Combining exploration and multivariate techniques to detect the Bjørnesund West gold occurrence, southern West Greenland

Denis Martin Schlatter and Bo Møller Stensgaard

Gold exploration in the Bjørnesund region has been carried out since the early 1990s, and gold was found in the central part of the Bjørnesund East area by NunaOil and the Geological Survey of Denmark and Greenland (GEUS). Records of stream sediment samples with elevated gold concentrations up to several hundred parts per billion led to the recognition that amphibolites in the central part of the Bjørnesund East could be a promising target and work in 1996 led to the discovery of hydrothermally altered amphibolites with up to several hundred ppb gold. However, exploration work was limited to grassroots prospecting and none of the targets were drilled. The aim of new field work was to target areas in the Bjørnesund supracrustal belt which mainly consists of amphibolites but also comprises significant proportions of diorite, anorthosite, leucogabbro, granitoid rocks and ultramafic to mafic rocks that occur as relatively thin slivers in the amphibolite. We tested if the targeted areas were favourable for gold mineralisation and investigated the relationship between the mineral potential mapping and the actual geology. Here we demonstrate that based on older data we located new gold mineralising systems in the western part of the Bjørnesund supracrustal belt, identified platinum-enriched mafic to ultramafic rocks and located new occurrences of corundum at amphibolite-anorthosite contacts (Schlatter

