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Geological and statistical validation of a gold-prediction model based on low-density surface geochemistry and other geoscientific data, Nuuk region, West Greenland

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ABSTRACT

Statistical prediction models for gold occurrences in the Nuuk region, West Greenland, based on low-density stream sediment geochemistry, regional aeromagnetic and aeroradiometric data have outlined favourable areas and provided multi-parameter signatures for them. The results have been validated during field studies of geological settings, lithology and lithochemistry. The favourable areas occur in mafic metavolcanic members of Archaean supracrustal belts that are characterized in the data by elevated Ni/Mg ratios and elevated Cs and Rb. The most promising gold mineralization has a distinct signature with high As, Al, U and Th. The chemical features identified by the statistical analysis have been verified as originating from properties of rocks within the areas of known and predicted gold mineralization. The study has shown that the regional data reliably identify chemical features that may be caused by extensive hydrothermal alteration in the environments where gold mineralization occurs. Furthermore, the regional data have drawn the attention to important differences in the setting of known gold mineralized sites but owing to limited data resolution the statistical prediction is unable to pinpoint the mineralized structures themselves.

INTRODUCTION

Statistical prediction models for specific mineral occurrences based on regional geochemical and geophysical datasets enable the explorationist to integrate large amounts of digital data and extract valuable information. Geological and statistical validation of the reliability of results arising from such a statistical approach is critical for its use and interpretation. However, such validations are commonly not carried out. In this study, results of a statistical prediction process in West Greenland are evaluated for geological as well as statistical reliability (Stensgaard et al. 2006).

REGIONAL GEOLOGY AND GOLD

The Nuuk region, West Greenland, is an assemblage of early to late Archean crustal terranes amalgamated during NW-directed thrusting at c. 2.7–2.6 Ga. Several high-grade metamorphic events and associated deformation have variably affected different parts of the region from the Palaeoarchean through to the Neoarchean (Nutman and Friend 2007). Supracrustal belts dominated by amphibolite-facies metavolcanic rocks are intercalated with tonalitic to granodioritic gneisses. The most

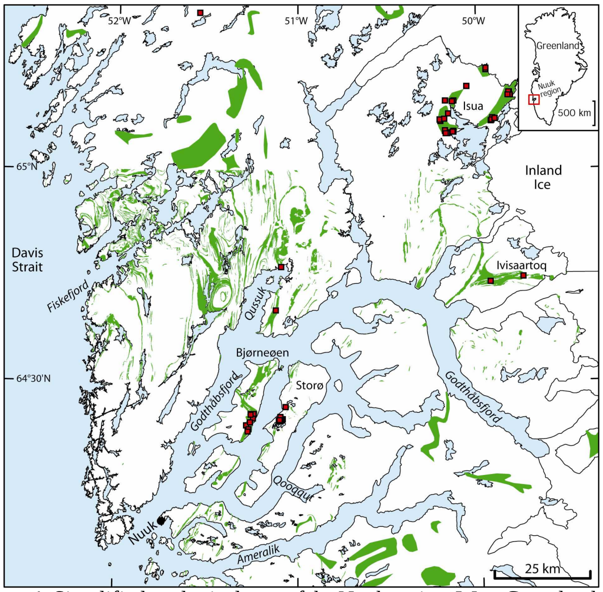

Figure 1: Simplified geological map of the Nuuk region, West Greenland. Green units are supracrustal rocks within other basement rocks, mainly gneiss (white). Red squares indicate fifty-two gold occurrences. Rock units are from 1:100 000 (for areas available digitally) and 1:2 500 000 geological maps published by the Geological Survey of Denmark and Greenland.

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common supracrustal rock is amphibolite of tholeiitic to komatiitic composition with local metaandesite to metadacite. A number of gold mineralized sites within the supracrustal belts show evidence of hydrothermal alteration, such as quartz veining, silicification, sericitization, garnetization and carbonatization. The genesis of the gold is still debated but it seems that both epithermal high-sulphidation gold and mesothermal lode gold systems are present. The most promising gold occurrences occur at Storø, Qussuk and Isua. The former two are targets for current commercial exploration. New aspects of the regional geology, the supracrustal belts and the gold occurrences have recently been addressed, e.g., Appel et al. (2005), Garde (2007), Hollis et al. (2004, 2006).

