

Geochemistry and petrology of gold-bearing hydrothermal alteration zones on Qilangaarsuit, southern West Greenland

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During field work in 2008, the Geological Survey of Denmark and Greenland investigated the gold potential of hydrothermal vein systems in the Nuuk region of the Archaean North Atlantic craton. A new gold occurrence was discovered on the island of Qilangaarsuit, 35 km south of Nuuk. Two cross sections through hydrothermal alteration zones, that locally contain up to 672 ppb Au, were mapped and sampled in detail. In this study, we present petrological and geochemical data in order to constrain the conditions for ore formation and transport of elements during fluid–rock interaction.

Geological setting

Qilangaarsuit in southern West Greenland (Fig. 1) is situated in the Godthåbsfjord gold province, a *c.* 20 km by 150 km wide, NE-trending sector along the Ivinnguit fault system. Several gold occurrences such as Storø, Qussuk, Bjørneøen and SW Isua have been described from this sector (Garde *et al.* 2012; Scherstén *et al.* 2012; Kolb *et al.* 2013). The Ivinnguit fault, situated north of the island, is a deep-crustal shear zone, which formed during terrane amalgamation and it represents the border between the Færingehavn and Akia terranes (Nutman & Friend 2007). Qilangaarsuit island is dominated by Eoarchaeon tonalite-trondhjemite-granodiorite (TTG) gneisses of the Færingehavn terrane, which are overlain by amphibolites and aluminous cordierite-orthoamphibole gneisses that originated from *c.* 2840 Ma old protoliths (Nutman & Friend 2007). Four deformation events can be distinguished, involving north-vergent thrusting, isoclinal folding and the formation of late, upright, open to tight folds (e.g. Kolb *et al.* 2013). The gold-bearing quartz veins are hosted by amphibolites in the central part of the island and surrounded by approx. 8 m wide hydrothermal alteration zones. The foliation-parallel, *c.* 10–20 cm wide, quartz veins can be followed over several hundred metres along strike. Structural data indicate that they formed in response to flexural, slip folding during the late-tectonic evolution of the region (Kolb *et al.* 2013). One sample from a hydrothermal alteration zone surrounding the veins contains up to 672

ppb Au and several other vein and alteration zone samples have elevated Au contents (> 20 ppb Au; Kolb *et al.* 2009).

