DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/45

Mineral resources of the Precambrian shield of central West Greenland (66° to 70°15'N)

Part 4. Mapping of kimberlitic rocks in West Greenland using airborne hyperspectral data

Tapani Tukiainen & Johan Ditlev Krebs

(1 DVD included)

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

G E U S

DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2004/45

Mineral resources of the Precambrian shield of central West Greenland (66° to 70°15'N)

Part 4. Mapping of kimberlitic rocks in West Greenland using airborne hyperspectral data

Tapani Tukiainen & Johan Ditlev Krebs

(1 DVD included)

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

GEUS

Contents

Abstract

A high-resolution (5 x 5 metre nominal pixel size) airborne hyperspectral survey was conducted in West Greenland in 2002 covering approximately 7500 km^2, where earlier investigations had discovered a number of kimberlite bodies. Some of these turned out to diamond bearing 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, which was the primary goal of the survey, was based on the detection of the Fe-rich serpentine, phlogopite, carbonate minerals and talc utilising their characteristic absorption features in the short wave infrared spectral region (2.0–2.5 μm).

The small size of the potential targets, typically corresponding to one or a few image pixels, and the relatively subtle spectral characteristics as established by the spectral 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 originally utilised methods, which are basically applied to flat terrain, failed to produce apparent surface reflectance data of adequate quality.

Based on the detailed digital elevation model, radiance data from one third of the entire survey area were pre-processed and new surface reflectance data 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 spectral mapping, apart from locating several known kimberlite occurrences, generated other potential targets for the field follow-up programme.

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. The Bureau of Minerals and Petroleum, Government of Greenland, financed the project. Previous investigations by GEUS and exploration companies had demonstrated that some of the kimberlites in West Greenland are diamond bearing, making the region an important target for diamond 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 in 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. 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) (attached as Appendix 2 of this report).
The scope of this report is, 1) to provide a general description of the hyperspectral data acquisition and data processing and 2) to present and discuss the results of the kimberlite mapping from that part of the surveyed area where detailed digital elevation data are available (Figure 1). Other ongoing projects focus on the mapping of other features (such as rock types, vegetation etc) and these more general results will be published elsewhere.

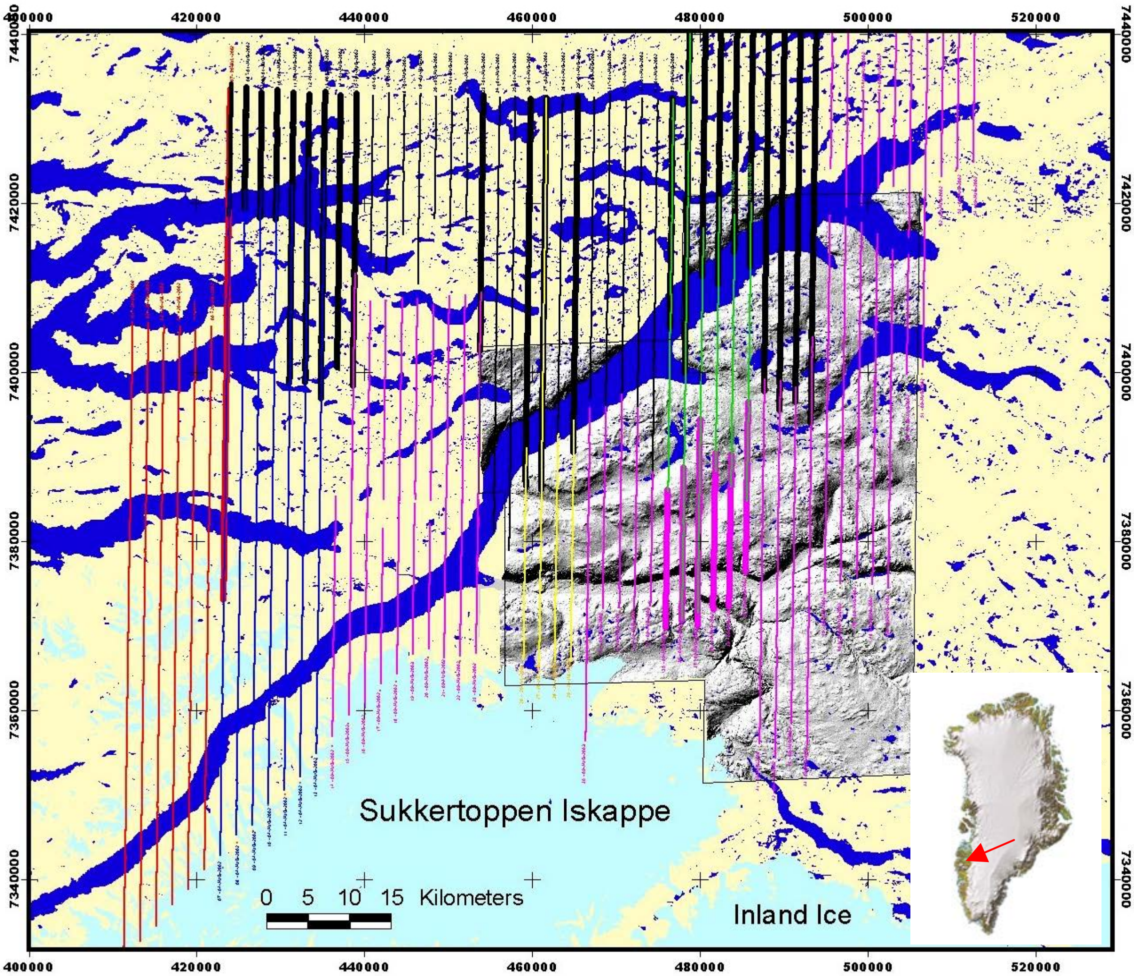


Figure 1. *Coverage of the airborne hyperspectral survey flown in 2002. Different colour and thickness of the survey flight lines reflect the chronological and spatial complexity of the flight operations needed to cover the survey area because of bad weather. The area described in this report is outlined by the shaded topographic relief map.*

Acquisition of Hyperspectral Data

The airborne system

HyMap is a state-of-the-art aircraft mounted commercial hyperspectral sensor (Figure 2) developed by Integrated Spectronics, Sydney, Australia and operated by HyVista Corporation, Sydney, Australia. The sensor provides data of unprecedented spatial, spectral and radiometric excellence (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 the Provincial Airways Limited, Halifax, Canada (Figure 3). The airborne system also contained a digital colour Duncantech camera for the acquisition of concurrent stereoscopic aerial photography.

Survey parameters

The survey areas were 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 correspond 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 Kangerlussuaq on 22nd of July 2002. The HS scanner and the digital camera were installed on the 23rd and after a successful test flight the same day, the airborne HS system was ready to commence the data

Figure 2. *Preparing for a test flight: HyMap scanner installed on the Piper Navajo Chieftain.*

data acquisition. Due to exceptionally bad weather conditions, data acquisition was only possible on 5 out of the 14 days when the system was available in Greenland. Table 1 gives the details of the flight programme.

