Detection of kimberlitic rocks in West Greenland using airborne hyperspectral data: the *HyperGreen 2002* project

Tapani Tukiainen and Leif Thorning

Previous investigations by the Geological Survey of Denmark and Greenland (GEUS) and exploration companies have demonstrated that some of the kimberlites in West Greenland are diamond bearing, making the region an important target for diamond prospecting.

High-resolution hyperspectral (HS) remote sensing data have been successfully used for the location of kimberlitic rocks, e.g. in Australia and Africa. However, its potential as a viable method for the mapping of kimberlite occurrences in Arctic glaciated terrain with high relief was previously unknown. In July–August 2002, GEUS conducted an airborne hyperspectral survey in central West Greenland (Fig. 1) using the commercially available HyMap hyperspectral scanner operated by HyVista Corporation, Australia. Data were processed in 2003, and in 2004 follow-up field work was carried out in the Kangerlussuaq region to test possible kimberlites indicated by the HS data (Fig. 1). The project was financed by the Bureau of Minerals and Petroleum, Government of Greenland.

Hyperspectral data and field work

The HyMap airborne hyperspectral scanner (Cocks *et al.* 1998), developed by Integrated Spectronics, Sydney, Australia, delivers high accuracy, calibrated radiance data over 126 channels covering the wavelength range between 400 and 2500 nm with 15–20 nm bandwidth. The HyMap system also generates the flight line ephemeris data (X, Y, Z and aircraft attitude data) utilising its satellite navigation system (DGPS) and integrated Inertial Monitoring Unit (IMU). These data are necessary for georectification and advanced processing of the HS image data.

The survey area in central West Greenland was flown with the following specifications:

Data coverage	7500 km^2
Number of lines	54
Line kilometres	3500
Nominal pixel size	4 metres
Overlap per line	20%
Approximate ground speed	140 knots (280 km/h)

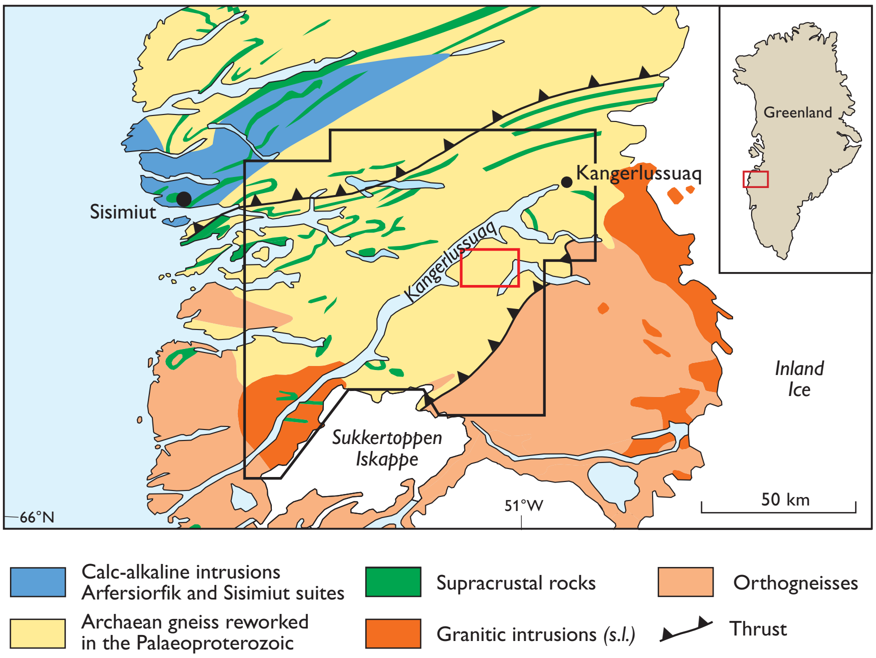


Fig. 1. Simplified geological map of the study region in West Greenland. The coverage of the *HyperGreen 2002* survey is indicated by the **black frame**. The **red frame** outlines the map area of Fig. 3.