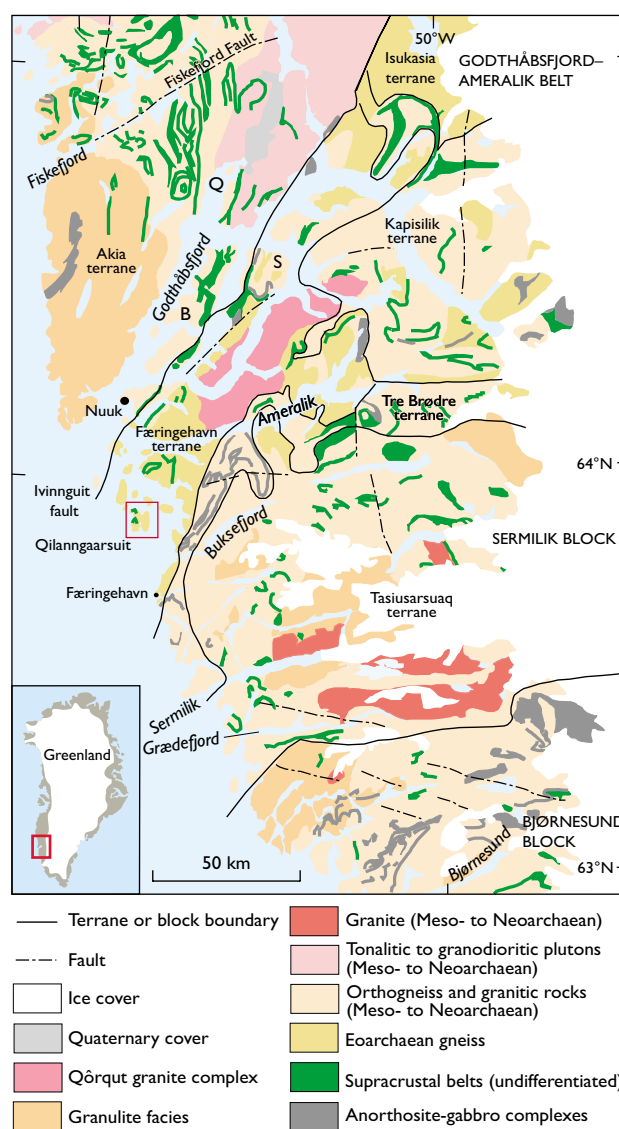


Fig. 1. Geological map of the Nuuk region (modified from Allaart 1984). B: Bjørneøen, Q: Qussuk, S: Storø.