Table 1. *Flight schedule for the HyperGreen 2002 operations*

Date	Activity	Comments
23-July-2002	Installation & test of the airborne system	
26-July-2002	Production flights	4.2 hours
30-July-2002	Production flights	3.1 hours
01-August-2002	Production flights	8.2 hours
04-August-2002	Production flights	3.7 hours
09-August-2002	Production flights	8.8 hours
10-August-2002	Demobilisation of the airborne system	28.0 hours (total)

Because of the unusually high number of standby days, when no flying could be done because of bad weather, and taking the unfavourable weather forecast for the period of 10th–15th of August into account, the contractor decided to stop the data acquisition programme after the production flights on 9 August, in agreement with his contractual rights to do so to honour other obligations in Canada and Europe.

The HyperGreen survey operations resulted in approximately 3500 line kilometres of data acquisition, recorded along 54 flight lines. The survey covered approximately 7500 km^2 of ground totalling ca. 95 % of the high priority area originally planned for the operation. This was acceptable considering the difficulties encountered.

The data coverage is reasonably continuous with only a few gabs in the data. However, 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 situation did not allow large contiguous areas to be covered. By combining the overlapping subsets, the cloud cover can be brought to less than 5 % of the surveyed area. Cloud cover has the most severe impact on the image quality along Sarfartoq Valley.

The digital photography only covers approximately 3500 km^2 due to the non-recoverable failure of the camera on the 4th of August.

Deliverables

Due to the course of events predominantly related to the weather conditions and the subsequent manner of flying, the original schedule for the delivery of data had to be revised. The first consequence was that the data could not be delivered in a meaningful way while the contractor was in the field at Kangerlussuaq. A processing session at HyVista's home office in Sidney was required, and the contractor's processing of the data was continued in Australia until all the data had been delivered in late September 2002.

Figure 3. *The Piper Navajo Chieftain aircraft at Kangerlugssuaq airport.*

The contractor delivered the data on 72 DVDs on a line by flown line basis; by agreement the data had not been rearranged to compensate for unsystematic flight lines and overlapping coverage. This made the subsequent GEUS processing of the data difficult.

Table 2. *Items delivered by HyVista*

Item	Format
Flight line radiance cubes & dark current and on-board lamp calibration files	ENVI (BIL)
Flight line ephemeris data (Data from DGPS and IMU)	ASCII
Flight line apparent reflectance data (Image data in units of apparent reflectance where atmospheric correction is implemented with HyCorr	ENVI (BIL)
Geo-correction files including a 3 band geocorrected image. Geocorrection is based on the existing digital elevation model by GEUS	ENVI
Images from the digital camera (RGB). The digital camera covers only parts of the area.	ENVI

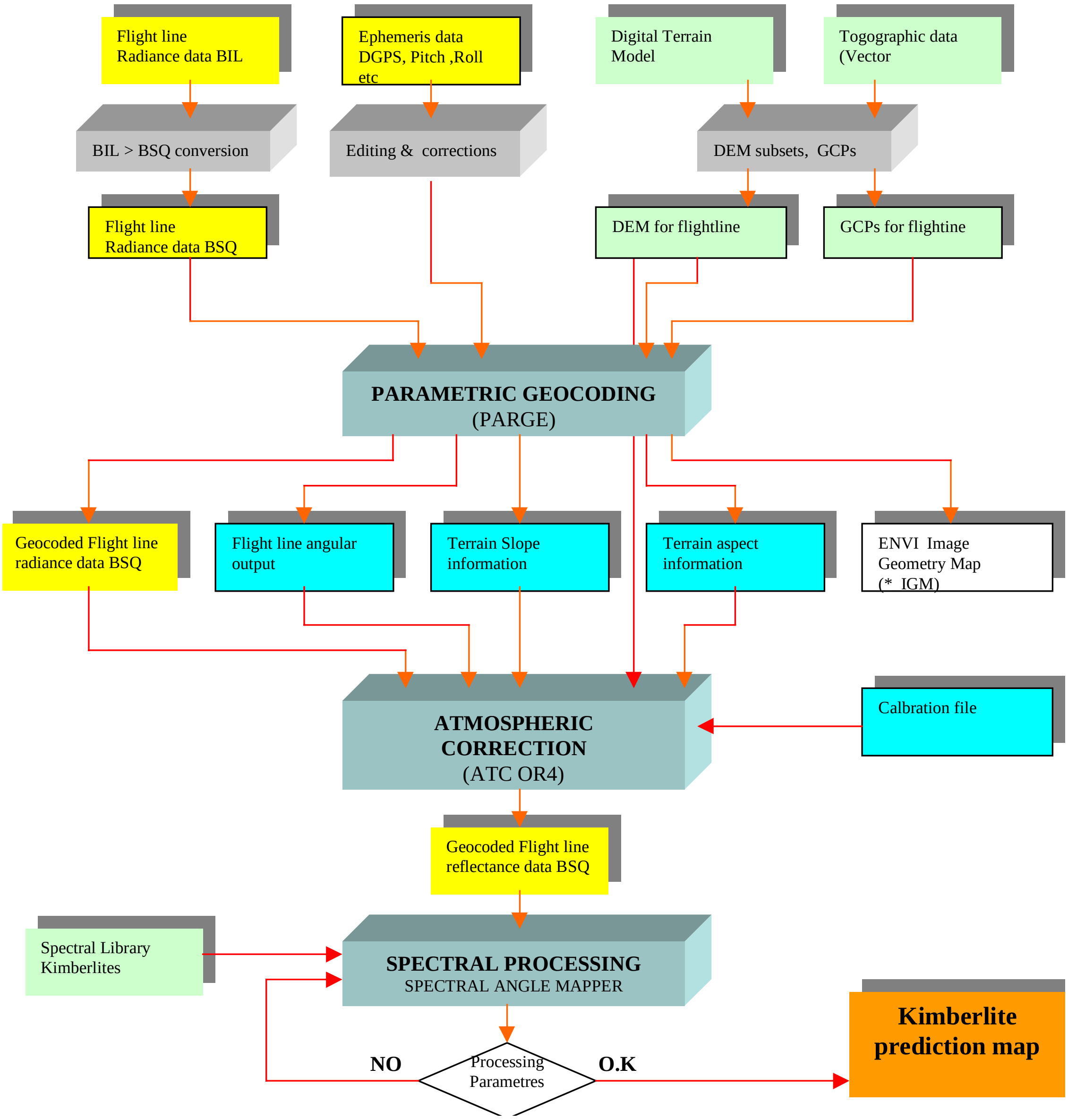


Figure 4. *The finally accepted processing scheme for the hyperspectral image scanner data.*

Processing of Hyperspectral Data

Processing of the HyperGreen 2002 data was done at GEUS using ENVI image analysis software. Some Fortran-based routines were developed for more complex editing and sub setting of the flight line ephemeris data.

Image processing of the HyperGreen 2002 data has been a complicated and time-consuming task, which has delayed the presentation of the results considerably, due especially to the following reasons:

- *Unsystematic coverage of data with overlapping data subsets:*
  The unsystematic organisation of the HS data as flown and delivered meant that much time was used to reorganise the data into a more systematic and easy to use set of coverages.
- *Extraction and delivery of data to the mining companies:*
  The amount of the processing work was further increased by the fact that GEUS, contrary to expectations, had to extract and deliver (on DVDs) the HS data subsets to the mining companies participating in the project.
- *Atmospheric* correction - research and development (see Appendix 1):
  It became clear that to fully exploit the possibilities of hyperspectral image data delivered as 'at sensor' radiance data by an HS scanner system, they must be converted to surface reflectance data.

