DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2006/68

Mapping of kimberlitic rocks in central West Greenland using airborne hyperspectral data

Tapani Tukiainen

(1 DVD included)

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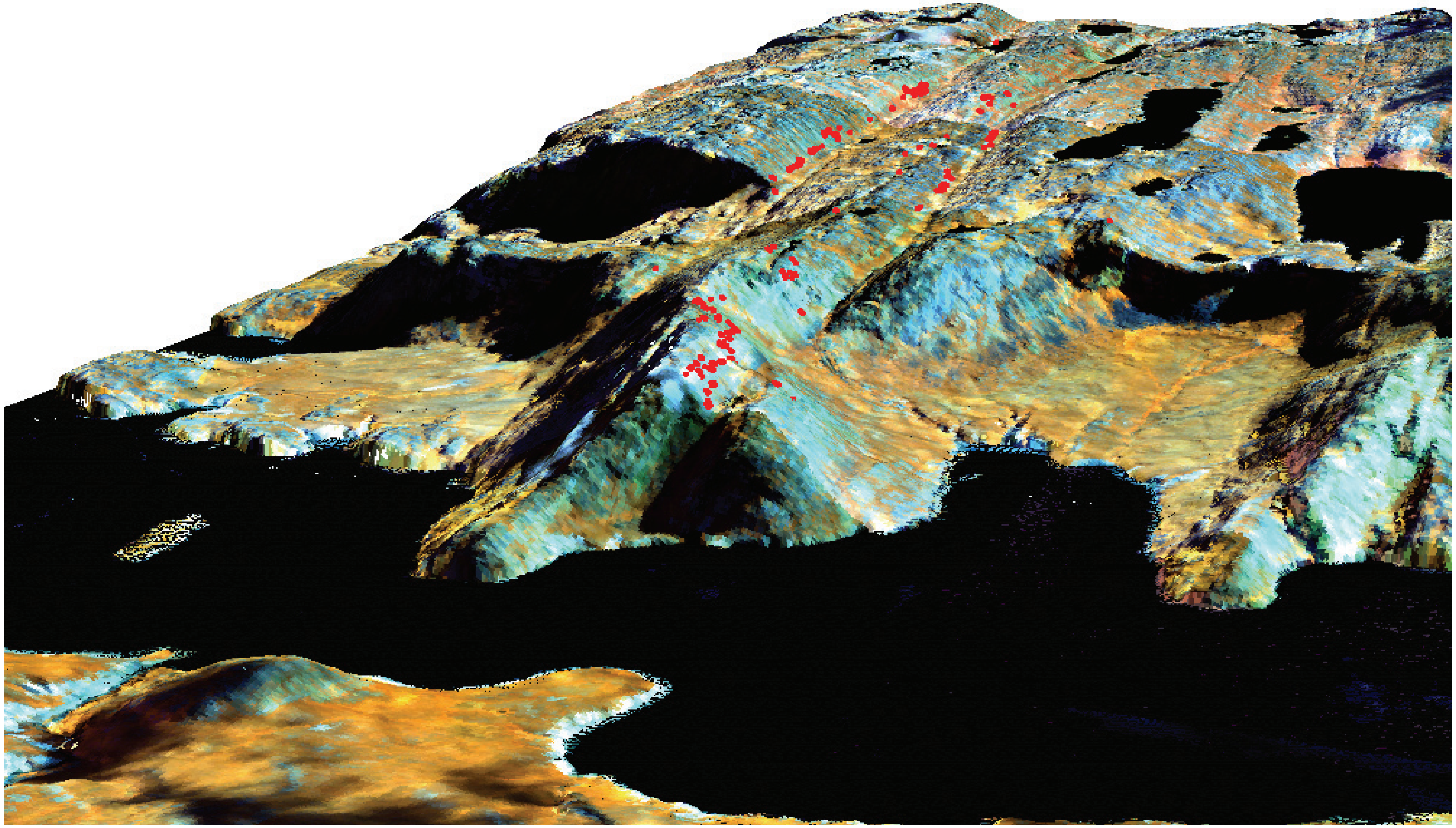


Frontispiece. Ikertôq thrust zone at the north end of Ikertôq Fiord seen from the northwest. Note the concentration of the pixels with kimberlitic character (red dots) along the thrust zone. Perspective view of HyMap colour composite R (band 28), G (18) and B (band 2) draped on the digital terrain model. Hues of brown = vegetation, grey; and blue = exposed rocks.

Contents

Abstract

A high resolution (5 x 5 metre nominal pixel size) airborne hyperspectral survey was conducted in central West Greenland in 2002 covering approximately 7500 km^2. The investigated area hosts a number of diamond-bearing kimberlite bodies, which has made the region an important target for diamond prospecting. The survey was done using a commercial hyperspectral imaging spectrometer covering the spectral range from 0.45 to 2.5 μm as 126 bands with bandwidths varying from 15 to 18 nanometers. Mapping of the kimberlitic rocks - the primary goal of the survey was based on the detection of the Fe-rich serpentine, phlogopite, talc and carbonate minerals utilising their characteristic absorption features in the short -wave infrared spectral region (2.0–2.5 μm).

Based on available detailed digital elevation model, radiance data from the survey area were pre-processed and new surface reflectance data were generated using advanced atmospheric and geometric correction software. The new reflectance data correlate well with spectral ground truth and the SAM (spectral angle mapper) method was applied to the data for the production of kimberlite prediction maps. The field evidence from selected areas shows that kimberlite occurrences with an exposed surface greater than c. 75% of the nominal pixel size (8-10 m^2) are likely to be detected by the hyperspectral survey. The illumination conditions have locally a drastic effect on the signal/noise characteristics of the HS data and the detection of kimberlitic targets.

Apart from locating a number of known kimberlite occurrences, the spectral mapping generated a numerous potential targets as 5619 pixels with kimberlitic character for the field follow up.

Introduction

Background and objectives

In July–August 2002, the Geological Survey of Denmark and Greenland (GEUS) conducted an airborne hyperspectral survey in central West Greenland, Project HyperGreen 2002. The Bureau of Minerals and Petroleum, Government of Greenland financed part of the project. Previous investigations by GEUS and exploration companies demonstrated that some of the kimberlites in central West Greenland are diamond bearing, which has made the region an important target for commercial prospecting. The prime objective of the airborne HS survey, was to assist in the mapping of the kimberlite occurrences and at the same time examine how well the hyperspectral method works under the arctic, high relief conditions of West Greenland. The activities were based at Kangerlussuaq International Science Support (KISS) facilities at Kangerlussuaq airport.

HyVista Corporation, Australia was selected as the contractor for the airborne operation using the company's HyMap hyperspectral (HS) scanner, manufactured by integrated Spectronics Pty, Ltd, Australia.

The airborne hyperspectral survey commenced on the 23rd of July and continued until 9th of August 2002. Simultaneously, 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 in West Greenland, and their erosional products. The results of this activity are described by Tukiainen *et al*. (2003).

The general description of the hyperspectral data acquisition and data processing was presented by Tukiainen & Krebs (2004) who also presented and discussed the results of the kimberlite mapping from an area south of Kangerlussuaq fiord (Figure 1). A limited field follow-up programme on the mapping results of Tukiainen & Krebs (2004) was carried out in July 2004.

The scope of this report is to present and discuss the results of the kimberlite mapping from the entire area of the HS survey, which is covered by new detailed digital elevation data (Figure 1). The results of the 2004 field follow-up programme are summarised and their impact on the continued HS-mapping of kimberlite is discussed.

The survey area (Figure 2) consists predominantly of tonalitic to granitic orthogneisses in granulite facies or retrogressed from granulite facies (2870 to 2780 Ma, Kalsbeek & Nutman 1996; Connelly & Mengel 2000). A Palaeoproterozoic dolerite dyke swarm, the Kangâmiut dykes, intruded the basement c. 2040 Ma ago (Nutman *et al.* 1999). The deformation of the Kangâmiut dyke swarm defines the Nagssugtoqidian front, which marks the southern limit of Nagssugtoqidian penetrative deformation (Escher *et al.* 1970).