STATISTICAL METHOD

The statistical analysis is performed on regional-scale stream sediment geochemical, aeromagnetic and aeroradiometric data. All parameters were gridded to a 200-m pixel size. Gold occurrences, in the statistical sense, were defined as pixels in which one or more rock samples contained 1 ppm of gold or more. The statistical analysis and characterization of pixel properties are based on the Bayesian Theorem and joint likelihood ratio functions derived from empirical distribution functions. The differences between areas with known mineral occurrences and those without constitute the basis for the statistical predictions. For a full description of the procedure see Chung et al. (2002) and Stensgaard et al. (2005, 2006).

For each data layer, empirical distribution functions (EDFs) were calculated; one for pixels with and one for pixels without gold occurrences. The latter are regarded as the regional 'background signatures'. The ratio of the two complementary EDFs for each data layer was used to calculate the likelihood ratio function (LF). A joint likelihood ratio function (JLF) was then calculated as the product of the LFs for all data layers included. This JLF is then used to estimate the favourability for gold occurrences in each pixel, i.e., the likelihood that a pixel has data signatures similar to those of known gold occurrences. As a part of the statistical procedure, the known gold occurrences in the Nuuk region were divided into groups.

GROUPS OF GOLD OCCURRENCES AND GOLD FAVOURABILITY MAPS

Fifty-two known gold occurrences in the Nuuk region where included in the statistical modelling and a gold favourability map was constructed for each. The capability of each occurrence to predict the remaining ones was then evaluated. Occurrences with mutual prediction capabilities, i.e., can predict others and are themselves predicted by these, were grouped. The analysis resulted in the identification of three main groups of gold occurrences: Storø, Bjørneøen and Isua group, comprising forty of the occurrences. The remaining occurrences had poor prediction capabilities and were not treated further.

Favourability maps were constructed for each group and the characteristic signatures listed (Table 1). The maps show that environs of known gold occurrences are predicted as being favourable and also that a number of favourable areas fall outside the known gold occurrences.

SIGNATURES OF GOLD OCCURRENCES

The systematic construction of data signatures of gold occurrences and their background, draw attention to signatures that are distinct for one or more of the groups. Some of the most characteristic data signatures identified are summarized in Table 1.

The stream sediment signatures for the three gold groups do not exhibit significant contrasts from the background for the following components: CaO, K2O, P2O5, Sb, SiO2, TiO2, V, Zr, and Zn. The three groups have high Ni/Mg ratios and high Cs as common features, but they are different in their remaining signatures. Medium to high Rb, La, U and Th characterize the Storø and Bjørneøen groups while these elements are low for the Isua group. The Bjørneøen and Isua groups have medium to high MgO, Fe2O3, Ni and Cr, whereas the Storø group is characterised by high Al2O3. The Isua group has low Na2O compared to the other groups. Gold in the stream sediment geochemistry is only found to be indicative for the Isua group. Trivial but important observations to keep in mind such as high gold values in low-density stream sediment geochemistry, are not often encountered. Arsenic is only found to be indicative for the Storø group.

Only the Isua group has a characteristic signature in the aeromagnetic datasets; very low and very high values are obtained in the vertical gradient of the total magnetic intensity field, and likewise, very high values are obtained in the amplitude of the horizontal gradients of the total magnetic intensity field. However, these signatures are not well defined and a considerable portion of the occurrences within the group fall within the range of the background values.

Aeroradiometric signatures are found to be indicative, especially for the Storø group. This group shows distinct high values in K, Th, Total Gamma, U and U/Th ratio signature which for the K, Th, and Total Gamma radiation, is different from the signatures of the other groups and the background. Moderate U values and moderate to high values in the U/Th ratio distribution occur for the Isua group. Occurrences of the Bjørneøen group are not different from the background in the aeroradiometric data.

GEOLOGICAL VALIDATION

A statistical model is not valuable to the exploration geologist without a geological validation that addresses questions like "Are the results verifiable, geologically reasonable and explainable?" Such validation greatly improves the understanding and usefulness of the results. Two approaches have been utilized to improve the understanding of the signatures and prediction results obtained in this study. Field visits were made to several of the areas with predicted favourability outside the known mineralized sites, and the lithology and available lithochemistry were studied in predicted areas.

Given the spacing (5 to 6 km) of the stream sediment data, it is obvious that the prediction is unable to characterize the small target of the gold mineralization itself but it may identify larger features, such as lithology and alteration within and characteristic for the mineralized environment.

