A lead isotope study of an Archaean gold prospect in the Attu region, Nagssugtoqidian orogen, West Greenland

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This paper presents a lead isotope investigation of a gold prospect south of the village Attu in the northern part of the Nagssugtoqidian orogen in central West Greenland. The Attu gold prospect is a replacement gold occurrence, related to a shear/mylonite zone along a contact between orthogneiss and amphibolite within the Nagssugtoqidian orogenic belt. The mineral occurrence is small, less than 0.5 m wide, and can be followed along strike for several hundred metres. The mineral assemblage is pyrite, chalcopyrite, magnetite and gold. The host rocks to the gold prospect are granulite facies 'brown gneisses' and amphibolites. Pb-isotopic data on magnetite from the host rocks yield an isochron in a $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram, giving a date of 3162 ± 43 Ma (MSWD = 0.5). This date is interpreted to represent the age of the rocks in question, and is older than dates obtained from rocks elsewhere within the Nagssugtoqidian orogen. Pb-isotopic data on cataclastic magnetite from the shear zone lie close to this isochron, indicating a similar origin. The Pb-isotopic compositions of the ore minerals are similar to those previously obtained from the close-by ~2650 Ma Rifkol granite, and suggest a genetic link between the emplacement of this granite and the formation of the ore minerals in the shear/mylonite zone. Consequently, the age of the gold mineralisation is interpreted to be late Archaean.

Keywords: Archaean, gold, magnetite, Pb isotopes, geochronology, West Greenland

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Discovery of the gold prospect described in this study was due to the find of a mineralised sample, which Karl Markussen from Attu submitted to the Bureau of Minerals and Petroleum in Greenland. The Geological Survey of Denmark and Greenland (GEUS) visited the locality in 2001 and in 2002 (Stendal *et al.* 2002, 2004), and the present paper reports Pb-isotopic data for minerals from the prospect and its surroundings.

The Attu gold prospect lies within the Nagssugtoqidian orogen of West Greenland (Fig. 1), where geological mapping and exploration has been carried out for decades by the Geological Survey, the Danish Lithosphere Centre, university research groups and exploration companies (e.g. Kalsbeek *et al.* 1987; Connelly *et al.* 2000; van Gool *et al.* 2002). In addition to the general investigations, Steenfelt (2001) has summarised geochemical signatures from stream sediments, Rasmussen & van Gool (2000) have described geophysical aspects, and Steenfelt *et al.* (2002), Stendal & Schønwandt (2003) and Stendal *et al.* (2004) have described mineral occurrences and their economic potential. An overview of the mineral occurrences in the entire region has been presented by Stendal *et al.* (2004).

Detailed, mainly zircon U-Pb geochronological data from the Nagssugtoqidian orogen have been presented by Kalsbeek & Nutman (1996), Connelly & Mengel (2000) and Connelly *et al.* (2000), and Pb-Pb, Rb-Sr and Sm-