The Kangerlussuaq area hosts an alkaline province comprising the 600 Ma old Sarfartoq carbonatite complex (Secher & Larsen 1980) together with a swarm of contemporaneous dykes described as kimberlites and lamproites (Larsen 1991). An older generation (c. 1200

Ma) of lamproites is clustered near Sisimiut. Diamonds are found in several of the kimberlite dykes (Jensen *et al.* 2003).

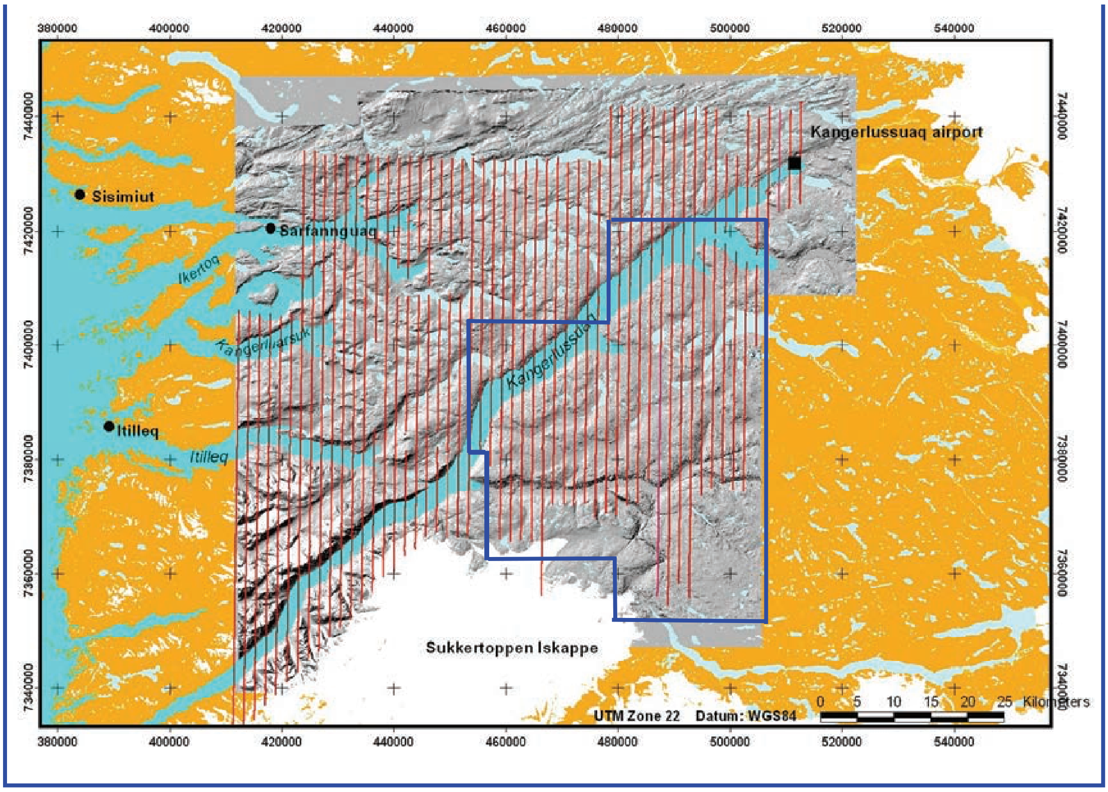


Figure 1. *Coverage of the airborne hyperspectral survey flown in 2002 with flight lines shown in red. The area described in this report is depicted by the shaded topographic relief. The area described by Tukiainen & Krebs (2004) is marked by the blue frame.*

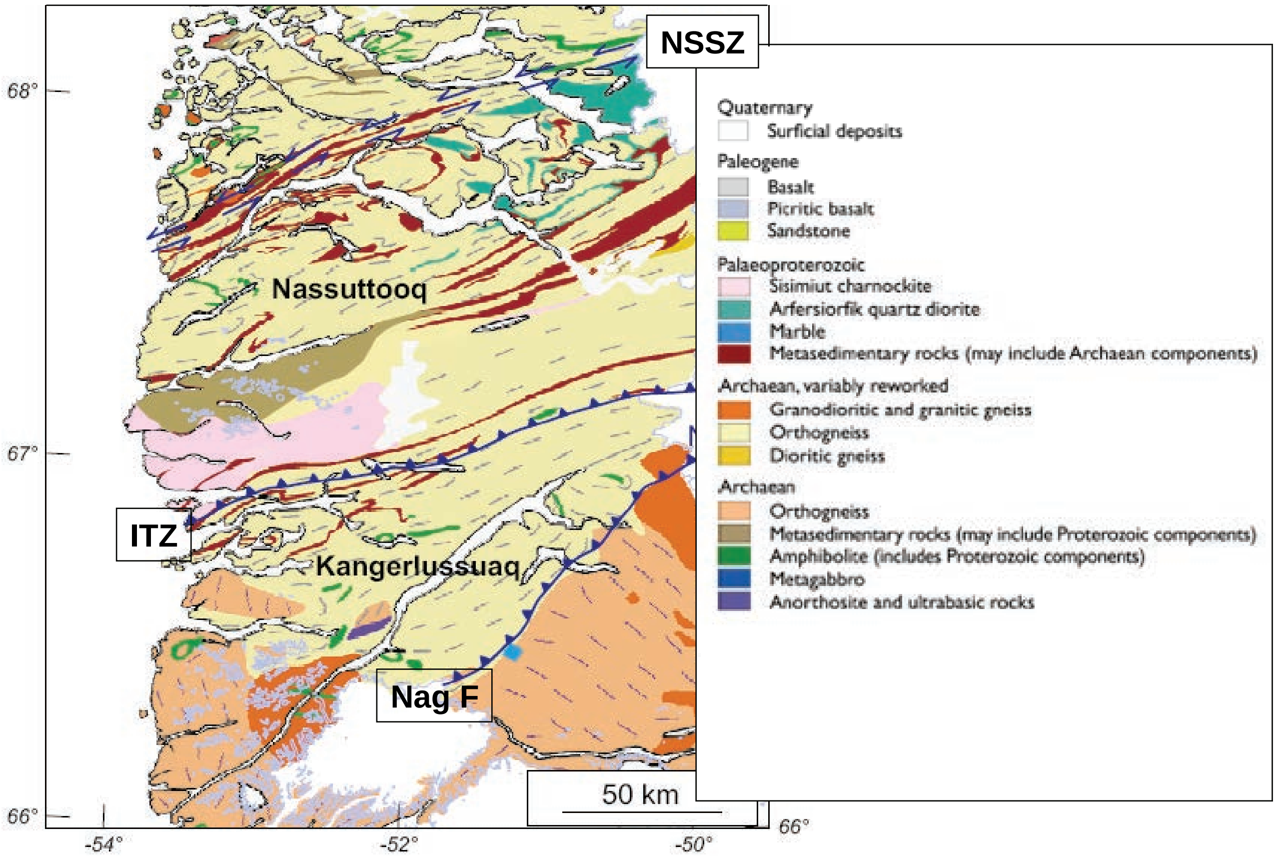


Figure 2. *Main geological features of central West Greenlan based on Escher & Pulvertaft (1995). ITZ: Ikertôq thrust zone. Nag F: Nagssugtoqidian front. NSSZ: Nordre Strømfjord shear zone.*

Acquisition of hyperspectral data

The airborne system

The project HyperGreen utilised an aircraft-mounted commercial HyMap hyperspectral sensor developed by Integrated Spectronics, Sydney, Australia and operated by HyVista Corporation, Sydney, Australia (Cocks *et al.* 1998). The HyMap system is a whiskbroom scanner utilising diffraction gratings and four 32-element detector arrays (1 Si, 3 liquid-nitrogen cooled InSb) to provide 126 spectral channels covering the 0.45–2.5 μm range over 512-pixel swath.

The HyMap system also generates the flight line ephemeris data (X, Y, Z and aircraft attitude data) utilising its DGPS and Integrated Inertial Monitoring Unit (IMU). These data are necessary for georectification of the hyperspectral image data.

The HyMap scanner used for the HyperGreen 2002 data acquisition was installed on a Piper Navajo Chieftain aircraft from Provincial Airways Limited, Halifax, Canada.

