Prospectivity mapping for orogenic gold in South-East Greenland

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Numerous studies have proven that conceptual targeting based on integration of various geo-datasets can aid exploration companies to identify exploration targets (e.g. Joly *et al.* 2013). This is particularly true in remote, underexplored areas that are commonly just covered by airborne geophysics and remote sensing and mapped geologically only on a regional scale. Such regions are 'exploration greenfields' and may possess undiscovered economic deposits.

The ice-free coastal strip of the Archaean craton in South-East Greenland overprinted by Palaeoproterozoic orogeny (Fig. 1) is such an area due to its remoteness and arctic-alpine conditions; and deep-seated, repeatedly reactivated structures and new magmatic episodes make large parts of this region potential for orogenic Au occurrences. Although only minor Au mineralisation has been found to date, a large number of Au-bearing rock samples (Petersen & Thomsen 2014) and stream sediment anomalies suggest an elevated potential particularly in the Tasiilaq area (Fig. 1B). A large field mapping campaign (Kolb *et al.* 2016) and regional airborne magnetic surveys (Riisager & Rasmussen 2014) were conducted from 2012 to 2015, resulting in a uniform coverage of relevant geological and geophysical information, which can be combined with satellite remote sensing data. It was therefore decided to apply a fuzzy logic-based mineral prospectivity mapping (MPM) procedure (see below and Fig. 2) combined with a mineral system approach of orogenic Au (McCuaig *et al.* 2010).

However, it was a challenge to apply this approach for several reasons: (1) Strong topographical variations in this region distort some of the evidential datasets used in the MPM and their effect has to be minimised (e.g. aeromagnetic data are strongly affected by flight height). (2) Fjords, ocean and glaciers strongly limit the accessible area for prospection, lead to a non-uniform data coverage for many datasets and affect the accuracy of evidential maps associated with the MPM. (3) lack of known *in-situ* Au mineralisation limits the validation of final prospectivity maps. (4) the geological history is not fully understood, making it difficult to discard irrelevant features (e.g. magnetic anomalies may be related to insignificant Palaeogene dykes or important older faults). Such difficulties occur in many parts of Greenland, and this study gives an idea of how meaningful MPM studies might be in other regions.

Regional geology

The study area comprises the Archaean North Atlantic craton (NAC) in the south and the Palaeoproterozoic

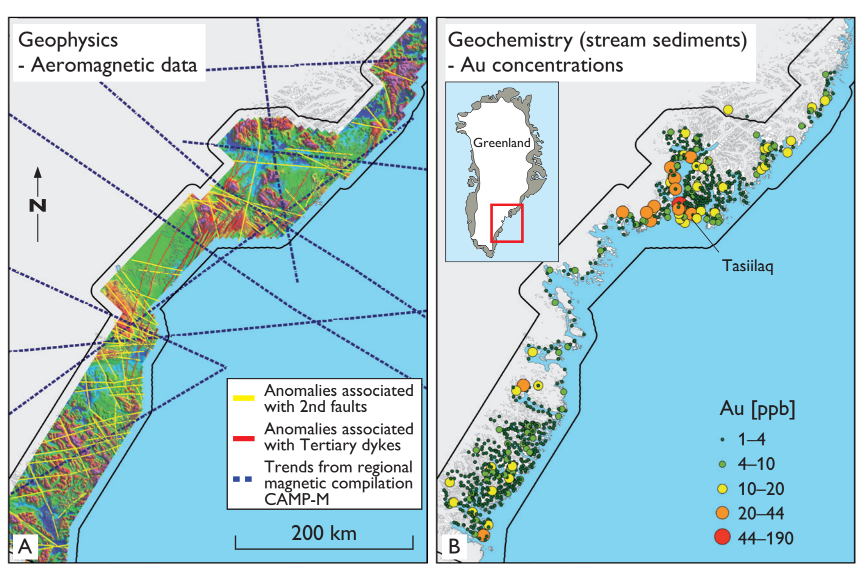

Fig. 1. Examples of data types used for the MPM study in South-East Greenland (framed area in index map). **A**: Mapped elongate anomalies from aeromagnetic data (see background map in Riisager & Rasmussen 2014) and regional magnetic compilations used as proxies for faults of 1st and 2nd order in the critical processes 'source' and 'pathways'. **B**: Stream sediment Au concentrations used as a proxy for the 'chemical scrubber'. Black lines in **A** and **B** mark the area used in the interference network.

