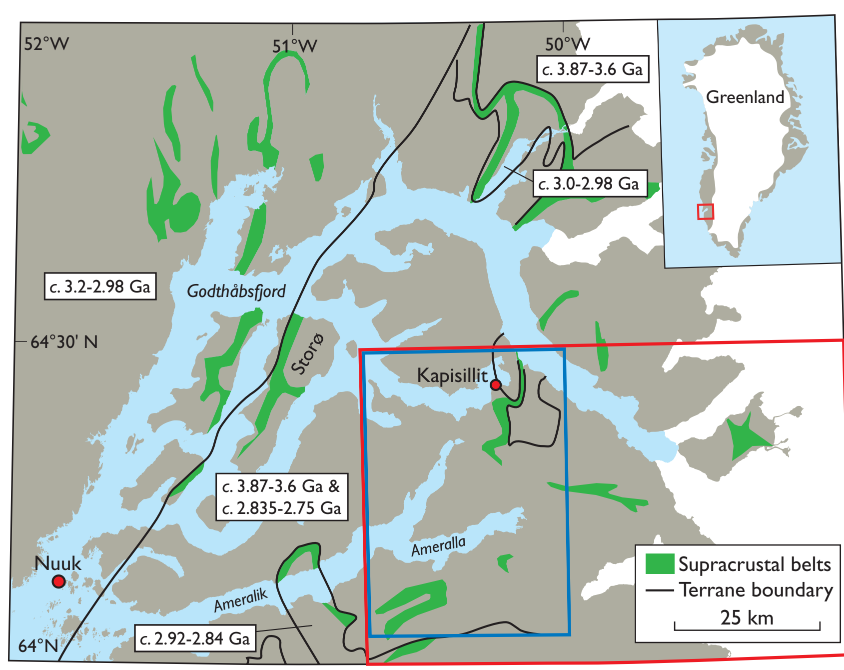

Fig. 1. Overview map of the Godthåbsfjord region. Inset shows the location of the main map in Greenland. Supracrustal belts are shown in **green**. The boundaries of the 1:100 000 scale Kapisillit geological map sheet area are in **red**. **Blue lines** outline the area shown in Fig. 3. **Bold black lines** are inferred terrane boundaries, with the major age components of the different terranes indicated (after Friend & Nutman 2005).

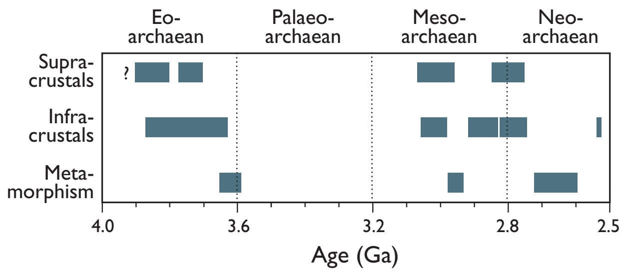

Fig. 2. Simplified summary of the major thermal events in the Godthåbsfjord region.

c. 2.7–2.6 Ga) during collisional tectonism (similar to that seen in modern mountain belts). Within, and often between, these different crustal blocks, or terranes, supracrustal belts made up of metasedimentary and metavolcanic rocks occur. Some of these are known to host potentially economic mineral occurrences, e.g. gold-mineralised supracrustal rocks on the island Storø (Fig. 1).

Several high-grade metamorphic events and associated deformation have affected different parts of the region from the Palaeoarchaean through to the Neoarchaean. These events resulted in partial melting, variable development of high-strain structural fabrics, and several generations of large-scale folds.