Especially the latter turned out to be time consuming. Internationally, several methods have been developed for such a task; the most common and widely used are those generating *apparent* surface reflectance data (Flaash, ATREM, ACORN, HyCorr). The quality of the apparent reflectance data resulting from these atmospheric modelling techniques has been widely discussed. They seem to deliver satisfactory results in some combinations of terrain and climate and the fact that these techniques do not require terrain elevation models makes them an attractive alternative in projects facing constraints of time and other resources.

It was also a tempting starting point for the present project to assume that the apparent surface reflectance data, which was one of the deliverables from the HS contractor, could satisfactorily fulfil the quality requirements for the atmospheric correction of the HyperGreen 2002 data. However, after some experimentation it was deemed necessary to test this assumption.

A straightforward way to control the quality of the HyCorr reflectance data was to compare them with the detailed field truth data from selected kimberlite localities obtained through the ground survey of spectral properties carried out simultaneously with the flying. It unfortunately became obvious that the spectral correlation between the ground truth data and the HyMap HyCorr reflectance data was very poor. Also, other modelling techniques (ATREM and Flaash) were experimented with to produce apparent surface reflectance data of good quality but the results were not satisfactory. It had to be concluded that these techniques failed to generate reflectance data of adequate quality in the rugged terrain conditions of West Greenland.

As a consequence, it was decided to base the atmospheric correction on a more advanced modelling method which takes the detailed terrain into consideration. The conversion of the data to surface reflectance was done using the ATCOR-4 – package (Richter & Schläpner 2002). A necessary prerequisite for the use of ATCOR-4 in rugged terrain is a detailed digital elevation model. This was produced at GEUS photogrammetric laboratory for a part of the survey area. Fortunately, the ATCOR-4 produced surface reflectance data, which correlated well with the spectral ground truth data (Appendix 2).

Use of the ATCOR-4 program package together with the parametric geocoding software PARGE, considerably increases the complexity of the image pre-processing and requires more IT resources to accomplish the HS image analysis (Figure 4). The complexity is, however, counterbalanced by the fact that the processing steps down to ATCOR-4 are to a large extent routine work, which can be done as batch processing by a trained technician.

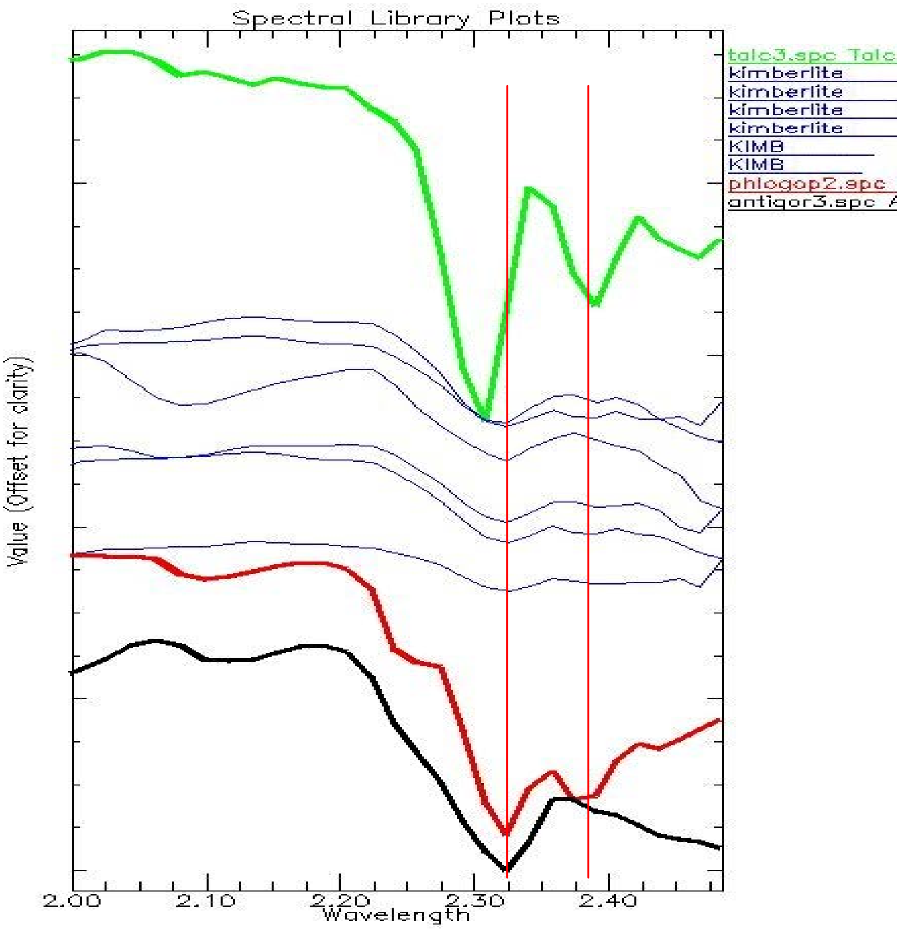


Figure 5. *Selected mineral spectra from USGS spectral library (Clark et al. 1993) compared to kimberlite field spectra from West Greenland. Spectra are resampled to HyMap bandwidths.*

Kimberlite targets

Size and characteristics of the targets

Field evidence (Jensen *et al.* 2003) has shown that the kimberlitic rocks of West Greenland typically occur as dykes and sills, which appear to be controlled by pre-existing joint systems and fracture zones. Kimberlite dykes occur at distances of up to 40 km south, 30 km north, 50 km west and 35 km east of the Sarfartoq carbonatite complex, i.e. the cone sheet zone (Secher & Larsen 1990). The intrusions are often flat-lying sheets, rarely over 1 metre thick and traceable for a few tens of metres or sub-vertical, 1-2 metres wide and traceable for hundreds of metres.

Apart from *in situ* occurrences of kimberlite, boulders of kimberlite and lamproite are ubiquitous throughout the entire project area. Boulder size varies from a few centimetres to several metres. These are often concentrated in clusters or trains containing hundreds of boulders suggesting that they may have been derived from a nearby outcrop or that they are almost in *situ* residual material on a kimberlite intrusion.

The kimberlite and lamproite intrusions are as a rule relatively deeply weathered implying that they occur as topographically negative features. The weathering of the kimberlite boulders may increase their surface expression significantly, as seen through hyperspectral data, but clearly the targets will in many cases be quite small and present a challenge for the hyperspectral methods.

Spectral basis for the mapping of kimberlitic rocks

An essential part of the present project was to establish the detailed spectral characteristics of the kimberlitic rocks in West. The importance of this has been proven by the fact that in this project accurate spectral ground truth from the known occurrences of kimberlitic rocks has been of crucial importance for the development of image processing procedures for the mapping of kimberlitic rocks. The description and results of the spectroradiometric field investigations are given in Appendix 2.

Kimberlites consist of predominantly ultramafic matrix material that has crystallised *in situ*, associated 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 include olivine, phlogopite, perovskite, spinel, chromite, diopside, monticellite, apatite, calcite and serpentine (commonly Fe-rich). Alteration of some of these minerals to serpentine and calcite is common.

The field spectra of the kimberlitic rocks in West Greenland are remarkably uniform which is contrasted by the wide variations in the mineral composition of these rocks (proportions of matrix and ultramafic nodules).