Survey parameters

The survey area was flown with the following survey specifications:

- IFOV (m) ('pixel size'): 5 metres
- Overlap per line (%): 20
- Approximate ground speed: 140 knots (277 km/h)

For the HyMap instrument the IFOV of 5 metres corresponds to the flight altitude of 2500 metres (8200 feet) at which the scanner's swath width is approximately three kilometres. For the mountainous areas, the flight altitude was determined from the local topographic base level taken as the approximate mean altitude of major valleys or the mean altitude of hilly/mountainous terrain. For a rugged terrain such as the HyperGreen 2002 project area, the true pixel size is variable from 5 metres down to less than 3 metres depending on the altitude of the surveyed ground.

Survey operations

The contractor (HyVista) and the survey aircraft arrived at Kangerlugssuaq on the 22nd of July 2002. Due to exceptionally bad weather conditions, data acquisition was only possible on 5 of the 14 days the system was available in Greenland.

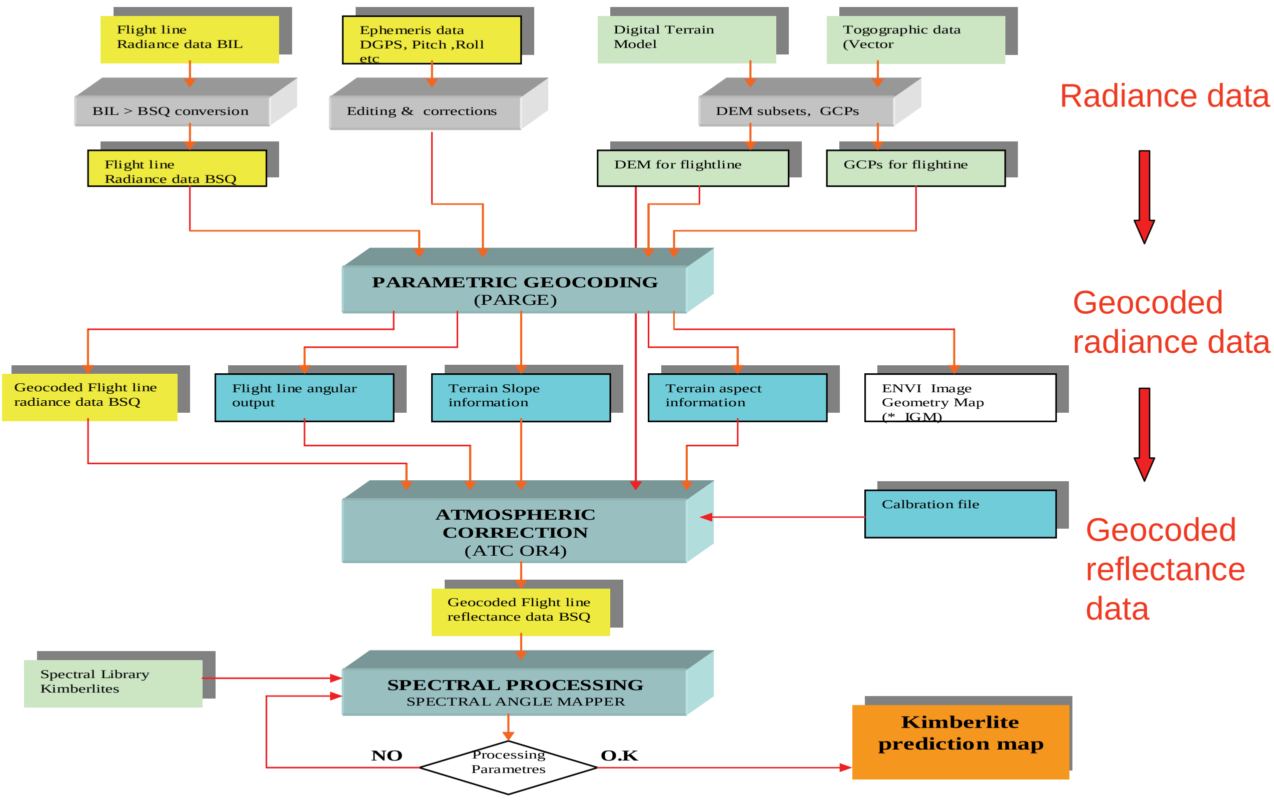


Figure 3. *Processing scheme for the hyperspectral image scanner data.*

The HyperGreen 2002 survey operation resulted in approximately 3500 line kilometres of data acquisition recorded along 54 flight lines. The survey covered approximately 7500 km^2.

The data coverage is reasonably continuous with few gaps. Because of the less than optimal flight pattern forced upon the operator by the bad weather, the data consist of ten partially overlapping subsets. The highly variable cloud cover did not allow large contiguous areas to be covered. By combining the overlapping subsets, the cloud cover can be reduced to less than 5% of the surveyed area. Cloud cover has the most severe impact on the image quality along Sarfartoq valley.

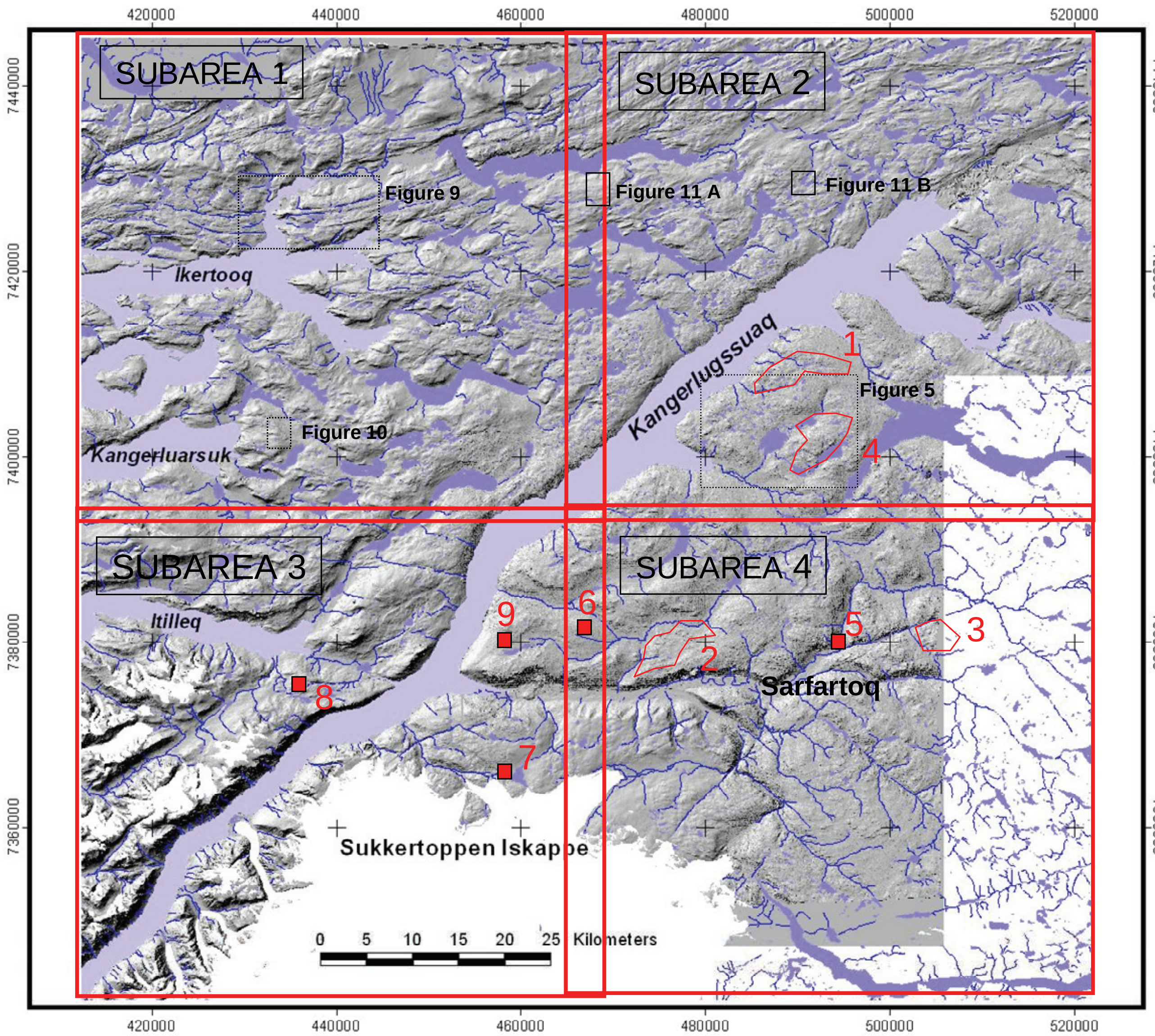


Figure 4. *Index map showing 4 subareas and the location of 5 figures shown in this report. Areas of follow-up investigations in 2004 are outlined with red, 1-9.*

Processing of hyperspectral data

Processing of the HyperGreen 2002 data was done at GEUS using ENVI image analysis software and some Fortran-based routines for more complex editing and subsetting of the flight-line ephemeris data. Pre-processing of the HS data was affected by a number of complications, many of which are related to the unfavourable weather conditions during the survey flights. The processing complications, and the research and development effort to establish the optimal conversion of the radiance data to surface reflectance, are described in detail in Tukiainen & Krebs (2004).