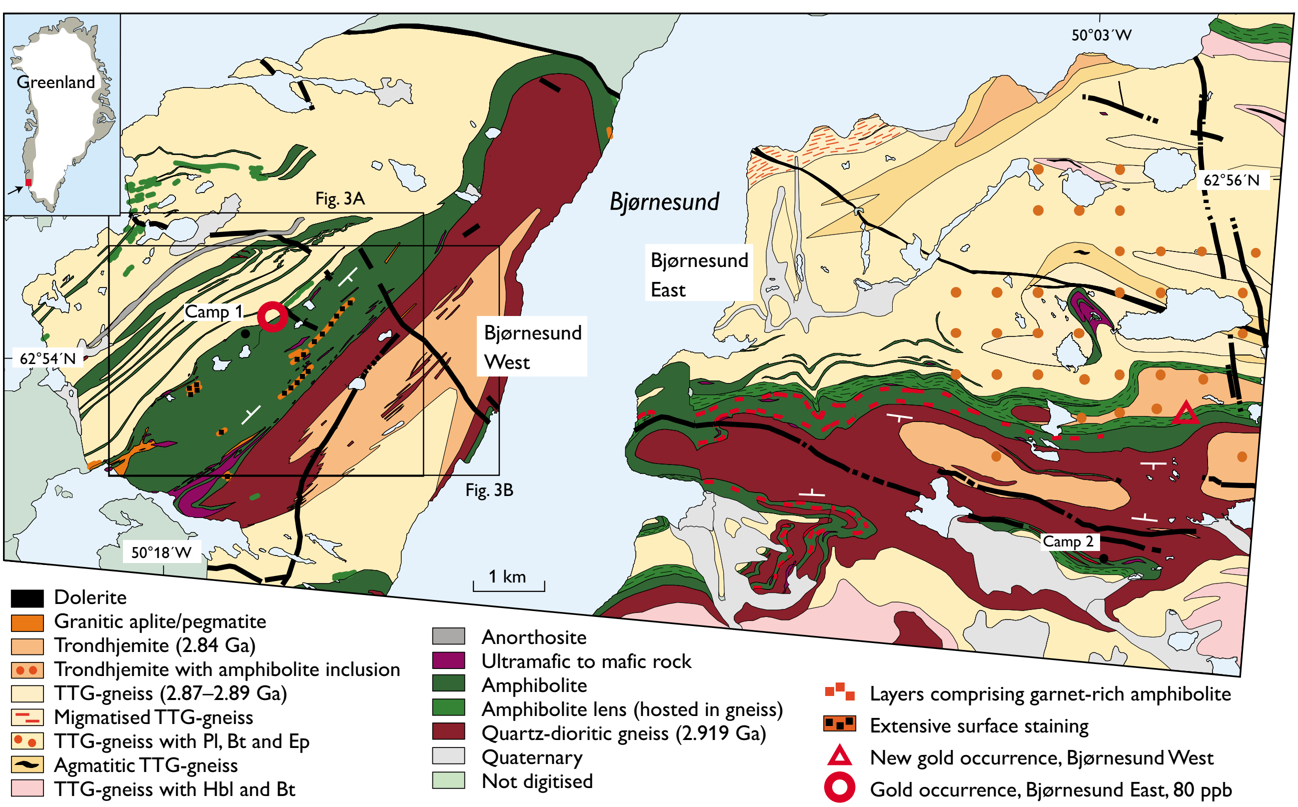

Fig. 1. Geological map of the Bjørnesund West and East areas showing the location of the newly discovered gold occurrence in Bjørnesund West. Prior to field work by GEUS in 2009, no gold occurrences were reported here. Black outlines indicate the sampled areas of Bjørnesund West, regarding sampling density see Fig. 3.

& Stensgaard 2012). We also show how lithogeochemical studies were useful to define the main rocks types, chemostratigraphic relations and hydrothermal alteration of the newly discovered gold mineralisation. Based on our study, we encourage the use of artificial neural network analysis and data interpretation prior to field work in Greenland in areas where only relatively little geological and mineral exploration work has been conducted and where the field season is relatively short.

Geology of the Bjørnesund area

The Bjørnesund supracrustal belt (Keulen *et al.* 2010) is of Mesoarchaean age, *c.* 50 km long and a few hundred metres to 3 km wide (Fig. 1). Amphibolites dated to 2947 ± 47 Ma are bounded towards the north and south by 2920–2810 Ma tonalite-trondhjemite-granodiorite (TTG) gneisses (Keulen *et al.* 2010; Kolb *et al.* 2013) that are interpreted to have been intruded into the amphibolites. Sheets of leucogabbro, gabbro and anorthosite are interpreted to have been intruded into the amphibolites at about 2950 Ma and were in turn intruded by quartz dioritic protoliths at 2920 Ma (Keulen *et al.* in press). Finally, late granites were intruded into the sequence of quartz-diorite amphibolite and anorthosite-gabbro between 2860 and 2830 Ma (Kolb *et al.* 2013). The rocks were affected by F1 folding into an isoclinal synform and F2 folding at 2850–2830 Ma with an E–W-trending fold axis, which is the most dominant structural feature in the Bjørnesund area (Keulen *et al.* in press). The F2 folding is associated with thrusting that caused shearing with only minor displacement. Finally, F3 NNW–SSE-trending folds have bent the regional foliation slightly.

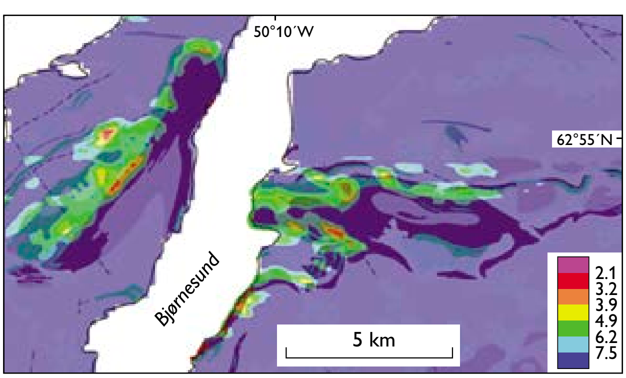

Fig. 2. Neural network analysis for gold favourable areas in the Bjørnesund West and East areas. Top 8.5% most favourable areas for gold in seven coloured intervals according to the neural network analysis of As, Cs, Rb, Sb and U stream sediment geochemistry and lineaments. A geological map is placed beneath the neural network analysis result, which is transparent.