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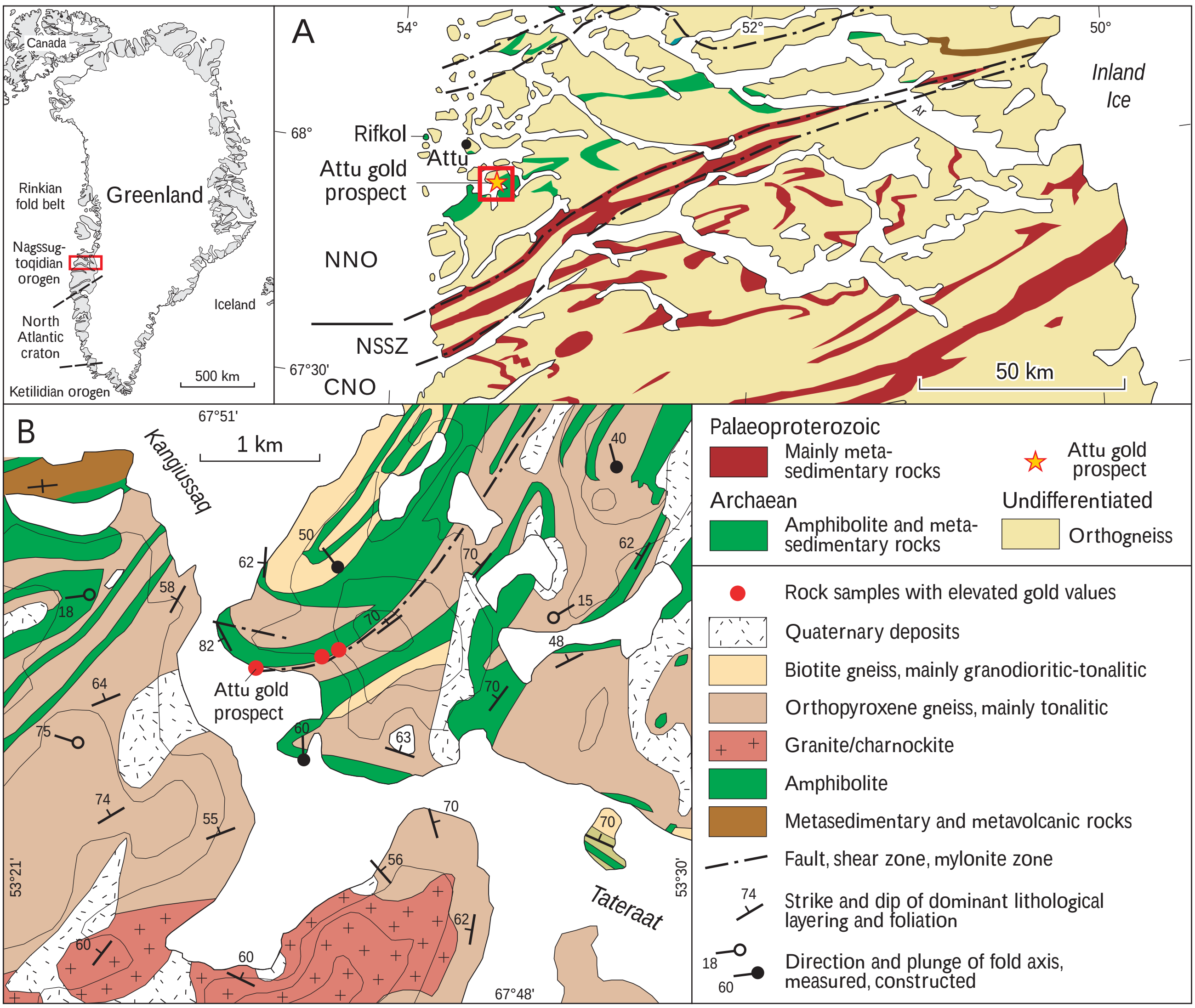


Fig. 1. A: Geological map of the Attu region with index map of Greenland. CNO, central Nagssugtoqidian orogen; NNO, northern Nagssugtoqidian orogen; NSSZ, Nordre Strømfjord shear zone. B: Geological map of the Attu gold prospect area (modified from Olesen 1984).

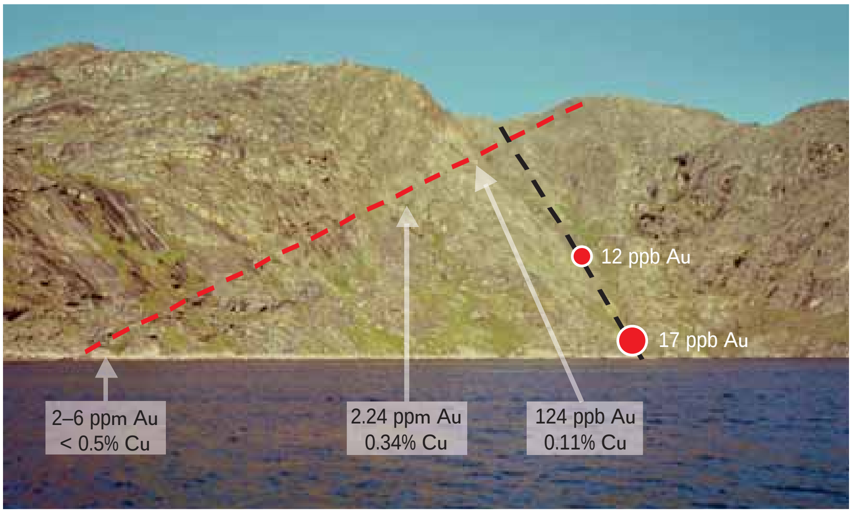
Nd whole-rock isotope data from the region have been reported by Kalsbeek *et al.* (1984, 1987), Taylor & Kalsbeek (1990) and Whitehouse *et al.* (1998). In addition, some Pb-isotopic work has been carried out on sulphide separates, mainly pyrite, from mineral occurrences in the Disko Bugt region (Stendal 1998).