The conversion of the radiance data to surface reflectance was done using the ATCOR-4 – package (Richter & Schläpfer, 2002). A necessary prerequisite for the use of parametric geocoding software PARGE and ATCOR-4 in rugged terrain is a detailed digital elevation model. This was produced at the GEUS photogrammetric laboratory for the entire survey area.

The processing steps to convert the “at sensor” radiance data to surface reflectance are illustrated in Figure 3.

Mapping of kimberlitic rocks

Follow-up field work, 2004

The kimberlite mapping by Tukiainen & Krebs (2004) of an area between Sarfartoq and Kangerlussuaq fjord resulted in 3711 pixels with kimberlitic character.

The mapping was based on the Spectral Angle Mapper (SAM) (Kruse *et al.* 1993). This algorithm compares the image spectra to the selected, characteristic kimberlite field spectra or mineral 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 spectral interval from 1.988 μm to 2.453 μm corresponding to the HyMap bands 97–124 were used in the SAM classification. The average kimberlite ground spectra from well-determined sites were used as reference spectra.

The field work was carried out from 4 field camps (Figure 4), one of which is outside the HS survey area. Helicopter-based reconnaissance was done in 5 localities. The work from field camps comprised traverses where as many kimberlitic HS-indications were visited as possible within the radius of c. 10 km from the camps. Apart from the routine sampling of the kimberlitic rocks, field spectroradiometric measurements of the outcrops and samples were done using the PIMA SP short wave infrared reflectance spectrometer (wavelength interval 1300-2500 nm).

The results of the field work are summarised as follows:

Field area 1:

Localities visited: 74

Results: Majority of the targets are weathered Kangamiut dykes; 2 targets with concentrations of kimberlite boulders and their weathering products in overburden/soil

Field area 2:

Localities visited: 42

Results: Weathered Kangamiut dykes and mafic-ultramafic supracrustal rocks

Field area 3:

Localities visited: None, since this field area outside the HS-survey area

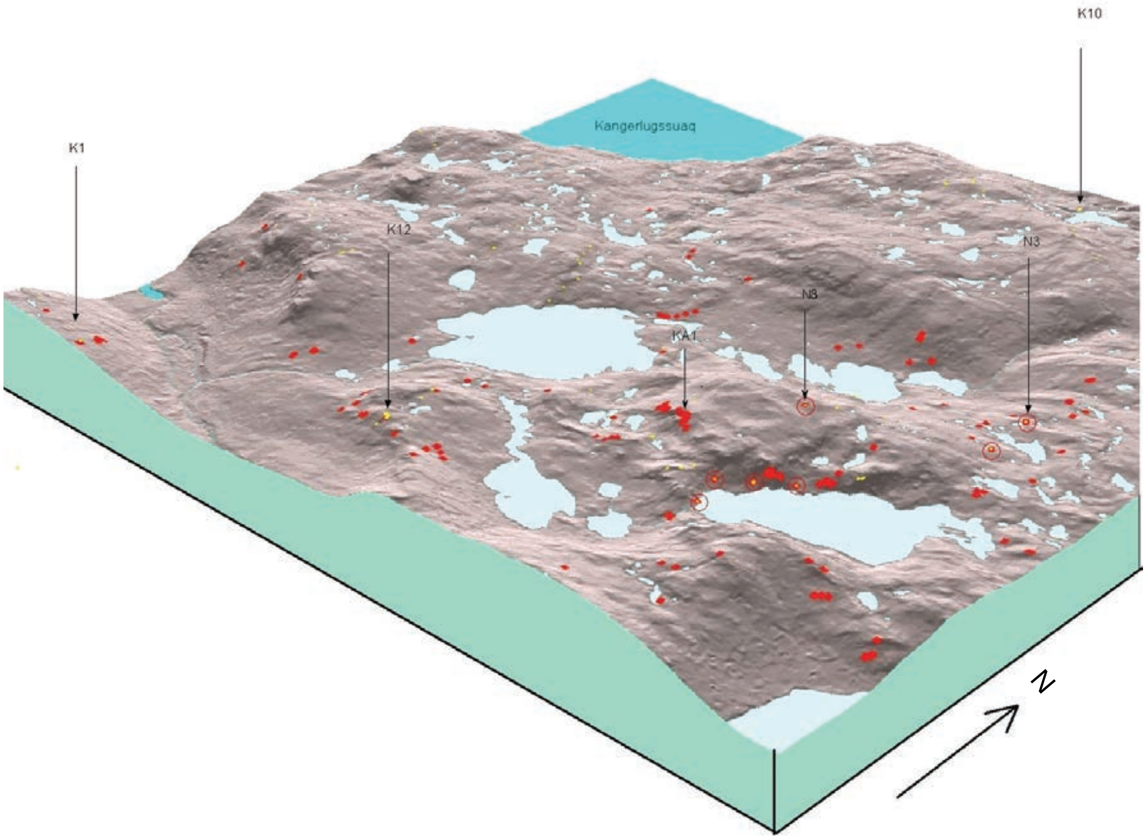


Figure 5. *Perspective view of the area containing the 4 field subareas located in Figure 4. Red dots: targets detected by the SAM mapping Yellow dots: kimberlite occurrences, with those discovered by the HS survey encircled in red.*

Field area 4:

Localities visited: 92

Results: 52 targets are related to the weathered Kangamiut dykes, 18 targets to the mafic–ultramafic supracrustal rocks, 2 targets to the weathering products of kimberlite in overburden and 6 targets to kimberlite. The rest of the targets relate to soil/overburden without visible kimberlite indications

Helicopter reconnaissance 5:

Localities visited: 7

Results: 4 targets are related to weathered Kangamiut dykes; 3 targets carbonate (= carbonatite ?) rich breccias

Helicopter reconnaissance 6:

Localities visited: 3

Results: Altered mafic-ultramafic supracrustal rocks

Helicopter reconnaissance 7:

Localities visited: 2

Results: Kimberlitic boulders and their weathering products in overburden

Helicopter reconnaissance 8:

Localities visited: 1

Results: Weathered Kangamiut dyke

Helicopter reconnaissance 9:

Localities visited: 1

Results: Loose blocks of kimberlite and weathering products in overburden

Approximately 230 localities (0.09% of the kimberlite targets of the HS mapping by Tukiainen & Krebs (2004)) were visited during the field work up and 6 new kimberlite outcrops/block fields were discovered. In addition to the exposures of kimberlite the HS-based mapping pinpointed 6 localities with abundant kimberlite blocks and their weathering products in overburden. Often these localities are characterised by light greenish colour of the loose material. The majority of the discovered kimberlite occurrences are situated in field area 4 (Figures 4 & 5). The characteristic exposures of kimberlite and kimberlite-rich material from this area are shown in Figure 5. The newly discovered occurrences of kimberlite and kimberlite-enriched overburden are characterised by the fact that the size of the exposure is no more than approximately 9–10 square metres. As the nominal pixels size is 5 x 5 metres, it is implied that targets bigger that c. 75% of the nominal pixels size may be detected by the HS mapping.