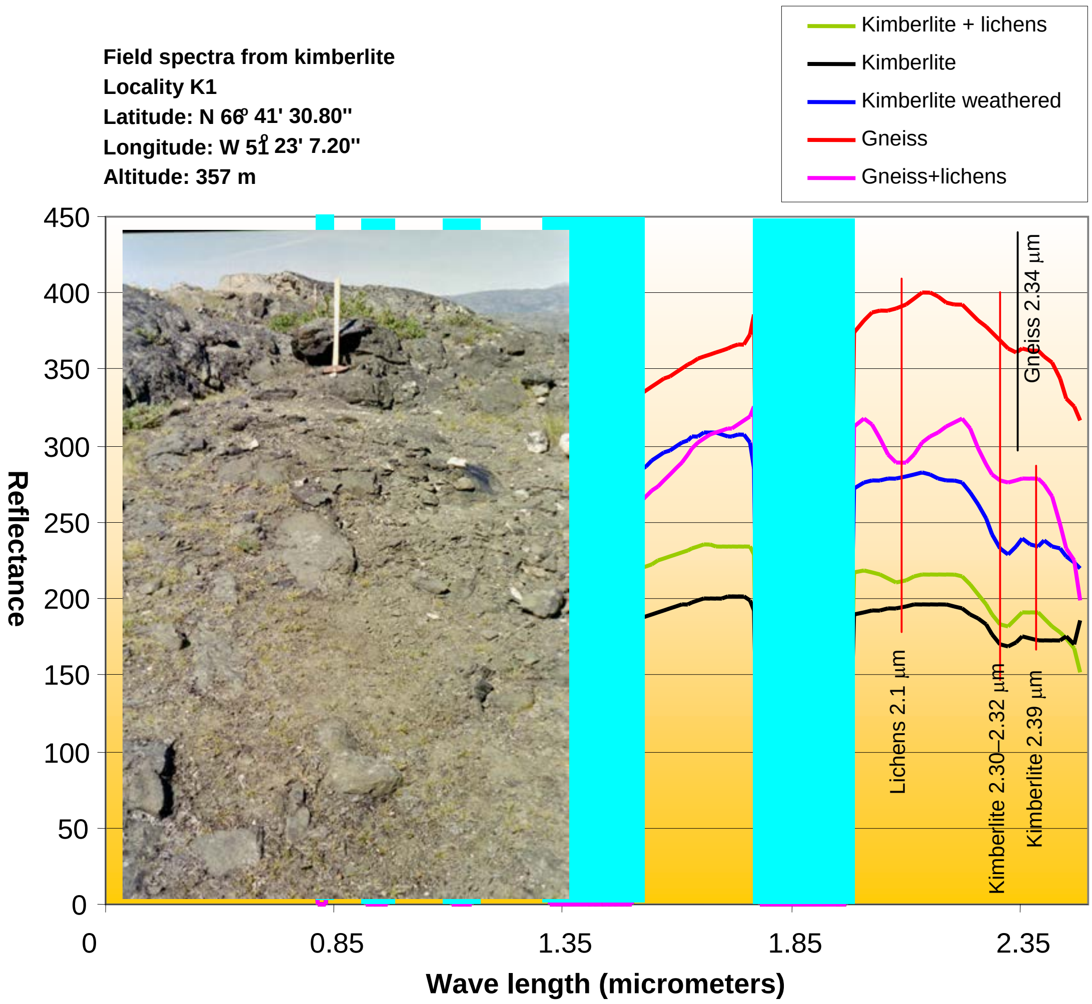


Figure 6. *Field spectra of kimberlite and gneiss measured under sunlight (spectra resampled to HyMap band widths) at the locality K1. Note the effect of weathering and lichen cover on the spectral responses. For location and details, see Tukiainen et al. (2003).*

From the point of view of hyperspectral mapping, the most interesting minerals are phlogopite, carbonate and Fe-rich serpentine (antigorite) and talc (Figure 5), because these minerals have characteristic spectral responses in the Short Wave Infrared (SWIR) spectral region (2.0–2.5 µm).

The field spectra from selected kimberlite localities (Figures 6, 7 & 8) illustrate the characteristic absorption features at 2.30–2.32 µm and 2.39 µm. The feature at 2.30–2.32 µm is particularly well defined. Weathering often dramatically enhances the spectral response of the kimberlites. (Figure 7 & 8).

The weathering in West Greenland is predominantly related to the mechanical disintegration of rock material, which increases the effective surface area of the minerals resulting in the enhanced spectral responses. The same effect is seen under laboratory conditions

(Appendix 2), where the powdered kimberlite samples return far more distinct spectra than those measured on the weathering surface of the respective samples.

