Application of airborne hyperspectral data to mineral exploration in North-East Greenland

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An airborne hyperspectral survey was organised by the Geological Survey of Denmark and Greenland (GEUS) and carried out in 2000 to test the use of spectral analysis in mineral exploration under Arctic conditions. The hyperspectral data were acquired by using the HyMap imaging system consisting of sensors that collect reflected solar radiation in 126 bands covering the 440–2500 nm wavelength range (Bedini & Tukiainen 2008). The spatial resolution was 4 × 4 m (Tukiainen 2001). Eight sites underlain by Caledonian or post-Caledonian rocks with known mineral occurrences (Fig. 1) were tested. The project was financially supported by the Greenland Bureau of Minerals and Petroleum and the data were analysed by GEUS. Here we provide a summary of the results.

Field work 2005–2009

Ground checks were undertaken in 2005, 2008 and 2009 by GEUS (Thomassen & Tukiainen 2008). The field work by the authors was carried out from light-weight camps in co-operation with International Molybdenum Ltd. that explored the Malmbjerg molybdenum deposit, and with other GEUS activities. The aim was to investigate hyperspectral anomalies and known mineral occurrences. The field work comprised ground measurements of rocks, minerals and their weathering products with a portable spectro-radiometer in order to determine their spectral character and to compare this information with the airborne data. In 2005 and 2008, a PIMA II portable instrument was borrowed from other institutions, but for the 2009 season GEUS purchased an advanced spectro-radiometer, model FieldSpec 3 HiRes. Our investigations showed that there is good correlation between the airborne spectra and the field spectra, thus confirming the quality and stability of the airborne hyperspectral data.

In general, sulphide minerals have poor to weak spectral response in the visible and near-infrared (VNIR) and short-wave infrared (SWIR) spectral regions whereas their alteration products, such as malachite, cerussite, smithsonite and jarosite, are distinctly SWIR-active. However, apart from jarosite, these minerals are virtually non-existent in the region. In contrast, it appears from our study that the hyperspectral detection of typical host- and wall-rock alteration minerals (jarosite, white micas, phengite, kaolinite, dolomite etc.) provides an effective method to outline potential exploration targets.

Main results

Below we present some results that are of relevance for mineral exploration in the region. The reader is referred to Harpøth *et al.* (1986) for a description of the mineral occurrences of the region and to Henriksen *et al.* (2009) for a description of the regional geology. The locations of the described areas are shown in Fig. 1.

Area 1 – Wegener Halvø. This horst-like peninsula exposes a complex pattern of fault blocks involving Neoproterozoic to Triassic sedimentary rocks, with stratabound base-metal mineralisation occurring in the Permo-Triassic section. Disseminated mineralisation hosted by Triassic sandstone and shale could not be detected by the airborne hyperspectral survey due to lack of alteration minerals. However, a close association of dolomitisation with Upper Permian, carbonate-hosted base-metal mineralisation is confirmed by our investigations, making the dolomite map a valuable exploration tool (Fig. 2).

Area 2 – Werner Bjerge. A well-known porphyry molybdenum deposit is hosted in the Malmbjerg granite stock, which is a unit of the Palaeogene Werner Bjerge alkaline intrusive complex. The alteration zones surrounding the deposit constitute an important target for our investigation. Conspicuous high-temperature, potassic and siliceous hydrothermal alteration outlined by muscovite and phengite is well displayed in the hyperspectral data. The high-temperature alteration apparently culminated in greisenisation of the Malmbjerg granite stock, as exemplified by topaz-muscovite-enriched rocks in the stock roof and in the roofing Permo-Carboniferous sandstone (Fig. 3). In addition, the hyperspectral mapping of typical alteration minerals outlines a large number of potential exploration targets with low-temperature argillitic and propylitic alteration elsewhere in the alkaline intrusive complex.

The hyperspectral mapping also defined a locality *c.* 1 × 1.5 km in size immediately south of Werner Bjerge, which displays many spectral similarities to Malmbjerg. The accessible part of this anomaly at 1300 m was found to host a significant number of pyrite- and fluorite-bearing trachytic