The results of the field work revealed that a majority of the HS kimberlitic indications were more intensively weathered surfaces of deformed Kangamiut dykes (Figure 7). In order to establish the spectral features of these rocks in more detail, field spectroradiometric measurements of the representative weathered surfaces of Kangamiut dyke rocks and the newly discovered kimberlite were carried out using the PIMA SP spectoradiometer.

The field work also revealed a number of localities where the targets are mafic–ultramafic supracrustal (metavolcanic) rocks, often showing a variable degree of alteration (chlorite, epidotic, serpentine). These rocks are common in some areas.

Revised parameters for the spectral mapping of kimberlitic rocks

The measured representative SWIR spectra from the kimberlitic rocks discovered in 2004 (attached as spectral library in APPENDIX 1) compared with the earlier measurements from other field instruments and the HyMap HS scanner are shown in Figure 8. The SWIR spectrum of the central West Greenland kimberlites clearly reflects the mixture of antigorite, serpentine, phlogopite and carbonate minerals with the characteristic stronger absorption feature at 2.32 mμ. A less distinct absorption feature at 2.38 mμ is present from measurement of kimberlites more enriched in talc and/or phlogopite.

The average SWIR spectrum of the rocks belonging to the Kangamiut dyke category is shown in Figure 8. The SWIR spectral characteristics of Kangamiut dyke rocks are dictated by the amphibole minerals as exemplified by the hornblende spectra in Figure 8. The absorption features in the SWIR region are at 2.34 and 2.42 mμ, respectively, and both features are of the same order of magnitude.

On the basis of the results from the field work in2004, parameters of the SAM mapping were adjusted to improve the discrimination between the kimberlitic rocks and the Kangamiut dyke rocks. The strategy of the improvement is to carefully take the differences in the absorption features at 2.34 and 2.42 mμ into consideration and also utilise the slight shift in spectral position of the absorption features for kimberlite and Kangamiut dyke rocks, respectively.

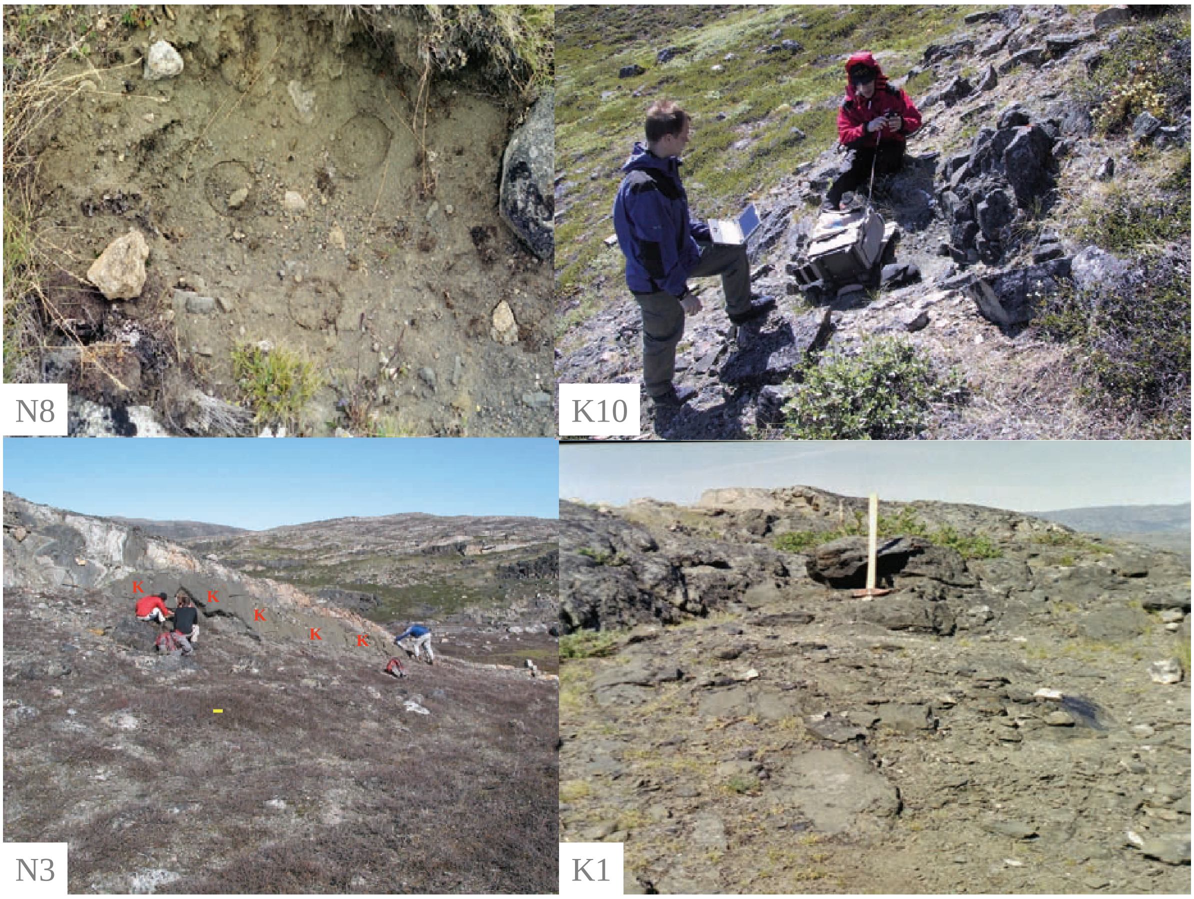


Figure 6. *Selected kimberlite occurrences detected by the SAM mapping (K1,N8 & N3). The exposure at K10 is too small to be detected by the present survey. The locations of the occurrences are shown in Figures 4 & 5. N3: K = kimberlite*

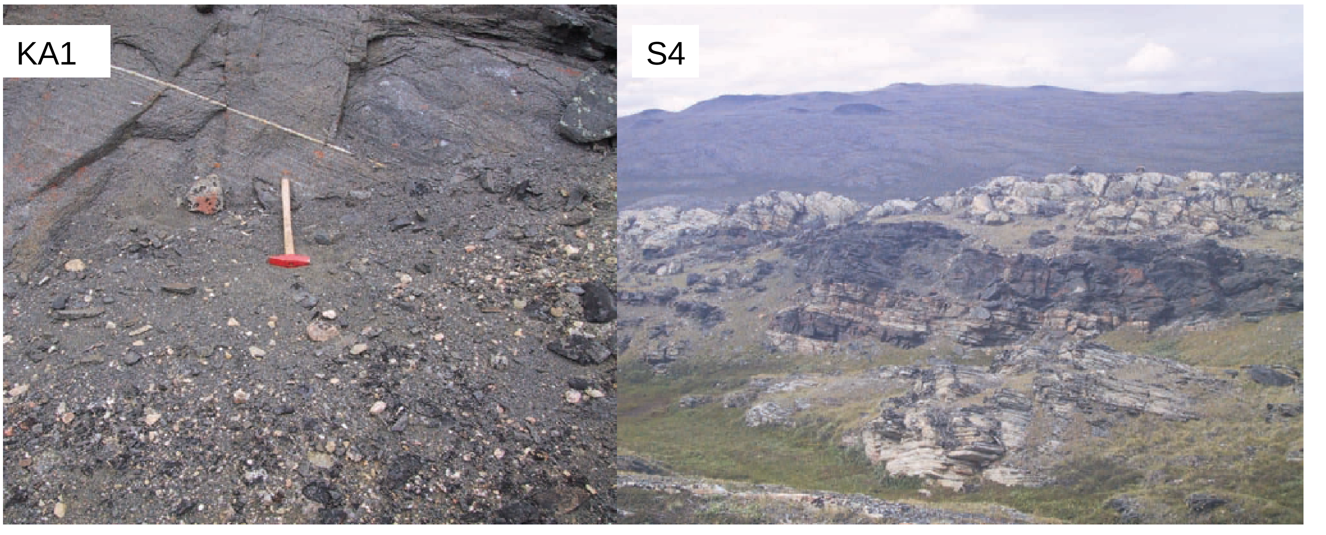


Figure 7. *"Misclassifications": The locations of the scenes are shown in Figure 5 KA1: Weathered surfaces and weathering products of Kangamiut dyke S4: Mafic–ultramafic supracrustal rocks*