Methods

A total of 116 rock samples (900 g) and 56 stream sediment samples (200 g) were collected during the field work and used for geochemical and petrographic investigations. Rock samples were crushed and milled by Actlabs laboratory in Ontario, Canada, and stream sediment samples were sieved at GEUS using a 0.18 mm sieve. The fine-grained fraction was sent to Actlabs for analysis. Gold was analysed by instrumental neutron activation whereas major and trace elements were analysed using Actlabs package '4Lithoresearch'. The U-Pb ages of zircon grains from four plutonic rock samples were also determined by Keulen *et al.* (in press). An artificial neural network is a mathematical and computational structure simulating the human neural network (the brain). Information, in the form of input data, which are presented to the network causes the network to learn and recognise patterns in the data. For instance, when a network is shown multiple datasets for known gold occurrences, it is able to identify and memorise possible patterns in the datasets associated with the occurrences which can be regarded as training points for the network. Afterwards, when the network is shown datasets from areas without any known gold occurrences, the network applies what it has learned and looks for patterns in the datasets that are similar to those recognised for the known gold occurrences. In that way, areas can be classified and mapped according to how similar their data patterns are to the patterns from the known gold occurrences. These areas can be regarded as potential to host gold occurrences.

Mineral potential mapping

Artificial neural network analysis (Stensgaard 2013) was used for mineral potential mapping (Fig. 2) together with Ni/Mg ratios from analysed stream sediment samples. This led to the identification of portions of the western and eastern parts of the Bjørnesund supracrustal belt as the most favourable for gold occurrences. Areas with anomalously high levels of Fe^{3+} were identified using ASTER satellite images, and correspond to ultramafic dunitic and pyroxenitic rocks (Schlatter & Stensgaard 2012). The most favourable areas, as identified from artificial neural network analysis, coincide with areas of stream sediments with elevated Ni/Mg ratios. Based on these detailed analyses, the Bjørnesund West and East areas were selected for field work with the aim to characterise the geological environment and evaluate the gold potential. A new detailed and geo-referenced digital geological map was compiled after the new field work (Fig. 1) and a new interesting gold occurrence was found in a hydrothermally altered shear zone in the amphibolites of the Bjørnesund