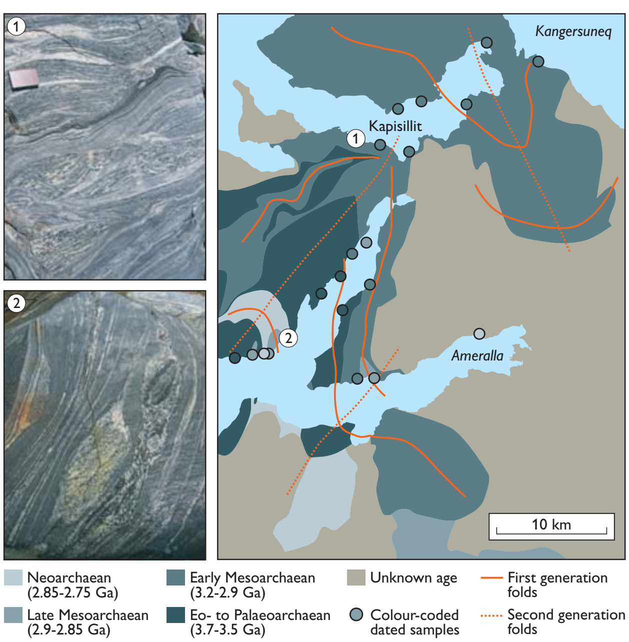

Fig. 3. Simplified version of map of major fold structures in the Kapisillit 1:100 000 scale geological map area. **Coloured circles** indicate the sites where zircons from rock samples have been dated. The **fill colours** indicate the obtained ages. These ages have been used to constrain the surface geometry of the folds. Photographs of outcrops of orthogneiss from two localities show that rocks of very similar appearance can be very different ages and therefore geochronology is useful in distinguishing them.

Mapping major regional structures

Although the orthogneisses that dominate the geology of the region were formed during several distinct events, different generations of orthogneisses are often very difficult to distinguish in the field owing to their similarity of composition (Fig. 3). The geometry of supracrustal belts is very useful in identifying the nature of regional structures, as these are lithologically very different from the orthogneisses and can be used as structural markers. However, where these are absent reconnaissance geochronology can be applied. Having identified several of the main crust-forming events in the region, it is possible to use the emplacement ages of orthogneisses as a guide to field mapping and the delineation of large-scale structures.

Selected samples collected during the 2004 field mapping were dated using LA-SF-ICP-MS U-Pb zircon geochronology (Fig. 2). Major fold structures inferred from field mapping data were dated using this method, in some cases resulting in significant advances in understanding. So far the results indicate that Mesoarchaean rocks were thrust northwards over Neo- and Eo- to Palaeoarchaean rocks and then deformed in kilometre-scale refolded folds (Fig. 3). The resulting map was used to identify problematic areas to investigate during the 2005 mapping.

Identifying and correlating supracrustal belts

Figure 1 shows the distribution of known supracrustal belts in the Godthåbsfjord region, typically comprising high-grade metamorphic volcanic, ultramafic, subordinate aluminous and siliceous sedimentary rocks. These were once thought to represent a single, dismembered suite of Mesoarchaean supracrustal rocks. It is now known that there are in fact several distinct belts deposited at *c*. 3.87 and 3.7 Ga (the Isua supracrustal belt), *c*. 3.0 Ga, and at *c*. 2.8 Ga (Fig. 2). These belts commonly occur along tectonised boundaries between chronologically distinct terranes.

Correlation between different supracrustal belts is important for understanding the regional structures and identifying areas of potentially economic mineral occurrences. Some belts show lithological and geochemical differences, and similarities that can be used to compare and contrast them. These indicate that there are at least three different environments that were important in forming the different belts: (1) basic volcanism in extensional oceanic environments; (2) gabbro-anorthosite magmatism at deeper levels within oceanic crust; and (3) andesitic volcanism and associated hydrothermal syngenetic alteration in island-arc environments (Garde 2005; Hollis 2005). However, the majority of