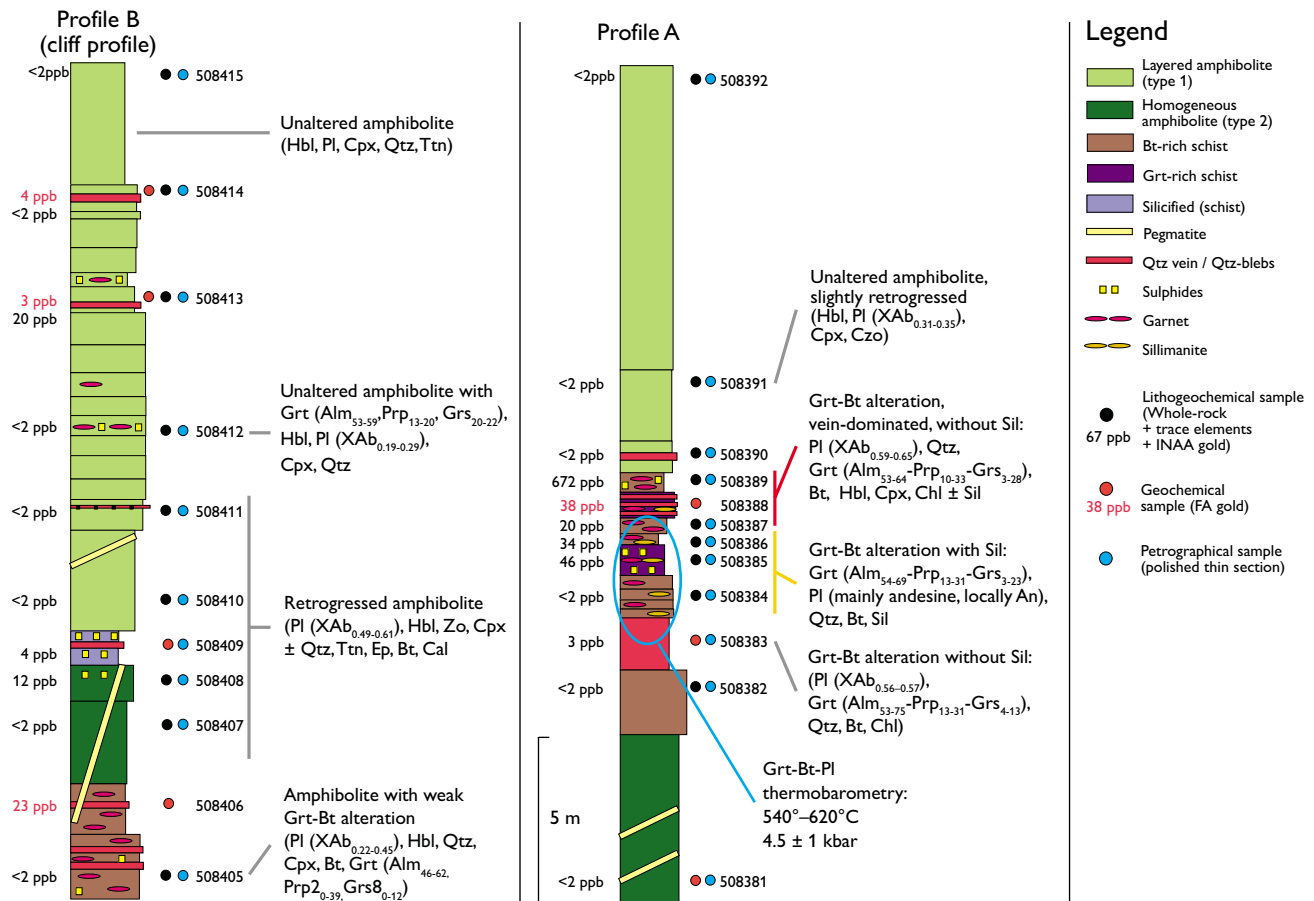


Fig. 2. Lithological logs of profiles A and B (modified from Schlatter 2009).

Petrology and geochemistry

Two profiles from the unaltered wall rocks through the hydrothermal alteration zones were investigated (Fig. 2). Two types of amphibolite can be distinguished: homogeneous amphibolite in the footwall and compositionally layered amphibolite in the hanging wall of the hydrothermal vein system. Their protoliths were low-K tholeiites depleted in light rare-earth elements (LREE), geochemically similar to other amphibolites in the Buksefjord region (Chadwick 1981). Generally, the amphibolites are fine- to medium-grained and consist of hornblende (40 vol.%), plagioclase (30 vol.%), clinopyroxene (20 vol.%) and clinozoisite/zoisite/epidote (10 vol.%). Metamorphic garnet is locally present in the layered amphibolite. Retrogression is indicated by the transformation of plagioclase to a fine-grained assemblage of zoisite and quartz, and by the replacement of amphibolite and clinopyroxene by epidote and clinozoisite.

Within the alteration zone, the amphibolite-facies mineral assemblages are replaced by a high temperature alteration assemblage of garnet, quartz, plagioclase, biotite, and sillimanite (Figs 2, 3). In contact with the veins, the hy-

drothermal alteration zone consists of up to 50 vol.% garnet, 15 vol.% plagioclase, 15 vol.% quartz, 10 vol.% biotite and 10 vol.% sillimanite (Fig. 2). Relict amphibole facies minerals such as hornblende and clinopyroxene are locally preserved, indicating that these minerals formed during regional metamorphism prior to the mineralisation. Ore minerals make up ≤ 1 vol. % of the rocks; they include pyrite, pyrrhotite and chalcopyrite. Mass-balance calculations based on whole-rock, major- and trace-element data (Kolb *et al.* 2009; Koppelberg 2011) and using the method of Gresens (1967) indicate that the ore fluid was enriched in Si, K, LREE, Au, Cr, Cu, Zn, Mo and As (Fig. 4). In Si-rich, vein-dominated samples, the hydrothermal overprint was associated with a volume increase of 14–62%. In contrast, the sillimanite-bearing samples record a significant volume loss of 15–50%, and are depleted in Si (Fig. 4). This suggests that at least some of the Si in the quartz veins was leached from the surrounding wall rocks.

Garnet in the alteration zones is rich in almandine (Koppelberg 2011). Most grains are essentially unzoned and have