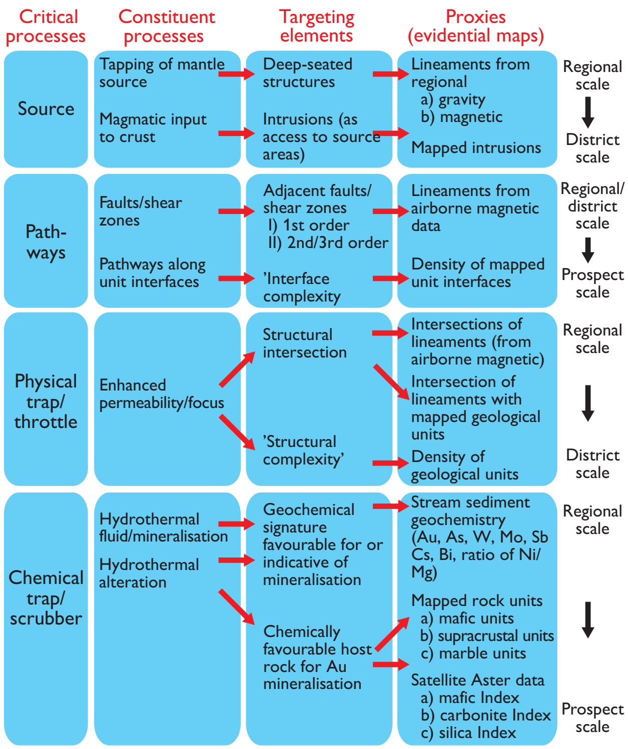

Fig. 2. The mineral system model used for the orogenic gold deposit type. The critical processes are associated with a series of constituent processes, targeting elements and proxies.

Nagssugtoqidian orogen in the north (Figs 1, 3; Kolb *et al.* 2016). To the north, the orogen includes an Archaean foreland that comprises rocks from the Rae Craton. To the south, the margin of the NAC is affected by deformation and intrusives of the Palaeoproterozoic Ketilidian orogen. The Nagssugtoqidian Orogen comprises tectonically reworked Archaean rocks subjected to high-grade metamorphism and slivers and belts of Palaeoproterozoic metavolcanic, metasedimentary and intrusive rocks. On the basis of differences in lithologies and tectono-metamorphic history, the orogen is divided into four terranes, from north to south the Isortoq terrane, the Ammassalik intrusive complex (AIC) and the Kuummiut and Schweizerland terranes. The NAC is dominated by felsic orthogneisses with subordinate supracrustal rocks, with syn- to post-tectonic alkaline intrusions in the Skjoldungen area (63°10′–63°40′N). Main deformation events within the NAC are the Timmiarmiut and Skjold-ungen orogenies.

Continental breakup in the Palaeogene led to the emplacement of coast-parallel dykes in the northern area (north of 64°N) that can clearly be identified as anomalies in aeromagnetic data (red lines in Fig. 1A).

The mineral prospectivity mapping approach

Mineral prospectivity maps used for targeted exploration highlight areas with coincident geological features that are important for a given commodity. For our mineral prospectivity mapping we use geoscience data that were selected on the basis of a mineral system approach for orogenic gold. The mineral system approach provides a holistic view of the critical geological, physical and chemical processes needed to generate a mineral deposit. For orogenic Au systems McCuaig *et al.* (2010) identified the following critical processes: (i) a source of Au in the upper mantle, (ii) active pathways allowing fluids to flow through the crust, (iii) physical traps in which fluids are throttled and focused and (iv) a chemical 'scrubber' associated with hydrothermal mineralisation and alteration (Fig. 2). Since ore-forming processes typically cannot be directly mapped, they must be inferred from geological features referred to as targeting elements. These are rarely directly measurable but are approximated from responses in geoscience data such as faults estimated from magnetic anomalies. These proxies are represented in this approach by uniform spatial grids named evidential maps (EM) that can easily be combined to build prospectivity maps.