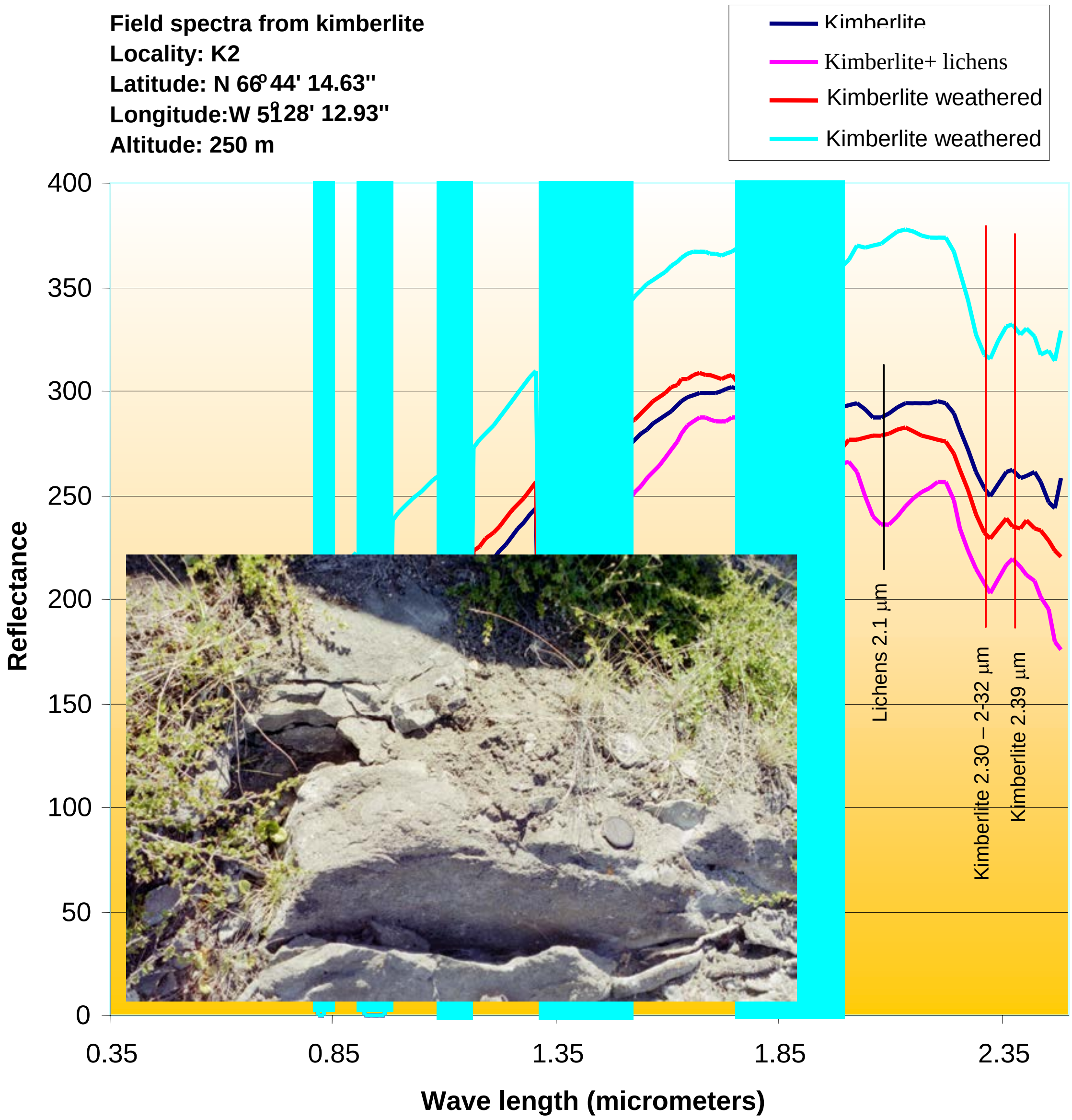


Figure 7. ***F****ield spectra of kimberlite measured under sunlight (spectra resampled to HyMap band widths) at the locality K2. Note the effect of weathering and lichen cover on the spectral responses. For location and details, see Tukiainen et al. (2003)*

The amount of (predominately) dark lichens on the rock outcrops is highly variable and affects the overall spectral response of the rock surfaces. Abundant, dark lichens reduce the overall signal level of the SWIR and cause a broad absorption feature centred at 2.1 µm. The abundance of lichens has a tendency to camouflage the kimberlite absorption feature at 2.39 µm (Figures 6 & 7).

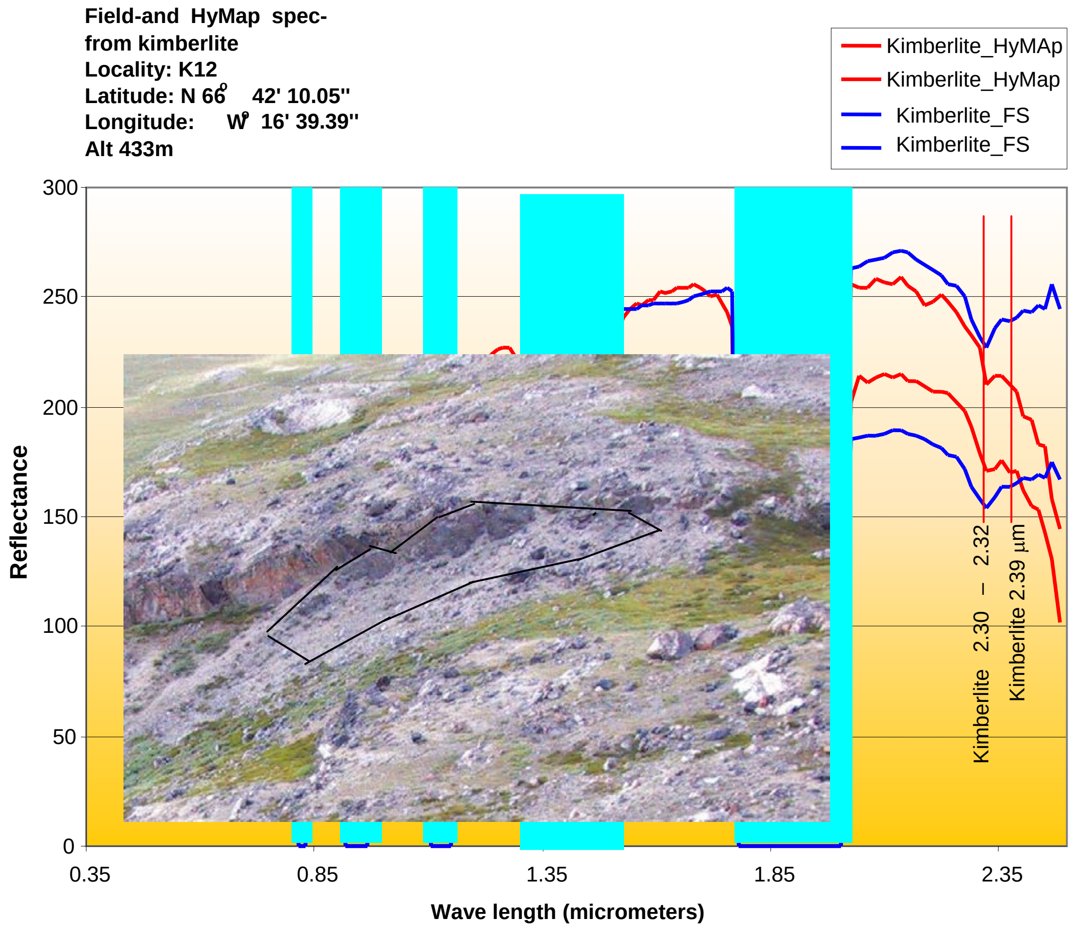


Figure 8. *Field spectra of kimberlite measured using tungsten-halogen lamp (Kimberlite_FS, resampled to HyMap bandwidths) and HyMap surface reflectance spectra (Kimberlite_HyMap) produced by ATCOR-4. Locality K 12 ("Big Dyke"). For location and details, see Tukiainen et al. (2003)*

Spectral mapping

The most important minerals for the hyperspectral mapping of kimberlitic rocks are phlogopite, carbonate, Fe-rich serpentine (antigorite) and talc. These minerals have characteristic spectral responses within 2.0–2.5 µm of the short wave infrared spectral region.
The field measurements have shown that the spectral response from the kimberlitic rocks is remarkably uniform, so 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 image spectra to the 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 insensitive to the unknown gain factor and all possible illuminations are treated equally. This is an important advantage when processing such data as acquired in

the HyperGreen 2002 project, where illumination levels vary between the flight routes and even within a single flight line.

The SAM algorithm implemented in ENVI calculates the angular distance (as radians) between each spectrum in the image and the reference spectra. The ‘rule’ image for each end member shows the actual angular distance between each spectrum in the image and the reference spectrum. The spectra that are more similar to the reference spectrum are characterised by lower values for the angular distance.

As pointed out earlier, subtle spectral features are utilised for the mapping of kimberlitic rocks. This implies that low signal/noise ratio is of fundamental importance for the reliability of the classification. Sun angle and the water vapour content of the atmosphere affect the signal/noise ratio of the spectral interval 2.0-2.5 μm.

The detailed analysis of the HyperGreen 2002 image data has shown that the atmospheric conditions (particularly H_2O content) were highly variable from one flight to another. The atmospheric H_2O content is particularly high above and adjacent to Kangerlussuaq fjord suppressing the SWIR signal and increasing the noise level of the image data within an approximately one kilometre wide coastal zone on both sides of the fjord. This is in particular seen clearly in the image data acquired on the 30th of July 2002 (flight route # 35–40).

The variable signal/noise ratio between and within the flight routes makes it impossible to utilise a fully automated SAM classification with a fixed tolerance value for the angular distances between the image data and reference data.

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 kimberlite ground spectra from a well-determined site were used as reference spectra. Also, other kimberlite field spectra were tested and again, testifying to the uniform spectral characteristics of the West Greenland kimberlites and lamproites, they yielded similar classifications results.