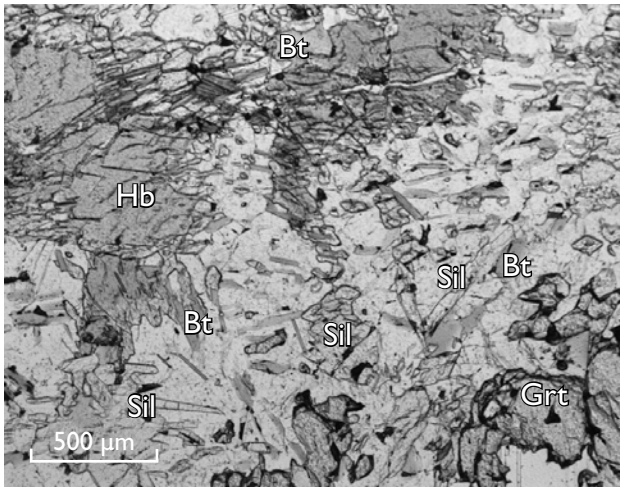


Fig. 3. Photomicrograph illustrating the replacement of the regional metamorphic amphibolite facies mineral assemblages by hydrothermal garnet, biotite and sillimanite in sample GGU 508405.

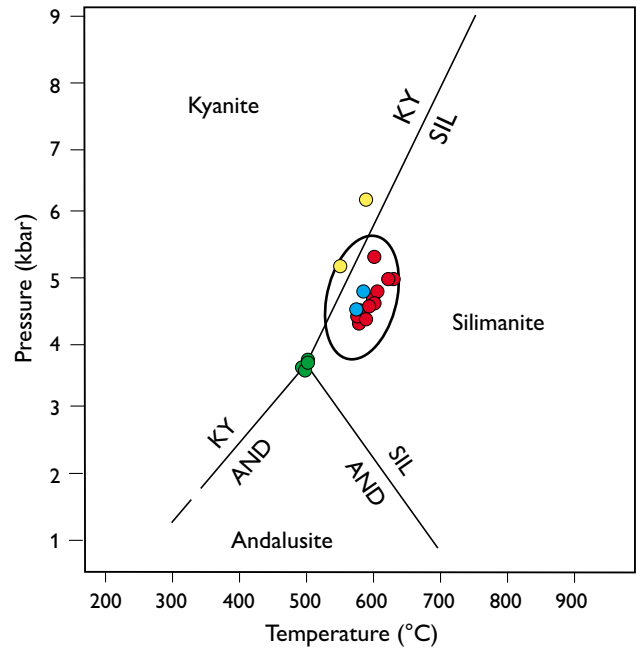


Fig. 5. Thermobarometry results (see main text). The Al_2SiO_5 diagram is from Holdaway & Mukhopadhyay (1993). Red: sample GGU 508384, green: 508385, blue: 508386, yellow: 508405. The Al_2SiO_5 triple point is at 500°C and 3.75 kbar.

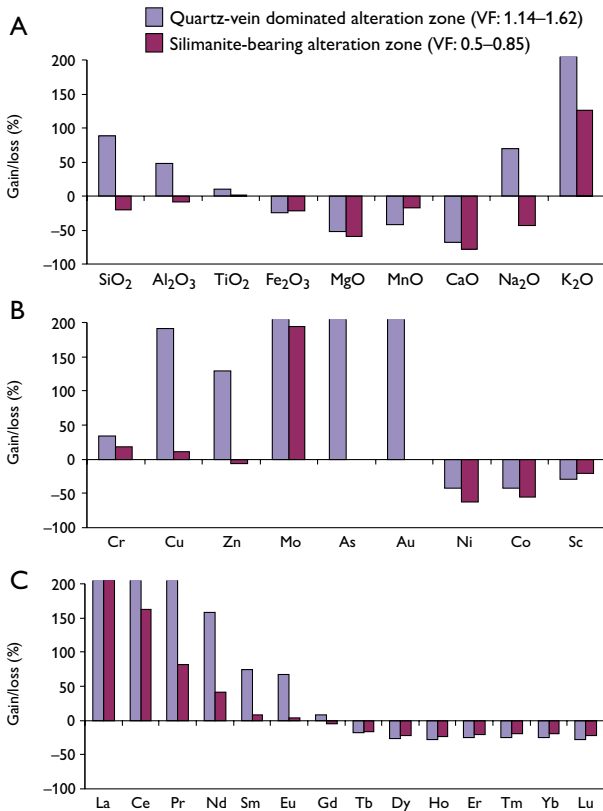


Fig. 4. Results of mass-balance calculations for quartz-vein dominated and sillimanite-bearing alteration zones. **VF**: volume factor – the change of volume of altered rock relative to unaltered rock. **A**: major elements, **B**: trace elements, **C**: rare-earth elements (REE).