To quantify and combine all information we use 'fuzzy logic' operations which have proven in many cases (e.g. Joly *et al.* 2013) to be suitable for building meaningful mineral prospectivity maps. First, all EMs were rescaled (i.e. transformed into maps with values ranging from 0 to 1) by employing so-called fuzzy membership functions to obtain representative maps describing how far the prospectivity is supported (0.0 = not at all; 1.0 = fully). In a multistage interference network, fuzzy OR (maximum operator equivalent to logical union) and AND (minimum operator equivalent to logical intersection) operators were then applied to combine the EMs to create first intermediate fuzzified maps representing the four critical processes and finally fuzzy prospectivity maps used to predict areas of high Au potential (electronic supplementary (ES) figure: Fig. ES1). Further details about the mineral prospecitivty mapping procedure, the underlying mineral system approach and data sets are given in Stensgaard & Heincke (2016).

Calculation of prospectivity maps

Most of the EMs associated with structural information were derived from anomalies in potential field data, either from regional data compilations (Gaina *et al.* 2011) or recent aeromagnetic surveys (Fig. 1A). A 1:500 000 scale digital geological map (Stensgaard *et al.* 2016) was used to extract additional structural information (Fig. ES2A) and to identify geological units and other settings favourable for Au mineralisation, e.g. intersections between units and cross-cutting structural elements. Other EMs associated with preferable rock types were obtained from mineral indices of ASTER satellite data (Fig. ES2B). Finally, the contents of Au and geochemical pathfinder elements for Au mineralisation (As, Sb, Cs, W, Bi, Mo, Ni/Mg) in stream-sediment samples (Fig. 1B) were presented in EMs that reflect relevant hydrothermal mineralising fluids as well as associated alteration halos.

The non-uniform spatial data coverage made it necessary to use interpolation (kriging and natural neighbour gridding) to create the related EMs. To rescale the EMs we used fuzzy membership functions that were estimated on the basis of qualitative and quantitative knowledge (see Fig. ES3). The region used to determine the EMs and perform the interference network calculations comprises both the ice-free onshore, adjacent offshore and ice-covered areas; however, only accessible ice-free areas were considered in the evaluation of prospectivity maps (Figs 3A, B).

There are uncertainties in all steps of the mineral prospecitivity mapping procedure (McCuaig *et al.* 2010), and it is important to test how reliable the final prospectivity maps are. If known mineral occurrences that originate from the assumed mineral system are present, one option is to construct prediction-rate curves to evaluate and adapt the prospectivity procedure (Carranza 2009). However, in the absence of such mineral occurrences, we used stream-sediment locations with Au concentrations > 20 ppb as 'deposits' in such curves (see circles in Figs 3A, C). This led to a number of inaccuracies, as sample locations typically do not coincide with locations in the catchment area where gold was eroded, and where no unique and simple function generally links concentrations of Au occurrences and stream-sediment samples. Hence, conclusions based on such validation should be considered carefully.

To evaluate the robustness of the mineral prospectivity mapping and the relevance of different targeting elements,