Presentation of results

The processed data cover an area of 48 by 62 kilometres. The nominal 5 x 5 m spatial resolution of the survey data implies that the dimensions of an image to cover the entire area in detail are 12 000 x 15 500 pixels, which 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 that are found on the CD-ROM enclosed with this report. Furthermore, to make the results available on more modest computing platforms, the GIS-layers are divided into three overlapping sub areas as shown in Figure 10. For each sub area the following GIS-layers have been compiled and stored on the enclosed CD-ROM (Appendix 3):

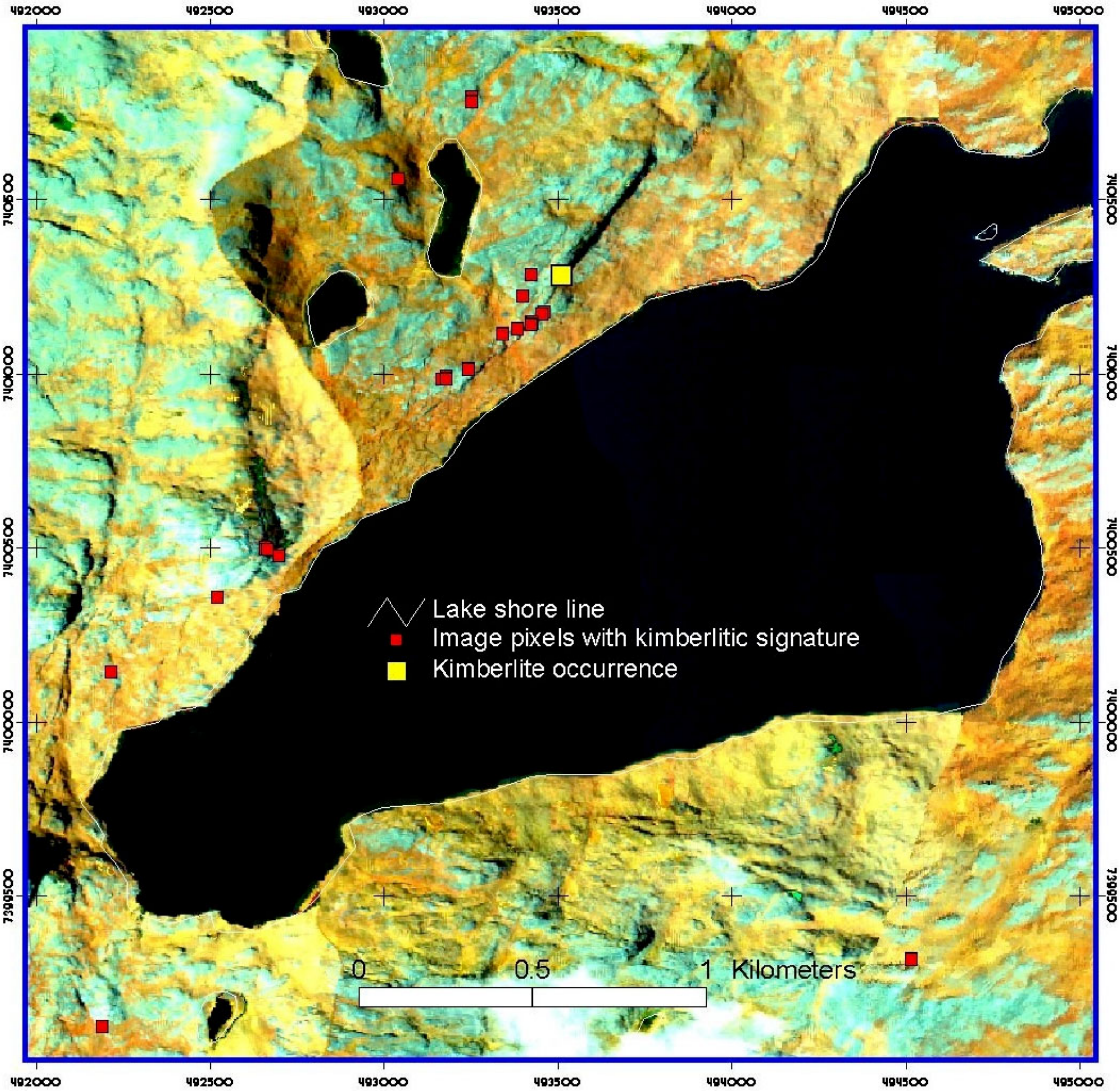


Figure 9. *Typical registration of the topographic vector data on the parametrically geo-coded HS image data. A know in situ kimberlite occurrence and image pixels with kimberlitic spectral signature superimposed on the image. The location of the figure shown in figure 10.*

- 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
- Classification results from Spectral Angle Mapper (SAM). Format ENVI vector file

(Projection: UTM Zone 22, Datum WGS84)