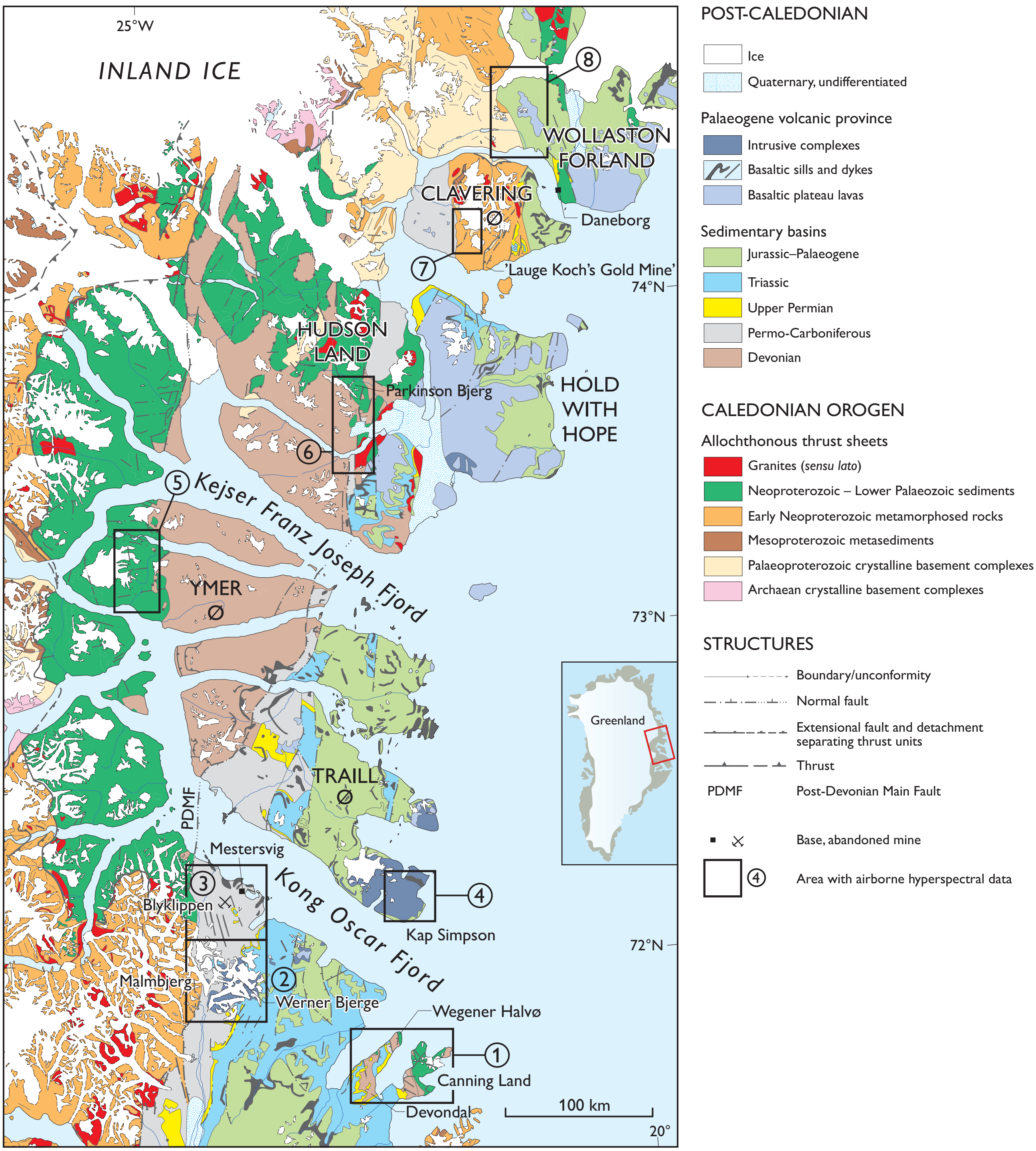

Fig. 1. Geological map of North-East Greenland showing areas covered by airborne hyperspectral data. The numbers refer to the areas discussed in the text. Modified from Henriksen & Higgins (2008).

dykes and sheets a few metres thick in Permo-Carboniferous sandstone. The intrusive trachytic rocks host abundant wall-rock fragments and are highly enriched in potassium and show elevated concentrations of tungsten (max. 35 ppm), molybdenum (max. 21 ppm) and thorium (max. 226 ppm). These rocks may represent the top of a porphyry system with an unexposed granite at a lower level.