Geological setting

The Palaeoproterozoic Nagssugtoqidian orogen of West Greenland (van Gool *et al.* 2002) is located between the Archaean North Atlantic craton to the south and a lesser-known continental mass to the north that includes the Palaeoproterozoic Rinkian fold belt. Most of the orogen consists of variably reworked Archaean orthogneisses. Several thin belts of supracrustal and intrusive igneous rocks occur within this gneiss terrain. Granitoid rocks and numerous pegmatites intrude the gneisses. Formations of Palaeoproterozoic age are limited to the Arfersiorfik and Sisimiut igneous suites and minor supracrustal sequences (Connelly *et al.* 2000).

The Attu area itself is located in the southern part of the northern Nagssugtoqidian orogen (NNO; Fig. 1). The metamorphic grade is granulite facies; metamorphism and deformation of the Archaean granitoid rocks in the NNO gradually decrease northwards, from granulite to amphibolite facies, and from high strain to lower strain with more open structures. Steeply and shallowly dipping shear and fault zones are common in contact zones between

Fig. 2. The site of the Attu gold prospect. Gold values are given for rock samples. **Red circles** are sample sites with gold values obtained from fine-grained stream sediments (see Fig. 1 for geographical location). The **red line** shows the approximate position of the gold-bearing zone in the shear/mylonite zone. The **black line** shows the approximate position of a stream.



different lithologies. Major fault zones generally strike NNE to NE. The major Nordre Strømfjord shear zone (van Gool 2002) is located *c*. 20 km south of the study area. The shear zone is traceable from the coast to the Inland Ice and forms the southern boundary of the NNO. The gneisses of the NNO are late Archaean, with ages between 2870 and 2700 Ma (Kalsbeek & Nutman 1996; Connelly & Mengel 2000; Hollis *et al*. 2006, this volume; Thrane & Connelly 2006, this volume). Discordant sheets of granitoid rocks of Archaean age occur in the centre of the NNO and large charnockite/granite bodies including the Rifkol granite are situated 20 km to the northwest and just south of the study area (Fig. 1; Hansen 1979; Kalsbeek *et al*. 1984). Only a few younger Palaeoproterozoic ages have been obtained from the NNO: Thrane & Connelly (2006, this volume) have obtained an approximate depositional age of the Naternaq supracrustal belt some 80 km north-east of Attu of *c*. 1950–1900 Ma, and an undeformed pegmatite between Attu and Aasiaat has yielded an age of *c*. 1790 Ma (Connelly & Mengel 2000).

The Attu gold prospect

The Attu gold prospect is located south of the village Attu within a 100–330 m wide, complex tract hosting several parallel shear/mylonite zones and faults that strike NNE to NE and dip 60–70°W (Figs 1, 2). The fault zone can be followed along strike in a north-easterly direction for several kilometres. The host rocks are layered, brown

Fig. 3. Layered brown gneiss with black bands of amphibolite. The hammer shaft is 50 cm long.

Fig. 4. The gold bearing mylonite zone. K-feldspar occurs on the right side of the yellow magnet pen (10 cm long). The zone also contains pyrite, chalcopyrite and magnetite.

weathering gneiss and amphibolite (Fig. 3). At the western border of the tract a gold-bearing shear/mylonite zone follows the contact between brown gneisses and amphibolites. The gold-bearing shear/mylonite zone (Fig. 4) is invaded by pegmatite sheets as well as centimetre-wide veins consisting of red alkali-feldspar and quartz with occasional pyrite and magnetite. The estimated relative volume of pegmatite in the tract varies from 1 to 10% (Stendal *et al.* 2002, 2004).