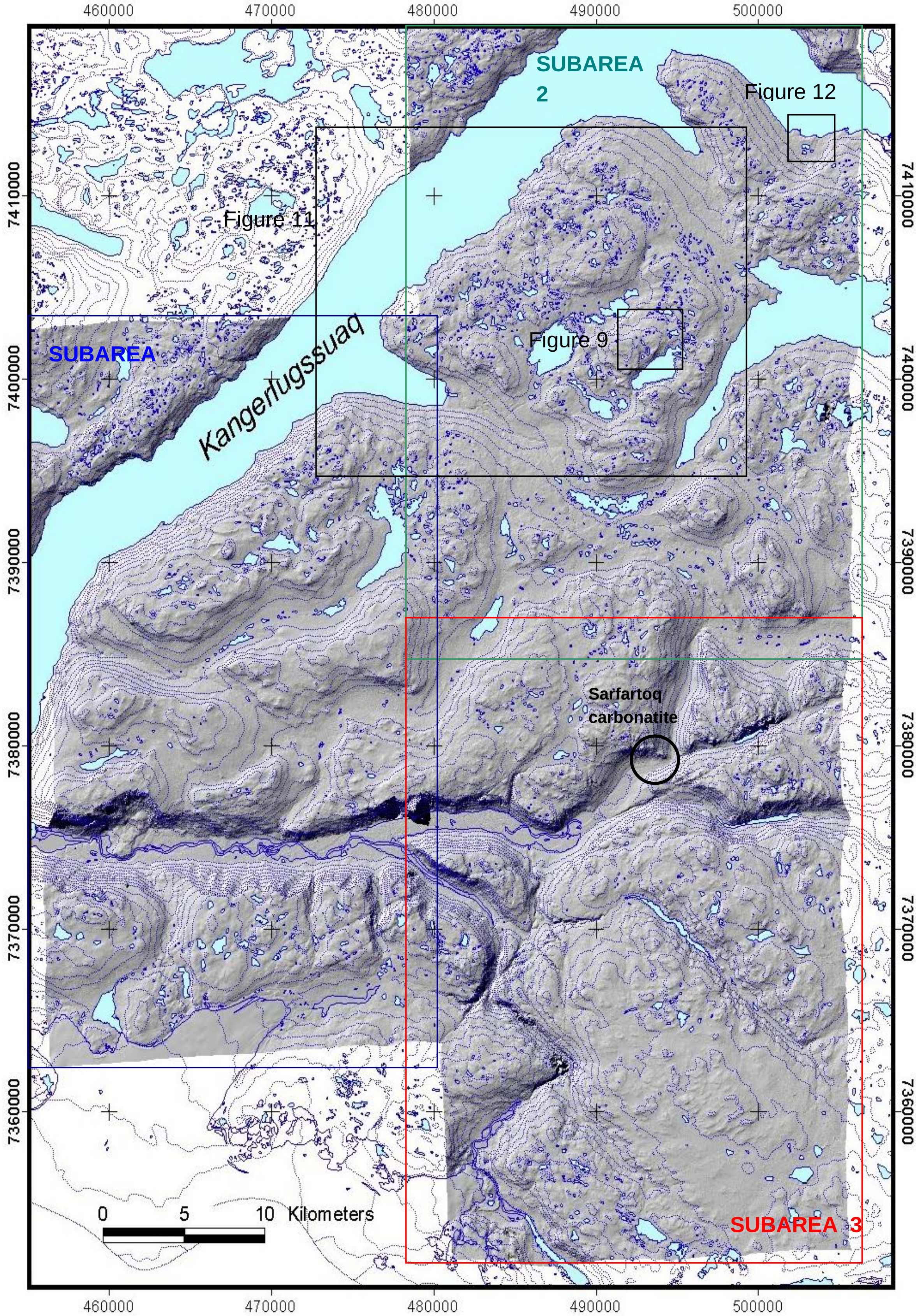


Figure 10. *Index map showing subareas and the localities referred in this report.*

Geocoding accuracy

Geocoding of the HS image data is primarily based on aircraft attitude data (pitch, yaw, roll) detected by the Inertial Monitoring Unit (IMU) and the aircraft's navigation data (X- Y- and Z- co-ordinate) from the Differential GPS.

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 theHyperGreen2002 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 survey 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 also located on the raw image data (e.g. rivers, shorelines).The vector data (coastlines, rivers) from GEUS photogrammetric laboratory were used to create GCPs for the parametric geocoding. These data have been generated manually from the 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 some tens of metres.

Discussion of Results

Comparison with known occurrences

Sources of ‘error’ or misclassifications

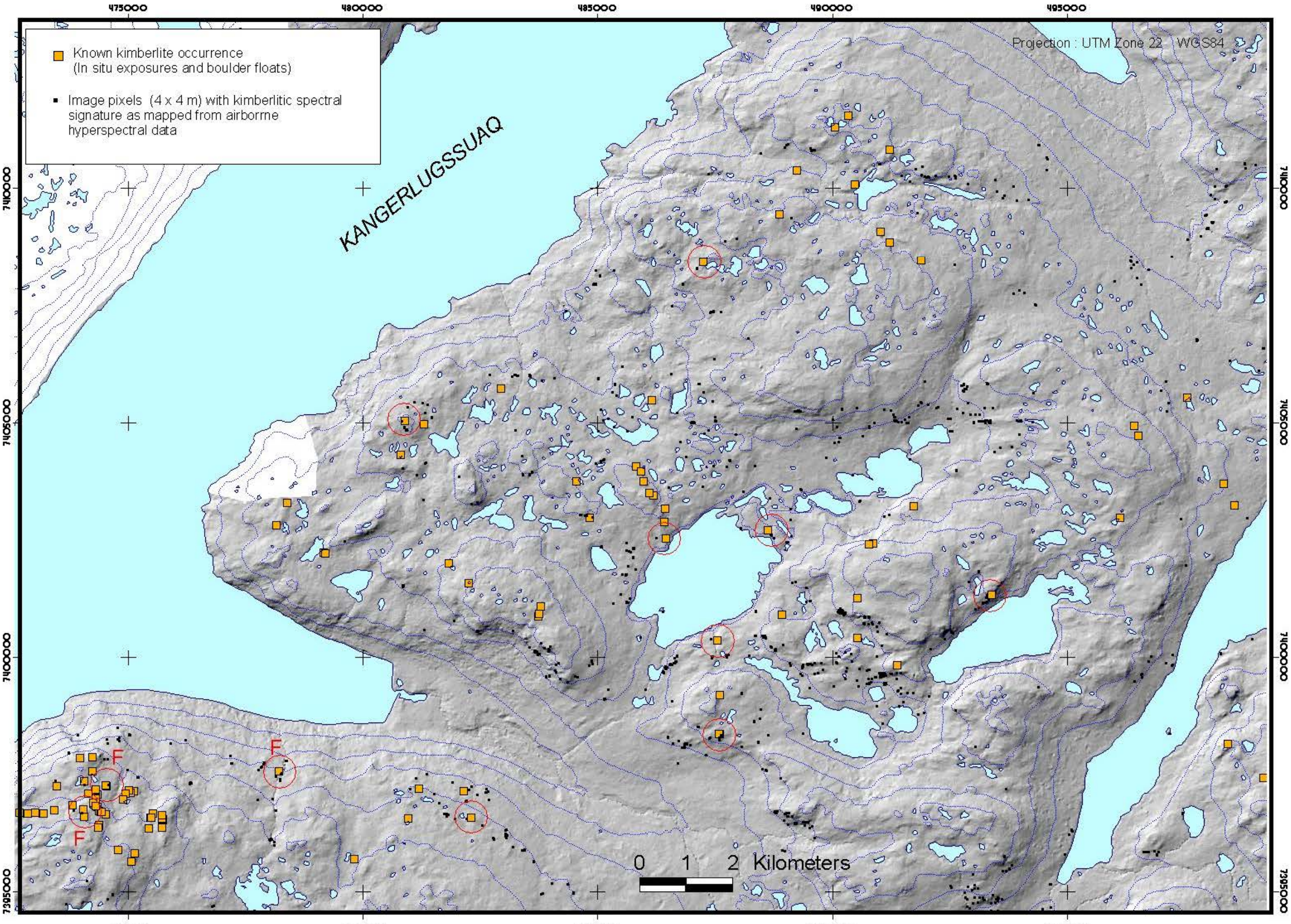


Figure 11. *Results of the kimberlite mapping from an area covering parts of subareas 1 & 2. Known kimberlite occurrences (in situ occurrences and boulder floats) are shown on the map. Some known in situ kimberlite occurrences detected by the mapping are encircled with red (F = boulder float).*