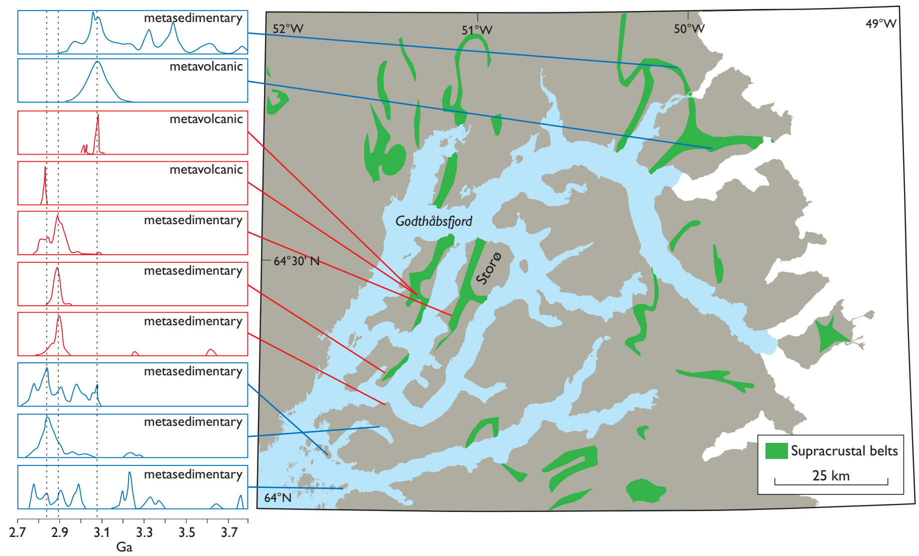

Fig. 4. Detrital zircon populations linked to the distribution of supracrustal belts. Inset shows the location of the main map in Greenland. **Red** zircon spectra were collected using the GEUS LA-SF-ICP-MS. **Blue** zircon spectra are taken from Nutman *et al.* (2004) and Schiøtte *et al.* (1988). **Dotted lines** show regionally significant age peaks at 3.07, 2.89 and 2.83 Ga.

the belts are strongly tectonised and extensive recrystallisation occurred during high-grade metamorphism. Locally hydrothermal alteration is very intense. Therefore, the protoliths are difficult to recognise and the different supracrustal belts are difficult to distinguish without detailed geochemical and geochronological information.

One of the most important tools for correlation is the study of detrital zircons. Siliceous and aluminous metasedimentary rocks carry detrital zircons derived from the erosion of the source regions for the sediments. Thus studies of their detrital zircons allow an assessment of both likely sources and their maximum age of deposition (given by the youngest detrital zircon). Furthermore, the detrital zircon age spectrum of a metasedimentary rock from a specific supracrustal belt is often characteristic, as the zircons are typically derived from the same source area. The detrital spectra can therefore be used to correlate between widely spaced supracrustal belts that would otherwise be difficult to compare from petrographic or geochemical data alone.

A compilation of existing and recently obtained detrital zircon data for metasedimentary rocks and primary zircons from metavolcanic or volcanoclastic rocks in the Godthåbsfjord region is shown in Fig. 4 (see also Hollis 2005). Distinct sources for supracrustal rocks of different ages are readily apparent. The volcanic rocks that form part of the Mesoarchaean supracrustal belts were deposited at *c.* 3.07 Ga, which is just slightly older than the dominant Mesoarchaean regional orthogneiss. Similarly, metasedimentary rocks within the Mesoarchaean supracrustal belts show dominant zircon age peaks at *c.* 3.07 Ga. However, significant proportions of older zircons show that there was also a contribution from Palaeo- and Eoarchaean sources. The Neoarchaean volcanic rocks were deposited at *c.* 2.83 Ga, which is also an age that is well represented in the detrital zircon population of most of the Neoarchaean metasedimentary rocks. A few metasedimentary samples show relatively minor contributions from older Meso- to Eoarchaean material. The synchronous sedimentation and generation of volcanic material at *c.* 3.07 Ga (Mesoarchaean) and at *c.* 2.83 Ga (Neoarchaean) suggests there may have been a common tectonic environment operating at both times.

When did metamorphism and mineralisation occur?

The Godthåbsfjord region records a complex history of high-grade metamorphism, which affected different parts of the Godthåbsfjord region at different times, from *c.* 3.8–2.5 Ga. The record of particular metamorphic events in different parts of the region has been used to establish the times when different terranes were amalgamated via collisional tectonism (e.g. Friend & Nutman 2005). The timing of metamorphism and contemporaneous deformation has also been used to constrain the timing of mineralisation events.

On Storø in central Godthåbsfjord (Fig. 1) detailed studies of the nature and timing of gold mineralisation have been carried out. Here gold-mineralised strataform horizons and cross-cutting quartz veins occur within a Neoarchaean supracrustal belt that was deposited at or after 2.8 Ga. The gold-bearing horizons are deformed by the kilometre-wide, high-grade Storø shear zone; thus the generation of the shear fabric post-dates the gold-mineralising event. To place absolute constraints on the timing of gold mineralisation the timing of emplacement of some of the abundant granitic pegmatites that either cross-cut or are deformed by the shear fabric has been investigated (Fig. 5). Four pegmatites contained