The most promising gold showings are found in a coastal profile along the shear/mylonite zone, which can be followed along strike for several hundreds of metres (Figs 1, 2). The studied site is a cliff exposure consisting of mylonite (Fig. 4) and a rusty weathered band (10–20 cm in width) mineralised with pyrite, magnetite and some chalcopyrite (Fig. 5). Pyrite and chalcopyrite replace magnetite. The magnetite is predominantly cataclastic in nature, but recrystallised ore also occurs. The gold is found within pyrite and chalcopyrite. The gangue mineralogy comprises quartz, K-feldspar, muscovite, biotite and carbonates (calcite, dolomite and/or ankerite).

The mylonite zone is silicified at the contact with the mineralised zone, and sulphide-rich parts are weathered. Secondary goethite and malachite are common (Fig. 5). The ore is structurally controlled by and confined to favourable sites (sulphide-bearing zones) within the mylonite/shear/fault zone.

The Attu gold prospect has returned reproducable gold

Table 1. Pb-isotopic ratios of magnetite, pyrite and K-feldspar from the Attu gold prospect and its host rocks

Sample number	Mineral	^{206}Pb/^{204}Pb	± 2σ*	^{207}Pb/^{204}Pb	± 2σ	^{208}Pb/^{204}Pb	± 2σ	r1**	r2†
Amphibolite and orthogneiss (host rocks)									
446601	magnetite	14.631	0.007	14.642	0.009	44.688	0.033	0.961	0.939
446602	magnetite	15.051	0.014	14.752	0.015	36.702	0.040	0.969	0.942
446610	magnetite	17.540	0.051	15.361	0.046	37.613	0.112	0.977	0.988
446614	magnetite	17.002	0.025	15.225	0.024	38.086	0.061	0.976	0.967
Shear zone and mineralised rock									
446616	magnetite	15.423	0.023	14.844	0.023	41.598	0.068	0.979	0.957
2000368	magnetite	15.286	0.009	14.832	0.010	41.201	0.034	0.962	0.936
481093	magnetite	14.247	0.042	14.625	0.044	41.821	0.130	0.982	0.960
446615	pyrite	14.241	0.009	14.587	0.010	42.001	0.035	0.963	0.934
481078	pyrite	14.447	0.011	14.633	0.012	40.805	0.039	0.967	0.925
446616	K-feldspar	15.123	0.008	14.893	0.010	36.451	0.029	0.958	0.932

* Errors are two standard deviations absolute (Ludwig 1990).

** r1 = ^{206}Pb/^{204}Pb versus ^{207}Pb/^{204}Pb error correlation (Ludwig 1990).

† r2 = ^{206}Pb/^{204}Pb versus ^{208}Pb/^{204}Pb error correlation (Ludwig 1990).

Fig. 5. The gold bearing zone (10 cm wide) within the mylonite zone, with malachite and rusty weathered sulphides.

concentrations in the range 2.3–5.8 ppm. Other localities in the same fault structure yielded 2.24 ppm and 124 ppb Au (Fig. 2). The gold concentrations are positively correlated with concentrations of copper, and gold-bearing samples often contain magnetite. Two stream sediment samples yielded anomalous gold concentrations of 12 ppb and 17 ppb Au, respectively (Fig. 2).

The host gneisses are brownish in colour and comprise orthopyroxene, amphibole, biotite and feldspar, but little quartz. Magnetite is in equilibrium with the rock forming minerals and has the same granular texture. In the amphibolites magnetite forms up to millimetre-thick layers, and also occurs in disseminated form. Within the mylonite zone, magnetite occurs as a primary phase in the host gneiss as cataclastic grains with cracks filled with pyrite and chalcopyrite, and as a residual phase resulting from sulphide replacement. Ten samples were analysed for Pb-isotopic compositions.