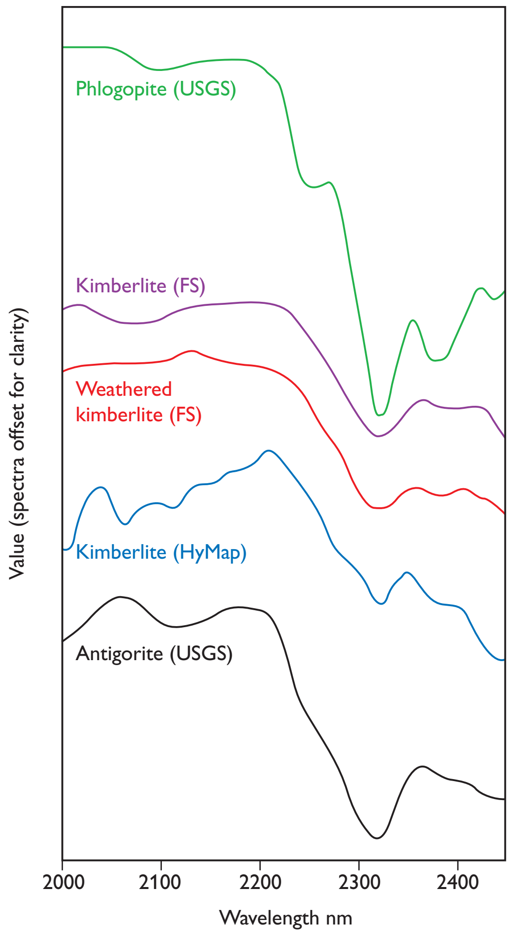


Fig. 2. Comparison of laboratory mineral spectra (USGS, Clark *et al.* 1993) to the kimberlite spectra measured by field instruments (**FS**) and airborne hyperspectral scanner (**HyMap**, locality K12 in Figs 3, 4). The field instrument covers the range 0.4–2.5 µm at a higher spectral resolution. Note that HyMap, though lower resolution, resolves the key spectral features near 2.3 µm. The spectral features in HyMap and field spectra of kimberlite near 2.3 µm are distinctly subdued when compared to the laboratory spectra of phlogopite and antigorite. This is probably due to the fact that the kimberlite spectrum is a linear mixture of all materials occurring within the HyMap pixel.

At the same time, a field programme was carried out to measure a number of spectra from selected kimberlite occurrences to establish the spectral characteristics of the kimberlitic rocks and their erosion products in West Greenland (Tukiainen *et al.* 2003).

Spectral basis for the mapping of kimberlitic rocks

Kimberlites consist of predominantly ultramafic material that has crystallised *in situ*, and commonly host megacrysts formed in the upper mantle from the kimberlite magma and mantle derived xenoliths (dunite, lherzolite, wehrlite, harzburgite, eclogite and granulite) incorporated during magma transport. Common matrix minerals are olivine, phlogopite, perovskite, spinel, chromite, diopside, monticellite, apatite, calcite and Fe-rich serpentine.

The most interesting minerals with respect to hyperspectral mapping are phlogopite, Fe-rich serpentine (antigorite) and calcite; these minerals have characteristic spectral responses in the Short Wave Infrared (SWIR) spectral region (2.0–2.5 µm).

Comparison of the HyMap spectrum of kimberlite to the spectra measured with a field instrument at the same locality demonstrates a close match (Fig. 2).

HyMap data analysis
Atmospheric correction

To fully exploit the possibilities of hyperspectral image data delivered 'at sensor radiance data', they must be converted to surface reflectance data. The small size of potential targets and the relatively subtle spectral characteristics as established by the ground truth survey, demonstrated that the rugged terrain conditions of West Greenland require the use of atmospheric correction methods, which take sensor viewing geometry and terrain information into consideration. The conversion of the data to surface reflectance was done using the ATCOR-4 package (Richter & Schläpfer 2002). The photogrammetric laboratory at GEUS produced a detailed digital elevation model which was used as terrain information for the ATCOR-4 system.

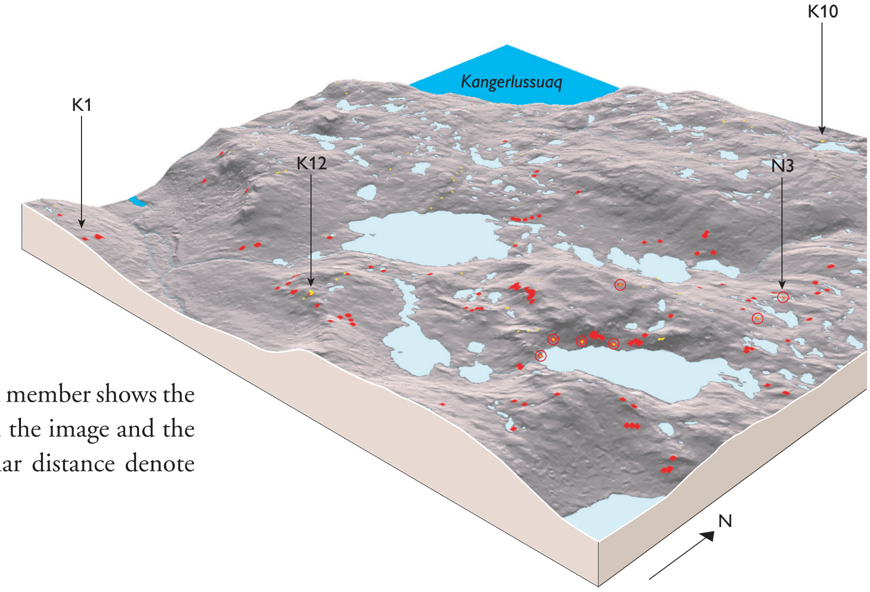
Spectral mapping

The field measurements have shown that the spectral response from kimberlitic rocks within wavelengths of 2.0–2.5 µm is remarkably uniform. Thus the simplest way to locate the kimberlitic rocks is to use selected characteristic kimberlite field spectra as end members for the spectral processing.