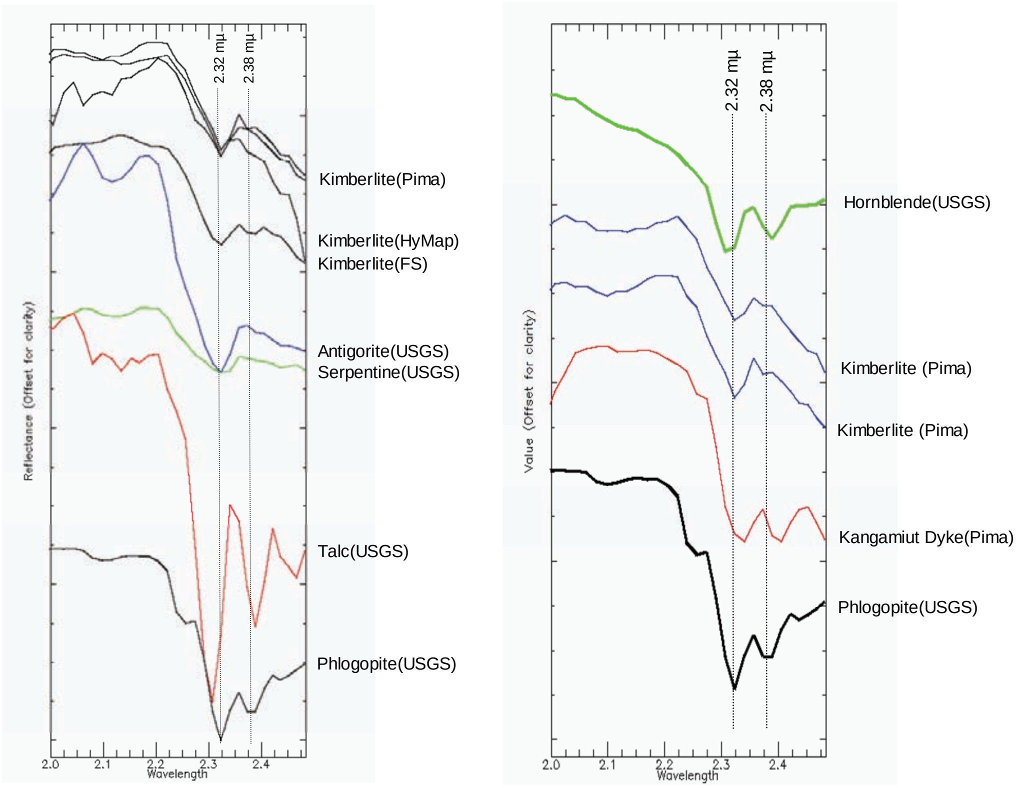


Figure 8. *SWIR spectra of kimberlitic rocks and rocks from Kangamiut dykes from West Greenland compared with selected minerals from the USGS spectral library (Clark et al. 1993). Measuring instruments:Pima = PiMa SP, FS = FieldSpec and HyMap = HyMap air-borne HS scanner*

Results

Presentation of results

The processed data cover 7400 square kilometres. The nominal 5 x 5 m spatial resolution of the survey data implies that the dimensions of an image covering the entire area in detail are 16000 x 22000 pixels. This makes it impractical to present the results as hardcopies. The majority of the kimberlite targets vary in size from one to a few pixels, which excludes the resampling of images to a coarser resolution. The 'kimberlitic signal' would in many cases be lost simply due to the filtering inherent in resampling.

In order to make the most effective use of the results, these are compiled as GIS-layers on the DVD enclosed with this report. Furthermore, to make the results available on more modest computing platforms, the GIS-layers are divided into four overlapping subareas as shown in Figure 4. For each subarea the following GIS-layers have been compiled and stored on the enclosed DVD (Appendix 1).

- Colour composite of HyMap bands 26 (R), 18(G) and 3 (B). Mosaic of HyMap flight strips. Format GeoTiff
- Classification results from Spectral Angle Mapper (SAM). Format ArcView shape file (pixels with kimberlitic spectral signature as point data)

Geocoding accuracy

The ephemeris data (combination of the IMU and DGPS) have been calculated for each scan line of the HS data. The parametric geocoding procedure generates an orthoscopic image utilising a digital elevation model (DEM) and the flight line ephemeris data.

The parametric geocoding of the HyperGreen 2002 data was done by using Parge software (Schläpfer 2003).

The accuracy of the geocoding is affected by the following factors:

- Accuracy and resolution of DEM
- Availability of accurate ground control points
- Atmospheric conditions during the survey flight
- Accuracy of the IMU instrument,

The IMU instrument used in the HyperGreen 2002 survey has proven very accurate in detecting the attitude of the aircraft. The instrument has been aligned to the N-S direction prior to every survey flight. During a flight the instrument may become increasingly offset from the original alignment, which must be corrected for in the parametric geocoding of the data. The magnitude of offset is calculated using suitable ground control points (GCP), which can be located in the raw image data (e.g. rivers, shorelines).

The vector data (coastlines, rivers) from the GEUS photogrammetric laboratory were used to create GCPs for the parametric geocoding. This data have been generated manually from 1:150 000 aerial photographs with frequent minor, although distinct, errors in displaying the shape of lakes and rivers.

The primary accuracy of the DEM used in this survey is 16 x 16 m, which inevitably generates a variable geolocation error when used for geocoding of 5 x 5 m resolution image data. The geocoded image in Figure 9 is a typical example of the registration of the GEUS topographic vector data on a parametrically geocoded HS image. The quality of registration is by no means poor. The overall geolocation accuracy is variable; in worst cases it appears to be within a few tens of metres.

Discussion of results

More than 99% of the known kimberlite occurrences in West Greenland are typically dykes < 0.5 m wide which can be followed only a few metres. The majority of the known kimberlite occurrences have areas less than 1 m^2 and they are beyond the detection limit of the spatial resolution of the HS survey unless the weathering phenomena enhance their expression by enlarging the surface area. The field evidence from the follow-up work in 2004 indicates that the kimberlite targets should have a minimum exposure of 8–10 m^2 to be detected by the HS data with the nominal resolution of 5 x 5 m.

The rugged terrain and the tendency of the kimberlite occurrences to occupy negative topographic features along linear structural elements, imply that optimal illumination conditions are a decisive factor for the detection of the kimberlitic rocks. This is well demonstrated by the two data acquisitions with a different sun azimuth angle on the biggest known kimberlite occurrence in central West Greenland (Figure 12).

Kimberlite mapping results of the project area are presented as 5500 pixels with kimberlitic character and these occur typically as scattered single pixels or clusters of a few pixels throughout the entire survey area. The HS data from the area described by Tukiainen & Krebs (2004) have been reprocessed using the new parameters in the SAM analysis reducing the number of kimberlitic pixels in this area by c. 25%.

Major concentrations of kimberlitic pixels are seen in the northern part of the survey area along and adjacent to the Ikertoq thrust zone (Frontispiece, Figure 9). The HS mapping depicts in a number of localities rock units whose geometry suggests that they could be mafic-ultramafic supracrustal rocks (Figure 9). However, some of these targets could be related to kimberlitic sills or dykes.

There seems to be a general tendency that the kimberlitic pixels become increasingly scattered and scarce in the north-western part of the survey area, but there are, however, other localities with conspicuous cluster of pixels with kimberlitic character (Figure 11).

Sources of ‘error’ or misclassifications

The mapping strategy of the present project is to locate pixel(s), whose spectra are indicative for the presence of the minerals phlogopite, carbonate, Fe-rich serpentine (antigorite) and talc. These minerals, and combinations of them, are not uncommon as major rock forming minerals in a number of rock types others than kimberlite (ultramafic rocks and various carbonate rocks, carbonate veined shear zones, altered mafic rocks etc.). It is very likely that a portion of the targets classified as ‘kimberlitic’ is related to other such lithologies. Some extreme illumination conditions (areas adjacent to snow/ice and bright surfaces) may also create image processing artefacts resulting in classification errors.