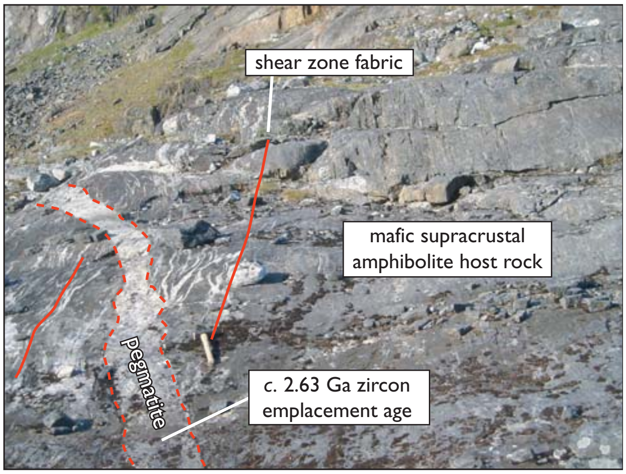

Fig. 5. Pegmatite on Storø cross-cutting and deformed by the Storø shear zone fabric, and Neoarchaean supracrustal amphibolite host rock. Zircons from the pegmatite indicate it was formed at *c*. 2.63 Ga, placing a minimum age constraint on gold mineralisation in the host rocks.

igneous zircon crystallised at *c*. 2.63–2.60 Ga. This is the same age as yielded by metamorphic zircons separated from a leucocratic amphibolite, and from metamorphic overgrowths on detrital zircons taken from a melt layer within a migmatised metasedimentary rock, both within the same supracrustal sequence on Storø. These results show that a gold-mineralising event occurred within the Neoarchaean supracrustal belt during or after sedimentation at *c*. 2.8 Ga and before the formation of the Storø shear zone during high-grade metamorphism and partial melting at *c*. 2.63 Ga. These results constrain the timing of mineralisation and may be extended to the investigation of rocks of similar age and setting elsewhere in the region.

Further work

This work forms part of ongoing studies of the supracrustal belts in the Godthåbsfjord region carried out with support from the Greenland Bureau of Minerals and Petroleum. In addition to the examples given here, the GEUS LA-SF-ICP-MS system can also be used to investigate the cooling history of rocks via U-Pb dating of zircon and other minerals, including titanite and monazite. Furthermore, by exploring other aspects of zircon geochemistry, such as Hf and O isotopes it may also be possible to delve deeper into issues of crustal evolution of the North Atlantic Craton through the Archaean.

References

Garde, A.A. 2005: A mid-Archaean island arc complex with gold mineralisation at Qussuk, Akia terrane, southern West Greenland. In: Hollis, J.A. (ed.): Greenstone belts in the central Godthåbsfjord region, southern West Greenland: Geochemistry, geochronology and petrography arising from 2004 field work, and digital map data. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/42**, 215 pp., 1 DVD.

Hollis, J.A. (ed.) 2005: Greenstone belts in the central Godthåbsfjord region, southern West Greenland: Geochemistry, geochronology and petrography arising from 2004 field work, and digital map data. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2005/42**, 215 pp., 1 DVD.

Frei, D., Hollis, J.A., Gerdes, A., Harlov, D., Karlsson, C., Vasquez, P., Franz, G. & Knudsen, C. 2006: Advanced *in situ* geochronological and trace element microanalysis by laser ablation techniques. Geological Survey of Denmark and Greenland Bulletin **10**, 25–28.

Friend, C.R.L. & Nutman, A.P. 2005: New pieces to the Archaean terrane jigsaw puzzle in the Nuuk region, southern West Greenland: Steps in transforming a simple insight into a complex regional tectonothermal model. Journal of the Geological Society (London) **162**, 147–162.

Nutman, A.P., Friend, C.R.L., Barker, S.L.L. & McGregor, V.R. 2004: Inventory and assessment of Palaeoarchaean gneiss terraines and detrital zircons in southern West Greenland. Precambrian Research **135**, 281–314.

Schiøtte, L., Compston, W. & Bridgwater, D. 1988: Late Archaean ages for the deposition of clastic sediments belonging to the Malene supracrustals, southern West Greenland: evidence from an ion probe U-Pb zircon study. Earth and Planetary Science Letters **87**, 45–58.

Authors' addresses

J.A.H., D.F., J.v.G., A.A.G., *Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark.* E-mail: *jho@geus.dk*
M.P., *University of Copenhagen, Øster Voldgade 10, DK-1350 Copenhagen K.*