The Spectral Angle Mapper (SAM, Kruse *et al.* 1993) was used in this project for comparing the HS image spectra to selected, characteristic kimberlite field spectra. The algorithm determines the similarity between two spectra by calculating the 'spectral angle' between them, treating them as vectors in space with dimensionality equal to the number of bands. The method is not sensitive to the unknown gain factor and all possible illuminations are treated equally. This is an important advantage when processing data acquired in the *HyperGreen 2002* project, where illumination levels vary between the flight routes and even within a single flight line.

The SAM algorithm calculates the angular distance (in radians) between each spectrum in the image and the refer-

Fig. 3. Results from the kimberlite mapping from an area covering a part of the surveyed area (location indicated in Fig. 1). Known and discovered kimberlite occurrences (*in situ* occurrences and boulder floats) are shown on the map; those detected by hyperspectral mapping are shown with **circles**.



ence spectra. The 'rule' image for each end member shows the actual distance between each spectrum in the image and the reference spectrum. Low values of angular distance denote high similarities between the spectra.

Mapping results

A subset of the area to which the HS mapping was applied in 2003 (Tukiainen & Krebs 2004) is here used to illustrate the use of HS data for the mapping of kimberlite occurrences (Fig. 3). The area was chosen because reliable field follow-up information is available. The largest known exposed kimberlite occurrence (locality K12; Figs 3, 4) where the exposure correspond to 4–5 HyMap image pixels, was readily detected by the SAM method, even when mapping is based only on the phlogopite mineral spectra measured in laboratory conditions. The limited field follow-up resulted in discovery of a number of kimberlite exposures and boulder floats. The newly discovered kimberlite occurrences are typically small, outcrops rarely exceeding the nominal pixel size of 4 × 4 m (Fig. 4).

Known limitations of the method and sources of error and misclassifications

The HyMap hyperspectral scanner is an optical sensor and can only detect targets which are visible. Illumination conditions caused by a combination of high and complex topography imply that parts of the terrain are in shadow where the poor signal/noise ratio camouflages the subtle spectral features.

The high atmospheric water vapour content, typically above and adjacent to major fjords and nearby valleys, suppress the signal from the short-wave infrared part of the spectrum thereby increasing the noise level of the image data. Extreme illumination conditions (areas adjacent to snow/ice and bright surfaces) and complex, steep topography may also create image-processing artefacts.

The applied HS mapping strategy is based on detection of the minerals phlogopite, serpentine and calcite when these are present as rock forming minerals. These minerals, or combinations of them, also commonly occur in rock types other than kimberlite (ultramafic rocks, and various carbonate rocks, carbonate-veined shear zones, altered and weathered mafic and ultramafic rocks). The field follow-up in 2004 showed that the most common source of error was caused by weathered and altered exposures of Kangâmiut dykes, which are the most common mafic rocks in the survey area. The spectral characteristics of the Kangâmiut dyke rocks were studied in more detail in 2004, and the processing scheme was hereafter adjusted to better distinguish them from kimberlite outcrops.

Conclusion

The airborne hyperspectral data acquired by the HyMap hyperspectral sensor are capable of detecting kimberlite occurrences in West Greenland when the exposed surface of kimberlite outcrops and/or the weathering products approaches or exceeds the image pixel size (4–5 m). The sometimes unfavourable terrain and illumination conditions may, however, seriously affect the detection success rate. The success rate for detecting rocks with phlogopite, serpentine and carbonates as main constituents is good, although distinction between rock types is more problematic.

The rugged terrain conditions of West Greenland and the small size of the potential targets, typically corresponding to less than one or a few image pixels, and the relatively subtle spectral characteristics near 2.3 μm in the SWIR spectrum, require the use of atmospheric correction methods which take the sensor viewing geometry and terrain information into consideration.

Fig. 4. Kimberlite outcrop localities K1, K10, K12 and N3 indicated in Fig. 3. **A**: Strongly weathered kimberlite (K1). **B**: Typical small exposure and weathered material (K10). **C**: Hanging wall of a kimberlite (**k**) dyke (N3). **D**: Largest known exposure of kimberlite in West Greenland (**outlined in red**), measuring 30 × 5 m (K12).

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Authors' address

Geological Survey of Denmark and Greenland, Øster Voldgade 10, DK-1350 Copenhagen K, Denmark. E-mail: *tt@geus.dk*