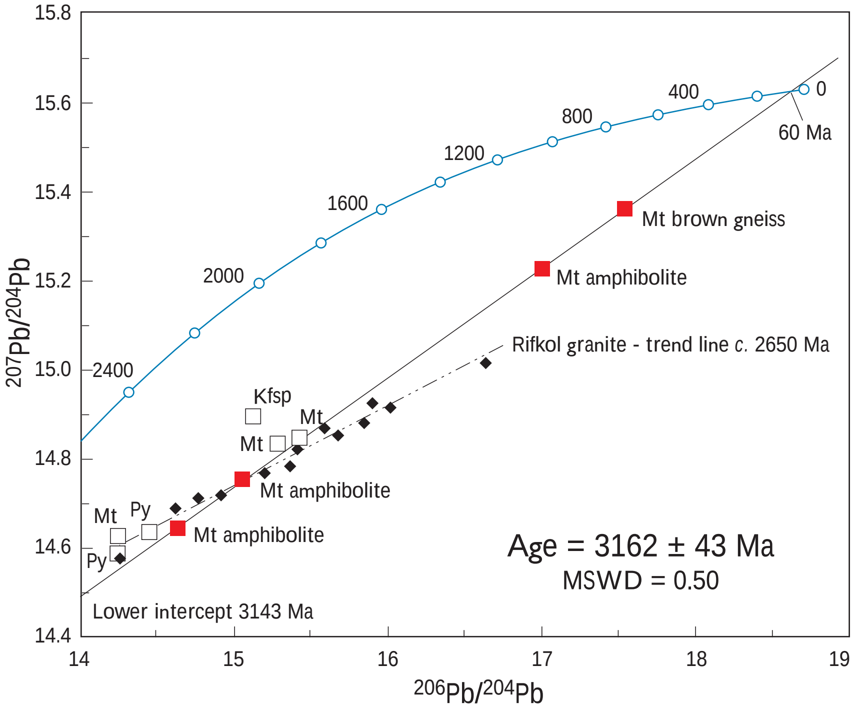


Fig. 6. $^{206}Pb/^{204}Pb$–$^{207}Pb/^{204}Pb$ diagram for minerals from the Attu area listed in Table 1. Open squares, mineral separates from the gold-bearing mylonite zone.
Red squares, host rock data.
Black diamonds, whole-rock samples from the Rifkol granite for comparison (data from Kalsbeek *et al.* 1984). Mt, magnetite; Py, pyrite; Kfsp, K-feldspar.
Blue curve, the Pb-isotopic growth curve from Stacey & Kramers (1975).

Analytical methods

The Pb-isotopic study was carried out on magnetite from host gneisses and amphibolites, and on K-feldspar, magnetite and pyrite from the shear zone-hosted mineralised zone (Table 1). The isotope analyses were carried out at the Danish Centre for Isotope Geology, Geological Institute, University of Copenhagen. Near-pure mineral fractions were separated from dry split aliquots of crushed and sieved (100–200 µm) rock powders using a hand magnet, a Frantz isodynamic separator and heavy liquid techniques. Ore minerals were dissolved in concentrated *aqua regia*. Total procedural blanks for Pb amounted to < 120 pg which is considered insignificant for the measured Pb-isotopic results, relative to the amount of sample Pb estimated from the mass spectrometer signal intensities. Isotope analyses were carried out on a VG Sector 54-IT instrument in static collection mode. Fractionation for Pb was controlled by repetitive analysis of the NBS 981 standard (values of Todt *et al.* 1993) and amounted to 0.103 ± 0.007% / amu (2σ; n = 11). All results are quoted with 2σ precisions.

Results

The Pb-isotopic compositions of mineral separates from the gold-bearing mylonite zone and its host rocks are listed in Table 1. In the ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb diagram shown in Fig. 6, the Pb-isotopic compositions of magnetite from the four host rock samples of brown gneiss and amphibolite (red squares) define a straight line with a slope corresponding to 3162 ± 43 Ma (MSWD = 0.50). This line has intercepts with the Stacey & Kramers (1975) Pb-isotopic growth curve at 3143 and 60 Ma. Based on the good fit of the data points on the isochron, and the agreement of the isochron age with the intercepts of the growth curve, we interpret the 3162 Ma date as the age of the rocks in question. However, farther south, in the central part of the Nagssugtoqidian orogen, Palaeoproterozoic granulite facies metamorphism has led to U loss in Archaean rocks, resulting in Pb-isotopic compositions plotting above and to the left of an 2800 Ma reference isochron (Whitehouse *et. al.* 1998). If this process had also taken place in the area of the present study, the 3162 Ma date might give a false impression of the age of the rocks. However, the good fit of the data points on the isochron and the agreement of the intercepts with the Stacey & Kramers (1975) growth curve with the isochron age would then be accidental, a coincidence which we regard as very unlikely.