All known gold occurrences are located within mafic metavolcanic rocks and the fact that all predicted areas are situated within mapped supracrustal rock units can be considered the initial verification of the results. Considering the prevalence of mafic rocks, it is to be expected that the geochemical signature of the predicted favourable areas contains features such as high Mg, Ni, and Cr.

Au: Elevated gold content (up to 200–380 ppb Au) was encountered in samples from some areas outside known mineralized sites that were predicted favourable for gold.

As: High arsenic content in stream sediment is only encountered in central Storø where rock analyses and microscopy have confirmed that arsenopyrite is associated with the leading gold mineralization.

Ni/Mg ratio: Rock samples from areas with known gold, and from favourable areas outside known occurrences, yield elevated Ni/Mg ratios confirming that this parameter is a true signature of gold-bearing areas. Ni-enriched samples suggest that some Ni-enrichment is tied to sulphide mineralization and other to calc-silicate alteration in which Ca replaces Mg (and Fe). Thus, the increase in the Ni/Mg ratios may be a sign of alteration/mineralization, and it has been sufficiently widespread to leave an imprint on the stream sediment geochemistry.

Cs-Rb: Mafic rocks with unusually high Cs are encountered in several of the known and predicted “new” favourable areas. It is very probable that Cs has been introduced into the mafic rocks as a result of hydrothermal alteration.

U-Th: Allanite-bearing pegmatites are abundant in the supracrustal sequences in the central Nuuk region (centered on Bjørneøen and Storø) and explain the high U and Th signatures of the stream sediment. Early pegmatites are dated at 2840 Ma whereas widespread pegmatite emplacement takes place between 2750 Ma and 2600 Ma, and is also associated with the intrusion of the c. 2550 Ma Qôrqut granite complex. This suggests for the existence of long or recurrent high-level granite magmatism capable of generating and maintaining hydrothermal circulation, thereby favouring mineralization.

Al_2O_3: Aluminous metasediments comprise a relative high quantity of the supracrustal package at Storø which confirms the signature picked up for the Storø group. Central Storø is also the only place in the region where anorthosite is known in close vicinity to gold mineralization. Metasediments occupy a larger proportion of the supracrustal package at Storø than elsewhere and that together with the high As emphasise that the Storø environment is distinct from the other mineralized areas.

Na_2O: This signature for the Isua gold group is ambiguous. It has not been possible to confirm enrichment in Na_2O in rock samples from predicted “new” favourable areas for the Isua group. Post-depositional alteration related to hydrothermal percolation along shear and fault zones can lead to the enrichment in SiO_2, CaO, Na_2O, K_2O and/or S, but such a relation cannot be established for Na_2O, though some of the favourable areas outlined for the Isua group are in the vicinity of shear and fault zones.

Aeroradiometric signature: The anomalous more radioactive environment at Storø has been confirmed by fieldwork. Uranium- and Th-bearing minerals are encountered in both pegmatites and surrounding mafic metavolcanic rocks, again suggesting fluid penetration.

STATISTICAL VALIDATION

Statistical prediction models are of little use if their reliability or capability to predict is not tested. Users need to know how reliable the prediction is.

For this purpose statistical cross-validation was carried out. One gold occurrence was selected from each group and its location was assumed to be unknown. A gold potential map was constructed based on the remaining occurrences of the group. The pixels occupied by the selected occurrence were then assessed in order to evaluate the ability to predict the occurrence pretended to be unknown. When the process had been carried out for each showing in a group, a prediction curve was constructed. This curve describes the cumulative distribution of that portion of deselected mineral occurrences which would be discovered if a certain area was assigned for exploration. The quality of the prediction can be judged from the slope of the prediction rate curve: the steeper the slope, the more reliable the prediction. By carrying out the cross-validation on favourability maps based on different combinations of data types, it was possible to evaluate their effect on the prediction results.

Satisfactory prediction rate curves were obtained for all three groups. In general, the importance of the stream sediment geochemistry data for the prediction of favourable areas is clearly seen from the prediction rate curves. None of the other data types would be able to affect the predictions so much as the stream sediment geochemistry. This has also something to do with the resolution of the data. The prediction rate curves also allow an evaluation of the effect of different data types. However, a general trend for all groups cannot be established. For example, the addition of aeroradiometric datasets to the Storø group predictions increases the prediction rate whereas the rate actually decreases with the addition of aeroradiometric data to the Isua group predictions.