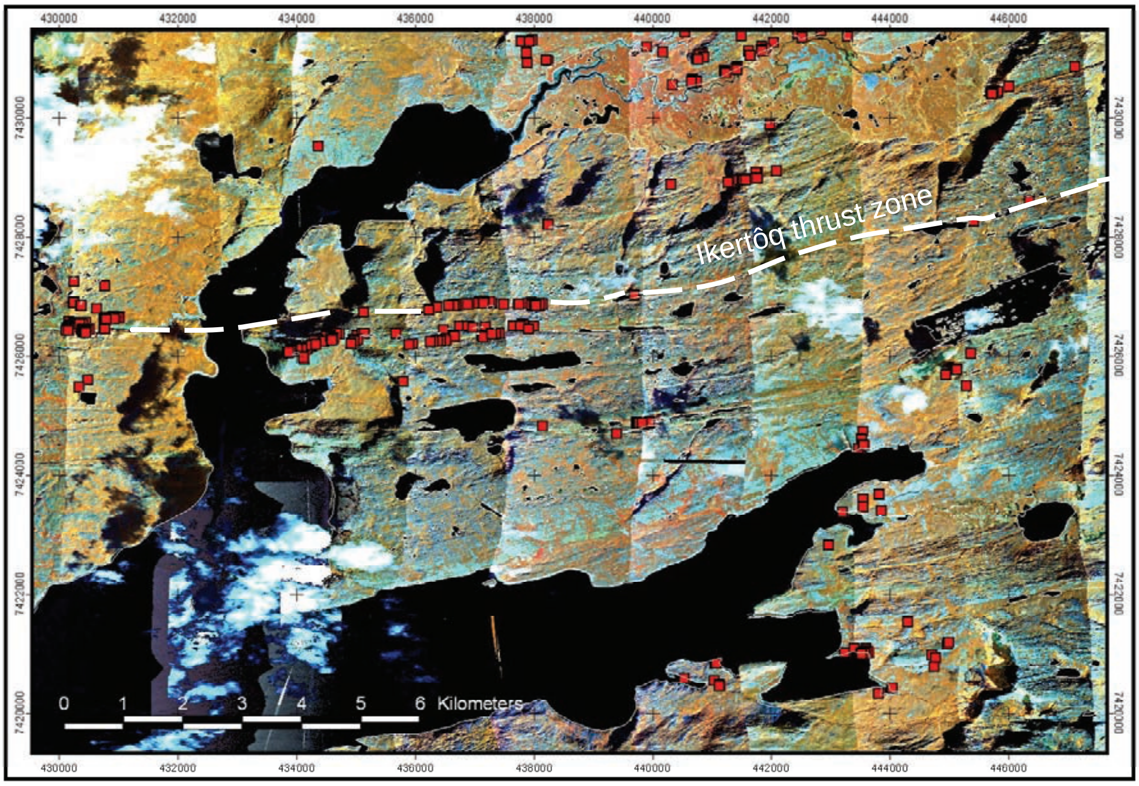


Figure 9. *Results of the kimberlite mapping from an area of the Ikerttôq thrust zone. Note the concentration of kimberlitic pixels along the thrust zone. The location of the area is shown in Figure 4, (see also Frontispice).*

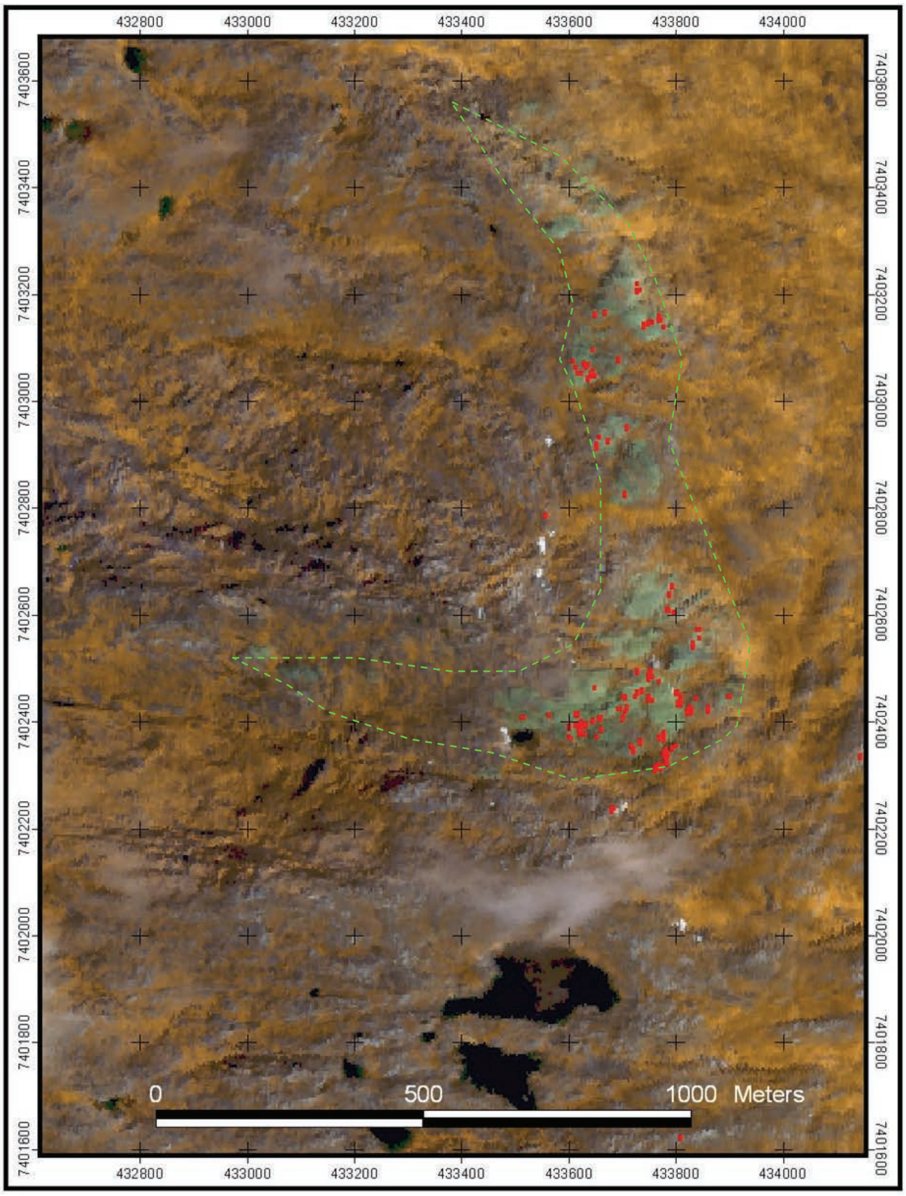
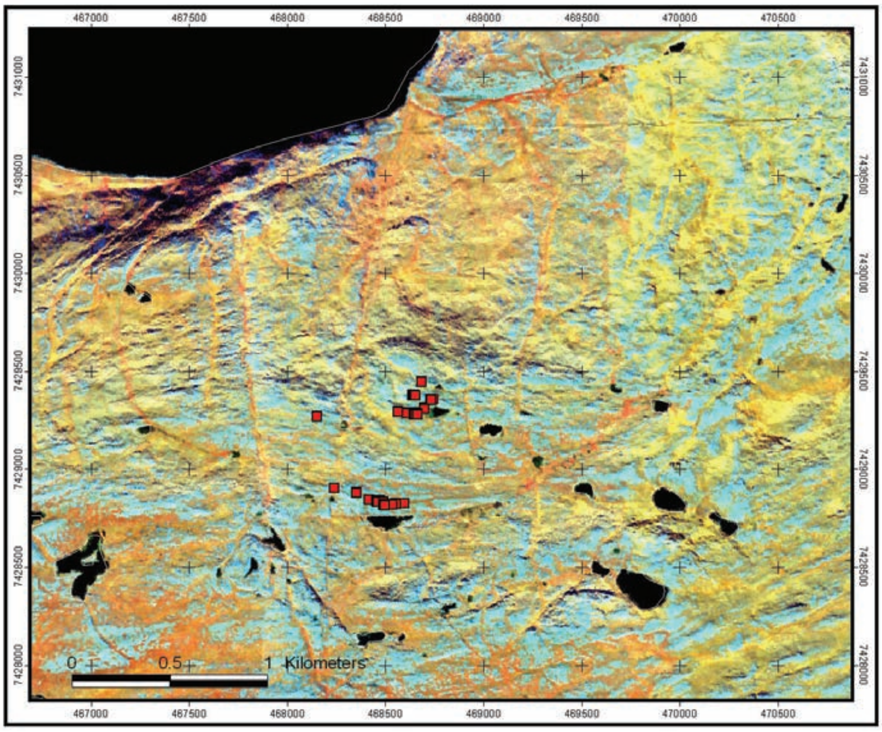