Area 3 – Mestersvig. The Permo-Carboniferous sandstones of this area host epithermal lead–zinc-bearing quartz veins, including the mined-out Blyklippen deposit. The min-

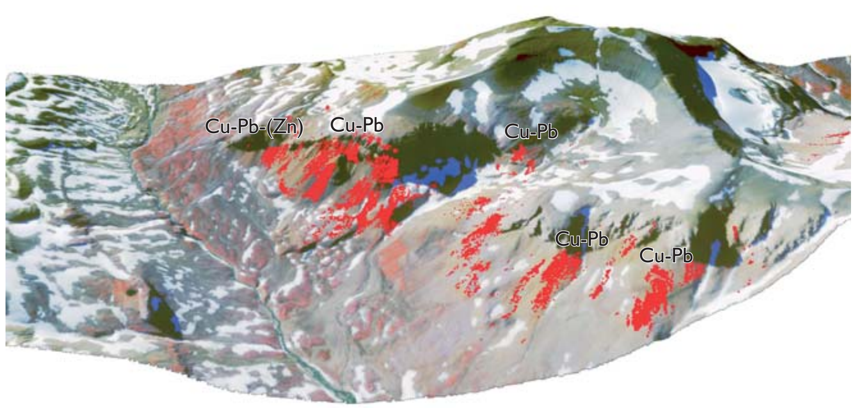

Fig. 2. Perspective view from the south-east of the north slope of Devondal showing dolomitic alteration (red) of Upper Permian limestone. The scree aprons enhance the surface impression of dolomite. Known occurrences of Cu-Pb-(Zn) mineralisation are indicated. Background image is a colour composite of HyMap bands 27(R), 18(G) and 4(B). No vertical exaggeration, relief is 600 m.

eralisation is accompanied by silicification and kaolinisation of the wall rocks, but this association did not clearly define the veins in the airborne survey. However, the airborne data reveal a distinct, *c.* 500 m wide zone of pervasive kaolinisation of the arkosic sandstone some 3 km north-east of the old mine. This could be related to unknown base-metal mineralisation of the Blyklippen type.

Area 4 – Kap Simpson. The Palaeogene Kap Simpson alkaline intrusive complex hosts a caldera structure displaying widespread and intensive hydrothermal alteration. Pyrite is common and traces of molybdenite are known, with base-metal and niobium-bearing quartz and calcite veins in the host Mesozoic sediments. The hyperspectral survey distinguished between low-temperature, fumarole-related alteration (montmorillonite-illite-jarosite and iron oxides) and high-temperature alteration (muscovite-phengite) associated with subvolcanic intrusions. High-temperature potassic alteration and greisen-like spectral signatures on a granite in the north-western part of the intrusive complex define a new exploration target with potential for porphyry-type mineralisation.

Area 5 – Ymer Ø. Ymer Ø hosts a number of E–W-striking, epithermal tungsten, antimony, gold, base-metal-bearing quartz veins in Neoproterozoic sediments. Samples from the antimonite-bearing veins returned up to 23.4% Sb and 4.7 ppm Au. These veins give a weak hyperspectral response, due to the presence of low-temperature argillitic minerals (kaolinite, illite and alunite) in the quartzitic wall rock. However, known scheelite-antimonite-bearing veins are not detected by the hyperspectral survey. This is due to lack of distinct alteration minerals other than quartz in the carbonate wall rock. Distinct linear anomalies detected in the airborne data turned out to originate from 3–5 m thick, E–W-striking, unmineralised rhyolitic veins with kaolinite alteration or weathering products, probably related to the mineralising system.

Area 6 – Hudson Land. Central Hudson Land exhibits various types of mineralisation in a complex pattern of Proterozoic to Palaeogene rocks transsected by a regional, N–S-trending structure, called the Post-Devonian Main Fault. Quartz veins 0.1–1.0 m thick with greisen mineralisation returned up to 1.4% Sn and 0.5% Cu but were not depicted in the airborne data due to their modest size. In contrast, extensive, low-temperature, hydrothermal alteration with associated epithermal base- and noble-metal-bearing veins along the Post-Devonian Main Fault is clearly seen in the hyperspectral data.

Special attention was paid to a Devonian granite stock at Parkinson Bjerg, which is surrounded by geochemical Sn-W-Mo-Nb anomalies. The granite was found to have a pegmatitic core rich in quartz, fluorite and tourmaline, corresponding to a distinct tourmaline and phengite response in the airborne data. This granite is a potential source for the geochemical anomalies. Rock samples returned up to 0.4% Sn, 0.17% Be and 0.1% Y.

Area 7 – Clavering Ø. Extensive rust zones caused by hydrothermal alteration and epithermal base-metal mineralisation along faults occur in Proterozoic metasediments on Clavering Ø. The mineralisation was investigated in the 1930s when a test adit was excavated at the so-called 'Lauge Koch's Gold Mine', which transpired to host a pyrite vein without anomalous gold. The mineralised structures are distinct in the hyperspectral mapping as lineaments with low-temperature alteration minerals such as illite and jarosite. Samples of massive, brecciated pyrite 'ore' with minor fluorite and galena returned <2 ppb Au.