CONCLUSIONS

The geological validation confirms that the features identified statistically in the regional data in fact reflect relevant properties of the rocks within the known and predicted areas. The identification and interpretation of these features add to the understanding of the geological environments hosting gold mineralization. However, the regional character of the survey data prevents a precise location of small features like the gold mineralization itself.

The statistical cross-validation testifies that the prediction results are reliable in a statistical sense. The cross-validation also allows an assessment of the importance and effect of different data types in the prediction and allows the estimation of the probability for new discoveries.

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Table 1: Data signatures for gold occurrence groups against the background signature. Range indications (lowest, low, medium, high and highest) refer to characteristic data values relative to the entire range of the specific dataset. A toned cell marks a data signature regarded as distinct for the group; a hatching refers to a signature which is moderately distinct; blank cells are non-characteristic for the group. Abbreviations: total magnetic field intensity (TMI); vertical gradient of TMI (VG-TMI); amplitude of horizontal gradients of TMI (Amp.-HG-TMI).

Data	Storø group	Bjørneøen group	Isua group	Background
Stream sediment geochemistry data				
Au	Low (as background, 0–40 ppb)	Low (as background, 0–40 ppb)	High (>60 ppb)	Low (0–40 ppb)
As	High (>20 ppm)	Low (as background, <4 ppm)	Low (as background, <4 ppm)	Low (<4 ppm)
Cs	High (3.5–5 ppm)	High (3.5–5 ppm)	Highest (3–6.5 ppm)	Low (<2.5 ppm)
Rb	High (40–80 ppm)	High (40–80 ppm)	High (30–70 ppm)	Low (10–50 ppm)
La	High (50–70 ppm)	Medium (35–55 ppm)	Low (30–10 ppm)	Medium (15–50 ppm)
U	Highest (>80 ppm)	Medium (17–35 ppm)	Low (as background, <15 ppm)	Low (<15 ppm)
Th	Highest (12.5–20 ppm)	High (10–15 ppm)	Low (as background, <8 ppm)	Low (<12.5 ppm)
Ni/Mg ratio	High (30–40)	High (30–37)	High (30–45)	Low (10–35)
Al2O3	Highest (15.5–16.5%)	Low (as background, 13.5–15.0%)	Low (as background, 14.0–15.5%)	Low (13.5–15.5%)
Fe2O3	Low (as background, 4–6%)	Medium (as background, 6–7.5%)	Highest (7.0–12.5%)	Low (3–9%)
Na2O	High (as background, 3.00–3.75%)	Medium (2.75–3.50%)	Low (2.50–3.50%)	High (3.00–4.75%)
Zn	High (60–90 ppm)	High (55–85 ppm)	High (50–110 ppm)	Low–Medium (20–100 ppm)
Zr	Low (200–450 ppm)	Low (200–450 ppm)	Low (< 300 ppm)	Medium–High (150–900 ppm)
Aeromagnetic data				
VG-TMI	Medium (-0.2–0.2 nT/m)	Medium (-0.2–0.2 nT/m)	Lowest and Highest (-0.5–-0.25 nT/m, 0.4–0.75 nT/m)	Medium (-0.3–0.4 nT/m)
Amp.-HG-TMI	Low (0.0–0.1 nT/m)	Low (0.0–0.1 nT/m)	Highest (0.1–1.0 nT/m)	Low (0.0–0.25 nT/m)
Aeroradiometric data				
K	High (1.75–2.5%)	Medium (as background, 0.25–1.5%)	Medium (0.50–1.25%)	Medium (0.25–2.5%)
Th	High (8–14 ppm)	Low (as background, 1–8 ppm)	Low (4–8 ppm)	Low (1–10 ppm)
Total Gamma	High (main 10–13 Ur)	Low (as background, 3–7 Ur)	Low (as background, 5–8 Ur)	Low (1–10 Ur)
U	High (2.5–5.5ppm)	Medium (0.5–1.5%)	Medium (1.0–4.0 ppm)	Low (0.0–3.0 ppm)
U/Th ratio	Medium–High (0.25–0.55)	Medium–Low (0.50–0.30)	Medium–High (0.10–0.65)	Low (0.00–0.30)