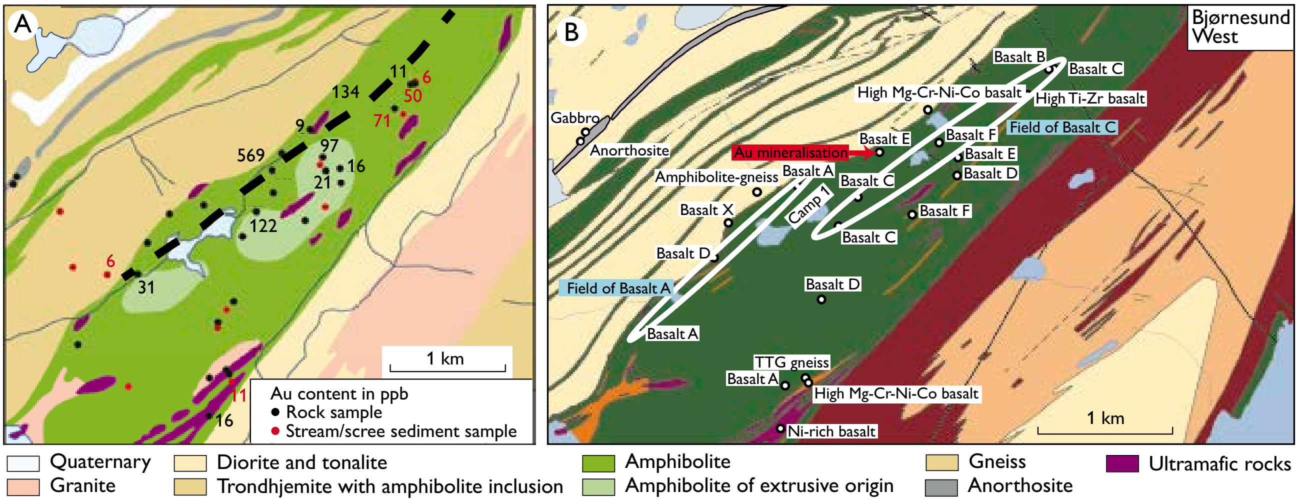

Fig. 3. **A**: Gold anomaly plot of sediment and rock samples from the Bjørnesund West area. A several tens-of-metres wide shear zone (dashed line) with gold-mineralised portions was discovered at 62°54.4′N, 50°16.2′W and at 555 m a.s.l. Legend below figure. **B**: Chemostratigraphic relation seen from the Bjørnesund West area. A rock unit which comprises mainly basalt A and a unit comprising mainly basalt C can be identified based on lithogeochemical immobile element techniques. The gold occurrence is found in rocks of basalt E type, and have basalt A and C in the structural footwall. For legend see Fig. 1.

West area. This several tens-of-metres wide NE–SW-trending shear zone (Figs 1, 3A) dips 80° SE. It can be followed over several hundred metres along strike and contains a 50 cm yellow-brownish, rusty-stained amphibolite, which hosts parallel quartz-carbonate-feldspar veinlets. Chip samples collected over this altered unit yielded 569 ppb Au (Fig. 3A), and alteration related to this gold occurrence was identified to be of the garnet-biotite-iron oxide-hydroxide type (Kolb *et al.* 2013). These new findings, together with elevated gold concentrations in stream sediment and rock samples along the same NE–SW-trending shear zone, indicate that the Bjørnesund supracrustal belt may host undiscovered gold occurrences and confirm that stream sediment sampling is a powerful exploration tool (Fig. 3A). Furthermore, nickel and platinum-group elements could also constitute a target as pentlandite was identified in an ultramafic rock sample with elevated concentrations of Ni, Cr, Co and PGE from Bjørnesund East (Fig. 1; Schlatter & Stensgaard 2012).

Chemostratigrapy and hydrothermal alteration

Based on lithogeochemical immobile-element-ratio classification (Barrett & MacLean 1994) seven types of amphibolite and three different types of other mafic to ultramafic rocks (high Mg-Cr-Ni-Co, Ni-rich and high-Ti-Zr basalt) were distinguished (Figs 1, 3B). The gold horizon was located at the contact of basalt A and basalt E (Fig. 3B). Amphibolites with elevated gold concentrations (less than 100 ppb) were also located in Bjørnesund East (Fig. 1, *c.* 2 km north-east of camp 2) where the ore horizon is also located at the contact of basalt A and basalt E (Schlatter & Stensgaard 2012). It appears that this basalt A – basalt E contact represents a good geochemical marker horizon in the Bjørnesund supracrustal belt. Changes were calculated for 35 basalt samples from the Bjørnesund area using the single precursor approach (MacLean & Barrett 1993). The results show that the richest gold-bearing basalt with 569 ppb Au from Bjørnesund West (Fig. 3B, encircled in white) is characterised by strong additions of FeO and silica (Fig. 4A) and by gain of CaO and loss of K_2O (Fig. 4B). In contrast, a basalt sample from Bjørnesund East with 80 ppb Au (Fig. 1) shows only a small loss of silica, no change of iron, gain of K_2O and loss of CaO (Fig. 4). We conclude that favourable alteration associated with gold mineralisation is characterised by silicification combined with addition of FeO and CaO.

Discussion and conclusions

Mineral potential mapping was successful because it indicated areas containing gold-mineralised rocks and pinpointed unusual mafic to ultramafic rocks where elevated concentrations of nickel and platinum-group metals were subsequently identified. Extensive rust zones were identified from ASTER satellite data, some of which correspond to the mafic to ultramafic rock units with elevated Ni, Cr, Co and PGE contents; several of the ultramafic to mafic rocks fall into the komatiite field and pentlandite was identified by microprobe analysis in one sample (Schlatter & Stensgaard 2012).