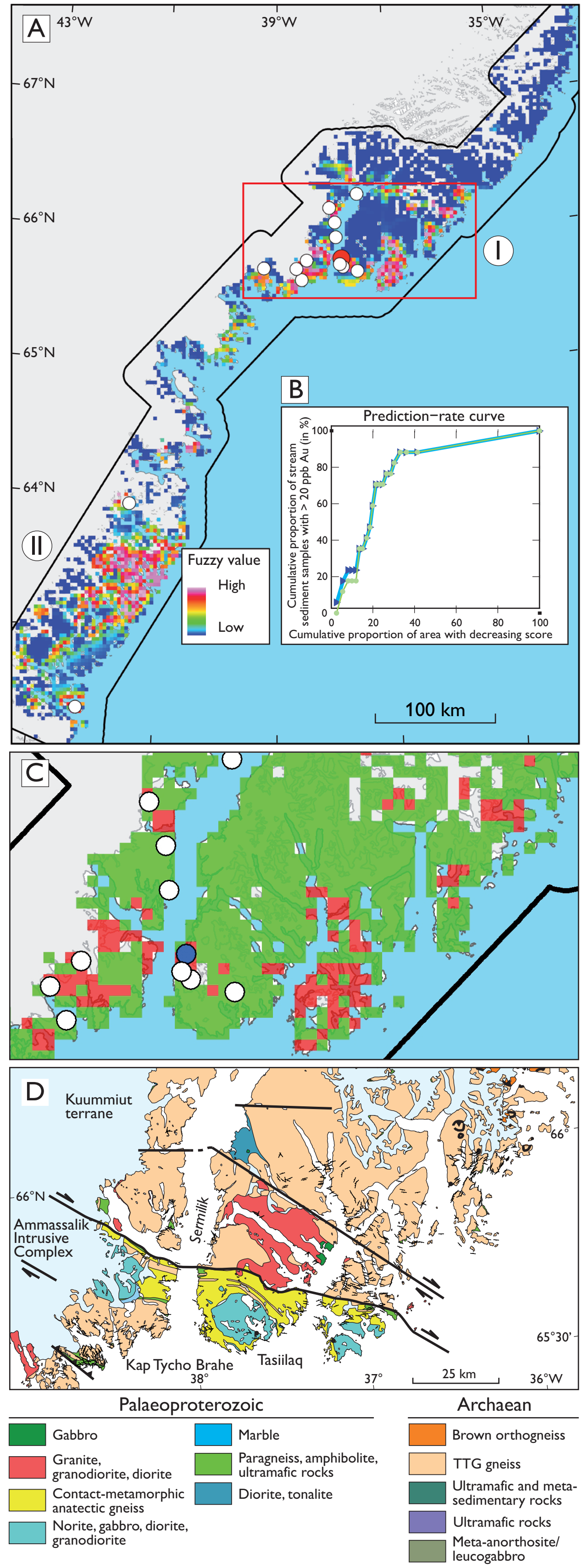

Fig. 3. **A**: Final prospectivity map obtained by using all evidential maps. White circles: Stream sediment locations with Au > 20 ppb. Red circle: the sample with highest concentration of 196 ppb. **B**: Validation curves showing the cumulative area with decreasing score versus the cumulative number of stream sediment samples with > 20 ppb Au in the same area. (In the blue and the green curves, EMs associated with stream-sediment data from Au and all elements are not incorporated). **C**: Map of the area around Tasiilaq (red rectangle in **A**). Pixels with a high fuzzy value of > 0.85 are shown in red. **D**: Geological map of the same area.

we repeated the procedure with several different combinations of EMs (e.g. all EMs, all EMs except for the one based on Au concentration from stream sediments). Irrespective of the combination of EMs, the resulting validation curves show that high fuzzy scores correlate strongly with elevated Au in stream sediment samples (Fig. 3B) suggesting that the mineral prospectivity mapping is reliable and robust.

Results and discussion

To identify areas with high orogenic Au potential, we highlighted pixels (pixel size: 3 × 3 km) in the prospectivity map with high fuzzy values > 0.85 (red colour in Fig. 3C) associated with ~8% of the total area. Particularly the Tasiilaq (I) and the Skjoldungen (II) regions are characterised by high scores (Fig. 3A). In region I, a couple of areas stand out as being anomalous in gold and its pathfinder elements; and locations of both stream sediment samples with high Au concentrations (Fig. 1B) and Au-bearing rock samples (Petersen & Thomsen 2014) coincide well with areas having elevated membership fuzzy values. The highest scores are aligned along a WNW–ESE-oriented corridor that coincides with the Ammassalik intrusive complex (AIC). In particular the boundaries of the AIC to the Kummuit and the Isortoq terranes in the north and south are identified as prospective (Fig. 3D; Kolb 2014). A major structure that likely represents a suture zone which may have acted as a mantle source-tapping feature is reported along the northern boundary of the AIC (Kolb 2014) and is confirmed by geophysics (Riisager & Rasmussen 2014). Other deep-seated structures have been suggested south of the AIC in the Isortoq Terrane (Nutman *et al.* 2008). This means that an elevated Au potential from the mineral prospectivity mapping is supported by the main geological settings. In contrast, no elevated Au concentrations from samples or other indications for Au occurrences exist within the cratonic Skjoldungen region (II). The latter area is characterised by predominant mafic granulites with thin belts of deep-crustal-formed mafic and ultramafic rocks considered unfavourable for orogenic Au mineralisation (Kolb *et al.* 2016). At this stage, the mineral system approach is set up to not exclude rock units formed at large depths, and it should be adjusted in future to take this information into account.

In summary, the results of this study suggest that modern mineral prospectivity mapping schemes based on an mineral system approach can improve the geological understanding of mineral prospectivity even in regions that are not densely covered by all data types and underexplored.

Acknowledgements

The project was jointly financed project by GEUS and the Ministry of Mineral Resources, Government of Greenland. We thank S. Weatherley and E.V. Sørensen, GEUS, for comments and contributions.

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