Area 8 – Wollaston Forland. Prior to 2000, no mineralisation had been reported from Wollaston Forland, and the area was included in the airborne survey for biological reasons. The survey showed hyperspectral anomalies caused by jarosite- and muscovite/sericite-rich zones or lithologies in the north-western part of the area, which is underlain by Proterozoic metasedimentary rocks. A scree sample of pyritiferous paragneiss below an anomaly returned 4.1 ppm Ir while another loose block returned 0.38 ppm Au. Surrounding blocks of ultramafic rocks indicate a magmatic component in the area with potential for platinum group mineralisation.

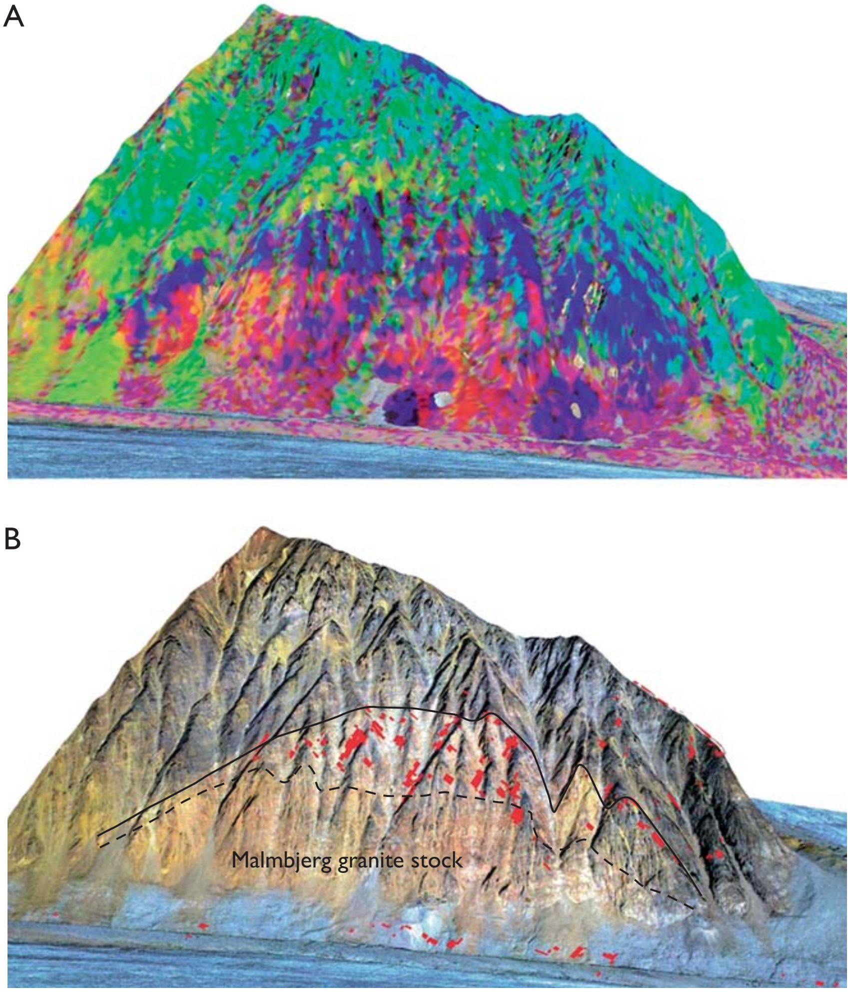

Fig. 3. Perspective view from the south-west of the Malmbjerg granite stock, no vertical exaggeration, relief is 500 m. The digital terrain model is based on Lidar data from International Molybdenum Ltd. (re-sampled at 1 × 1 m resolution). **A**: Minimum noise fraction transformed shortwave infrared data draped on the detailed Digital Terrain Model. Note the compositional zoning of the granite stock and intensive high-temperature alteration of the roofing rocks (hues of yellow and orange). **B**: Orthoscopic Lidar image draped on the detailed Digital Terrain Model. The pixels mapped as topaz/tourmaline-bearing greisen are shown in red. The boundaries of the granite stock are indicated.

Concluding remarks

The present study demonstrates that the hyperspectral method is well suited for mineral exploration in remote and mountainous Arctic regions. The most obvious target for future use of this method in Greenland seems to be the Palaeogene igneous province that stretches for 1100 km along the east coast. This province should be investigated for host- and wall-rock alteration indicative of subvolcanic porphyry-type molybdenum mineralisation.

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