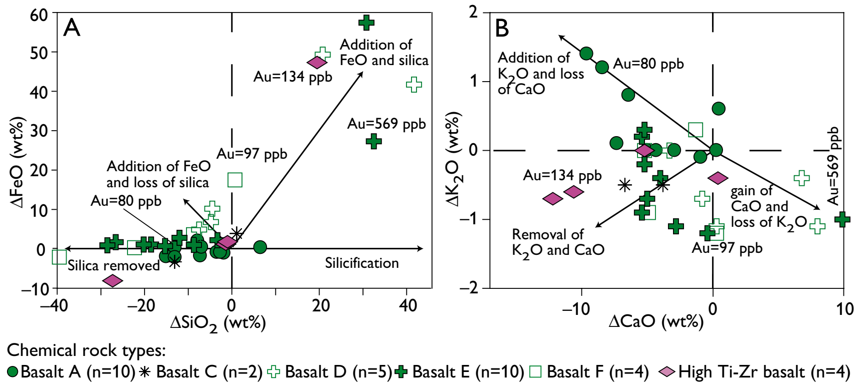

Fig. 4. Hydrothermal alteration based on mass-change calculations for 35 rocks from the Bjørnesund West and East areas. **A**: ΔSiO_2 versus Δ FeO. **B**: ΔCaO versus ΔK_2O. Mass changes were calculated using the method described by Barrett & MacLean (1994). Mass changes are reported in wt% change (Δ) relative to the precursor rock.

Chemostratigraphic interpretations show that the Au horizon is located at the contact between basalt A and basalt E and can be followed along the Bjørnesund supracrustal belt for at least 10 km (Figs 1, 3) so that this horizon represents an exploration target for gold and provides evidence of an E–W continuation. Alteration related to Au mineralisation is of garnet-biotite-iron oxide-hydroxide type and quartz-carbonate-feldspar veinlets occur in an amphibolite-hosted thrust-shear zone between quartz-dioritic gneiss and gneiss. Mass-change calculations show that favourable 'Au-alteration' is characterised by gains of FeO, SiO_2 and CaO and enrichment of As, Sb and Zn (Schlatter & Stensgaard 2012). The spatial association of gold occurrences and granite-trondhjemite rocks (Fig. 1) possibly indicates that the granitoids played a role in the emplacement of the gold. The association of gold and nickel is intriguing (Schlatter & Steensgaard 2013) and could be related to deep structures which might have been activated during events similar to those described by Fiorentini *et al.* (2012) from the highly nickel-enriched Agnew-Wiluna greenstone belt in western Australia where felsic and komatiitic magmas are related to deep crustal conduits.

With respect to the timing of events of the Bjørnesund supracrustal belt, we suggest that ultramafic rocks, leucogabbro and anorthosite were intruded into amphibolites (Fig. 1). This event may have been coeval with orthomagmatic nickel-platinum group-element mineralisation and isoclinal F1 folding. It is suggested that gold was then orogenically emplaced between 2860 and 2830 Ma (Kolb *et al.* 2013) at peak regional metamorphism. Finally, late F3 deformation events created faulting in a staircase-like outcrop pattern at 2710–2700 Ma (Keulen *et al.* in press). This study represents a coupled effort of artificial neural network analysis and targeted field exploration and shows that such an approach can be efficient and successful in identifying new exploration targets of gold, nickel-platinum group elements and corundum.

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Authors' addresses

D.M.S.* & B.M.S., *Geological Survey of Denmark and Greenland,* Øster *Voldgade 10, DK-1350 Copenhagen K, Denmark.*

*Present address: *Helvetica Exploration Services GmbH, Carl-Spitteler-Strasse 100, CH-8053 Zürich, Switzerland.*

E-mail: *denis.schlatter@helvetica-exploration.ch*