a composition of Alm_{53-69} , Prp_{21-31} , Grs_{3-12} , depending on bulk composition. In some of the larger grains, the rims have slightly higher Fe concentrations (Alm_{62-72} , Prp_{20-25} , Grs_{3-10}). Metamorphic garnet in the unaltered wall rocks is unzoned and enriched in grossular (Alm_{53-59} , Prp_{13-20} , Grs_{17-21}). Both types of garnet have very low REE contents (<2 ppm), and are depleted in LREE. Biotite in the alteration zone has Al^{IV} contents between 2.4 and 2.65 atoms per formula unit and $\text{Mg}/(\text{Fe}+\text{Mg})$ ratios between 0.25 and 0.45. The composition of plagioclase from the amphibolites varies from andesine to anorthite; most grains can be classified as labradorite and bytownite. Plagioclase in the hydrothermal alteration zone is depleted in Ca and is mostly andesine.

In order to achieve reliable pressure–temperature (P – T) estimates, only mineral cores of neighbouring minerals were used for geothermobarometry. Due to the presence of retrograde reaction rims in some of the garnet grains, it was assumed that the mineral cores reflect the equilibrium mineral composition and were not altered by retrograde processes. P – T estimates on the alteration assemblage using the garnet-biotite-plagioclase-quartz geothermobarometer of Wu *et al.* (2004) give conditions of *c.* 540–620°C and 4.5 ± 1 kbar (Fig. 5). P – T pseudosection models using the computer program *PerpLeX* developed by Connolly (1990) confirm these conditions (Koppelberg 2011).

Discussion and conclusion

The majority of the world's gold deposits formed in the Archaean (*c.* 2.7 Ga) as a result of crust-forming processes during collision events of converging continental plates (Groves *et al.* 2005). These epigenetic deposits are called orogenic gold deposits, and occur in metamorphic terranes that mainly show greenschist facies metamorphism (Groves *et al.* 1998). Other orogenic deposits are known to have formed at amphibolite-facies metamorphic grades, and these are termed hypozonal deposits (Groves *et al.* 1998). The replacement of regional, metamorphic, amphibolite-facies mineral assemblages by hydrothermal minerals surrounding the gold-bearing quartz veins as well as the late timing of quartz-vein formation by ductile, flexural slip folding (Kolb *et al.* 2009), indicate that the gold mineralisation and associated hydrothermal alteration formed late in the metamorphic evolution on Qilangaarsuit. The low-pressure amphibolite-facies metamorphism in the surrounding amphibolites has been dated to *c.* 2715 Ma (Nutman & Friend 2007), while the mineralisation probably occurred between 2660 and 2600 Ma (Kolb *et al.* 2013). The Qilangaarsuit mineralisation is, therefore, interpreted to represent a new example of hypozonal orogenic gold mineralisation in the Godthåbsfjord gold province. The origin of other gold prospects (Storø, Qussuk) is still a matter of debate, and both metamorphosed epithermal and orogenic models have been proposed (Garde *et al.* 2012; Scherstén *et al.* 2012; Kolb *et al.* 2013). The alteration systematics, timing and conditions of the gold mineralisation on Qilangaarsuit are, however, similar to those of other gold occurrences, in particular Storø, in the Godthåbsfjord gold province. The deposits are spatially closely associated with a major terrane boundary, the Ivinnguit fault, suggesting that this shear zone may have acted as a major pathway for the gold-bearing fluids between *c.* 2660–2600 Ma.

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