Figure 10. *Results of the kimberlite mapping from an area east of Kangerluarssuk fjord Note the concentration of kimberlitic pixels (red) outlining a lenticular body of kimberlite/lamproite or mafic-ultramafic supracrustal rocks? The location of the area is shown in Figure 4.*

A



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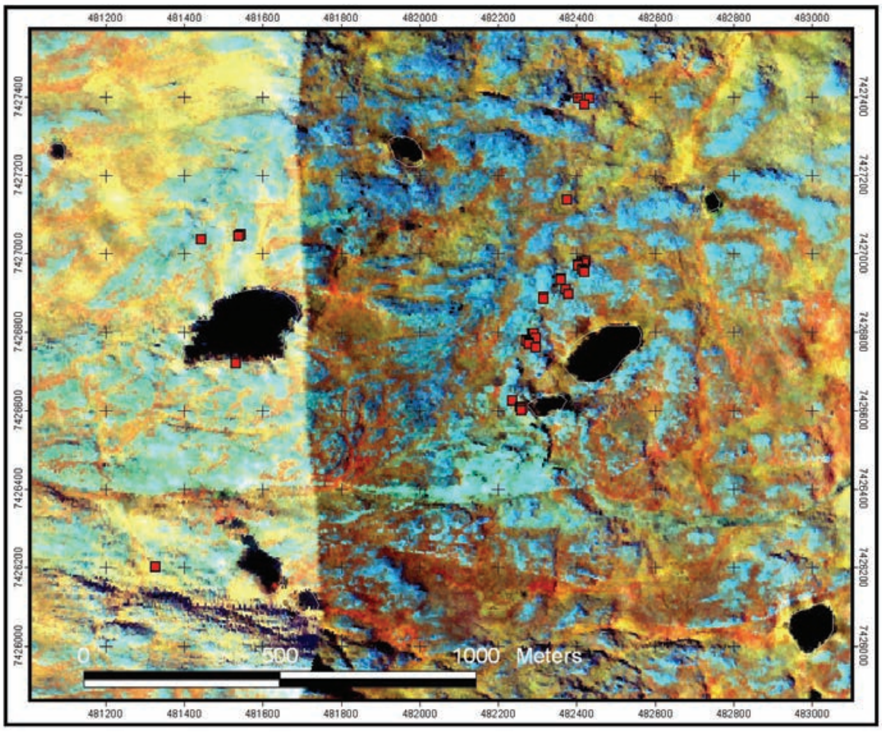

Figure 11. *Results of the kimberlite mapping from two areas on the northern side of Kangerlugssuaq fjord.* ***A:*** *clusters of pixels with kimberlitic character in an area with diffuse circular features.* ***B:*** *Linear SW-NE trending cluster of pixels with kimberlitic character. The locations of the figures are shown in Figure 4.*

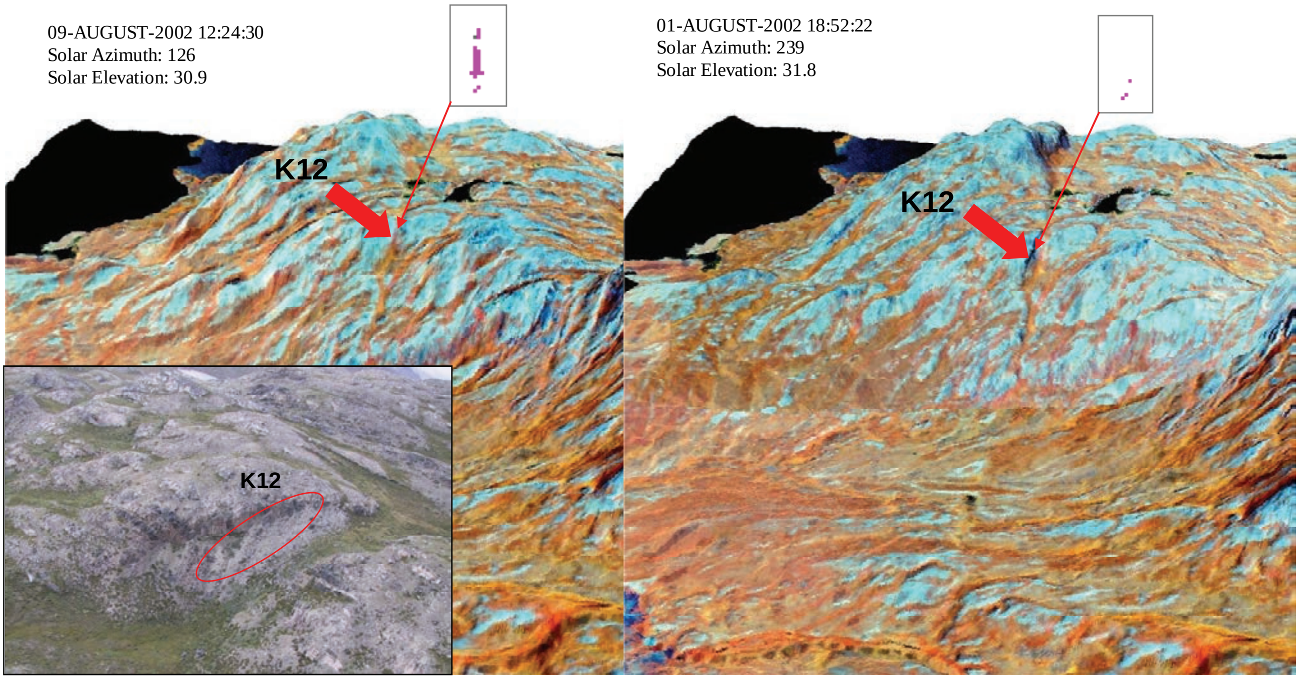

Figure 12. *Perspective view of HS data of the flight route 41 draped on the digital terrain model. Hues of red and brown = vegetation, grey and blue = exposed rocks. The kimberlite occurrence K12 ("Big Dyke") seen from the south. SAM-mapping results from the data acquisitions of the 1st and 9th of August 2002 are shown as magenta coloured pixels. Note the strong effect of the illumination conditions (solar azimuth) on the kimberlite mapping results.*

Recommendations for future work

Follow-up fieldwork of the kimberlite targets outlined by the present HS data analysis should be carried out. The kimberlitic targets are spatially scattered which makes helicopter based follow-up work the most effective method to cover the selected areas.

Acknowledgements

This project was financed by the Bureau of Minerals and Petroleum, Government of Greenland. The opportunity to loan the portable field spectroardiometer PIMA SP for the field work was kindly arranged by Mag. Klemens Grösel**,** Geologische Bundesanstalt, Fachabteilung Geophysik, Austria. The manuscript benefited from comments and criticism by Leif Thorning, Bjørn Thomassen and Peter Dawes who also corrected the English spelling.

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APPENDIX 1. Kimberlite mapping results

The mapping results on the enclosed CD-ROM comprise the following files:

- Index map & map projection information. Format *.RTF –document.
  INDEX.RTF

- Colour composite of HyMap bands 26 (R), 18(G) and 3 (B). Mosaic of HyMap flight strips. Format GeoTiff
  SUB1.TIFF
  SUB2.TIFF
  SUB3.TIFF
  SUB4.TIFF
- Shaded relief map based on the digital terrain model
  SHA1.TIFF
  SHA2.TIFF
  SHA3.TIFF
  SHA4.TIFF

- Classification results from Spectral Angle Mapper (SAM). Format ArcView shape file
  KIMBERLITE.SHP

- Pima SP spectrometer measurements
- Report text as PDF-file