Six mineral separates from the gold-bearing mylonite zone (Fig. 6, open squares) lie close to or slightly above the isochron obtained for magnetite from the host rocks. The most primitive ^{206}Pb/^{204}Pb and ^{207}Pb/^{204}Pb ratios have been measured in pyrite and magnetite from the ore-bearing zone, whereas the two primary magnetites with cataclastic texture from within the shear zone plot very close to the host rock magnetite isochron. This suggests that their crystallisation took place at about the same time as the magnetites from outside the shear zone. Whole-rock Pb-isotopic ratios from the Rifkol granite (Kalsbeek *et al.* 1984) are also plotted on Fig. 6 for comparison, and the isotopic values are listed in Table 1. The errorchron defined by these samples has a slope corresponding to an age of 2653 ± 110 Ma, which has been interpreted as emplacement age of the granite (Kalsbeek *et al.* 1984). This errorchron is oblique and discordant to the isochron obtained for magnetite from the host rocks, but the three least radiogenic data points from ore minerals associated with native gold from within the shear zone are conformable with this younger trend. This suggests that the fluids in the shear zone from which the gold mineralisation was deposited were somehow genetically linked to the intrusion of the Rifkol granite. Alkali feldspar from the shear zone has its own Pb-isotopic signature, which is neither compatible with a 'Rifkol' source nor with a source typical of the immediate host rocks.

The uranogenic vs. thorogenic isotopic pattern (not shown in a figure) is more disperse than the uranogenic pattern and does not add to the understanding of the uranogenic Pb-isotopic data; as expected, it mostly reflects the differences in U and Th concentrations in the different analysed minerals.

Summary, discussion and conclusions

The Attu gold prospect is small. The gold mineralised zone does not exceed 0.5 m in width, and its length is now known to be only a few hundred metres. Gold has also been detected along strike several kilometres away, but the mineralisation does not show a continuous outcrop pattern. However, the fact that gold is present indicates that the NE-striking shear/mylonite zone is mineralised and that hydrothermal activity seems to have occurred in most of the prominent lineaments in the region. The gold-bearing sulphide deposit is of replacement type, where pyrite and chalcopyrite grew at the expense of e.g. magnetite. It is envisaged that gold was introduced contemporaneously with the replacement processes.

Reworked Archaean orthogneisses dominate all segments of the Nagssugtoqidian orogen. Published age determinations range from 2870–2700 Ma (e.g. Kalsbeek & Nutman 1996; Connelly & Mengel 2000), but no chronological information has yet been available from the Attu region. The 3162 ± 43 Ma magnetite age obtained from the Attu host rocks suggests that the rocks in this part of the Nagssugtoqidian orogen may be significantly older than similar rocks elsewhere in the orogen. However, Sm-Nd isotope data from Archaean gneisses in the central part of the orogen suggest the involvement of pre-2800 Ma crustal material (possibly 3100 Ma or older) in their source (Whitehouse *et al.* 1998). Large parts of the Nagssugtoqidian orogen underwent Palaeoproterozoic granulite facies metamorphism around 1850 Ma (e.g. Willigers *et al.* 2001), which resulted in severe disturbance of the Pb-isotopic evolution of the rocks (Whitehouse *et al.* 1998). In view of the well-preserved 3162 Ma isochron relationships for the Attu gneisses it appears possible that these rocks escaped high-grade Nagssugtoqidian metamorphism and that granulite facies metamorphism here is of Archaean age, in agreement with the conclusions of Mazur *et al.* (2006, this volume) and Thrane & Connelly (2006, this volume).

The Pb-isotopic data of the gold bearing samples (Fig. 6) suggest a genetic link between the Rifkol granite intrusion and the fluids percolating through the shear zone, implying an Archaean age of the mineralisation. Without further analytical work we are unable to elaborate and comment on a possible source of the Pb that has been incorporated into the K-feldspar in the shear zone.

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