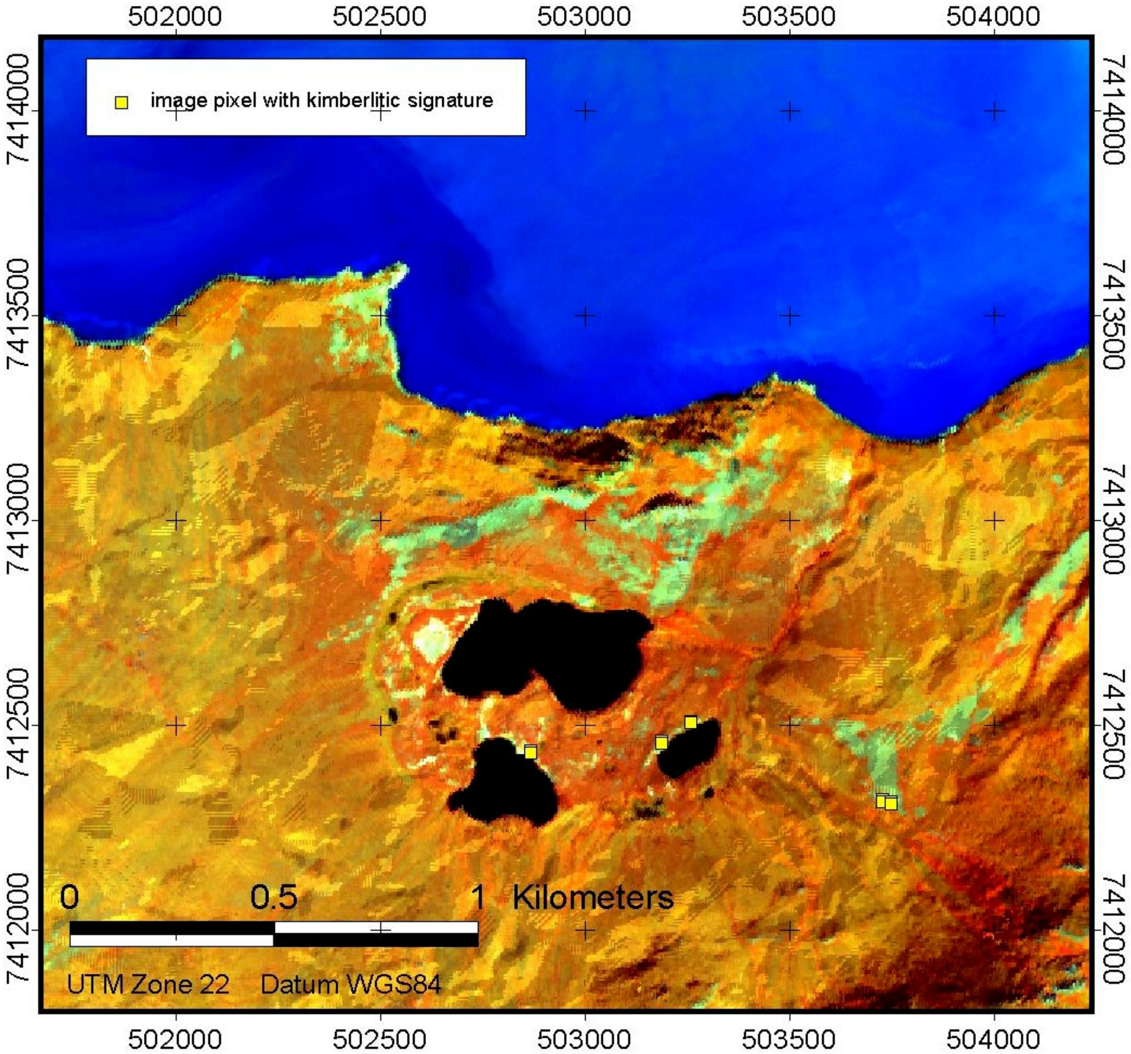


Figure 12. *Pixels with kimberlitic signature within a circular feature (diameter approximately 0.6 km) around the cluster of lakes. Background image is a colour composite of HyMap bands 26 (Red), 18 (Green) and 3 (Blue)*

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, or 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 and ultramafic rocks, etc.). It is very likely that a portion of the targets classified as 'kimberlitic' probably is related to such lithologies. Some extreme illumination conditions (areas adjacent to snow/ice and bright surfaces) may also create image-processing artifacts resulting in classification errors.

Kimberlite mapping results from the northern part of the project area (Figure 11) illustrate the tendency of pixels with kimberlitic signature to form clusters, which frequently appear to follow the linear features visible on the topographic base map. Many of the major known *in situ* occurrences and boulder floats can be located by SAM classification.

The known occurrences are typically dykes more than 0.5 m wide that can be followed for more than a few metres. The majority of the known kimberlite occurrences in Figure 11 are less than 0.5 m^2 and they are beyond the detection limit of the spatial resolution of the HS survey unless the weathering phenomena enhance their surface expression, e.g. by enlarging the surface area because of weathering products from the kimberlitic rocks.

During the inspection of the many possible targets for future ground checks of hyperspectral kimberlitic anomalies, many interesting features can be studied and will be the subject of attention during the field work summer in 2004. One such feature can be seen in the northern part of the project area (Figures 12), where pixels with kimberlitic signature are seen to cluster within a peculiar, circular feature with a diameter of about 600 metres. The feature is located in a topographic depression and it also exhibits hyperspectral signs of the vegetation being different from its surroundings. Various explanations could be attributed to this feature (e.g. carbonatite or mafic intrusion), but such anomalies are obviously also high on the list of anomalies to be tested during the field work. The geometry and spectral indications make this feature an interesting target for diamond exploration.

General considerations for the use of hyperspectral data

The nature of the HyperGreen2002 project has to a large extent been research and development, where considerable resources in terms of time and computing have been used to test and develop the image processing and analysis routines for mapping kimberlitic rocks in glaciated, arctic rugged terrain conditions.

However, in a normal mineral exploration programme a far more rapid turnaround of results is required. Targets determined in the image analysis should ideally emerge soon after the data acquisition and pre-processing has been concluded. Based on the experience gained and the image processing schemes developed in the present project, it should be possible in future campaigns to speed up the delivery of results thus aiding the exploration activities. The most relevant issues to be considered with this in mind are discussed in the following.

Required location data

The modern airborne HS scanners generate accurate ephemeris data for each flight line that enables the use of parametric, and to a large extent automatic, geocoding of the HS image data. The results from the airborne HS surveys are likely to be combined and analysed together with other thematic geodata layers, so appropriate accuracy of geocoding is necessary. There are a couple of prerequisites for this to be possible: availability of a good digital elevation model and ground control points.

Digital elevation model

There are numerous methods of generating accurate digital elevation models (DEM) from various satellite data as well as classical stereoscopic aerial photography. Other extremely accurate, although very expensive methods require the use of airborne laser techniques (e.g. Lidar).

Ideally, the original DEM resolution should be equal to or better than the spatial resolution of the used HS imagery. The high-resolution DEM data ensure good geolocation accuracy and contributes to a detailed analysis of the illumination and viewing geometry conditions as input to the accurate atmospheric correction of the HS image data.

The DEM resolutions 20 x 20 m or better are still capable of resolving the topographic details in a satisfactory way to be used in the parametric geocoding and atmospheric correction of the data.

Ground control points

The Inertial Monitoring Unit (IMU) of the airborne HS data acquisition system is a delicate device which may introduce a variable drift or offsets in the aircraft attitude data. Mode-rate drift and offset errors of the IMU data can be controlled and corrected by suitable GCPs along the survey flight lines.

The ground control points should be distinct topographic features (coast/lake line details, rivers, etc) with geolocation information generated by GPS instruments or photogrammetric devices. In most cases, the available geocoded topographic vector data at scale 1: 100 000 or larger yields topographic features of reasonable accuracy.

Atmospheric corrections

A full account of the experiences with atmospheric corrections is given in Appendix 1; here only the main points are given.

The objective of any optical sensor is the extraction of physical, earth surface parameters such as reflectance, emissivity and temperature. To achieve this, the influence of the atmosphere, the solar illumination, the sensor viewing geometry and the terrain must be taken into account.

Several models have been developed for atmospheric corrections: ATREM, HATCH, ACORN and Flaash are the most widely used. The latter two are commercially available.

These programs attempt to infer such parameters as amount of water vapour, distributions of aerosols and scene visibility from their imprint on hyperspectral radiance data. These properties are then used to constrain highly accurate models of atmospheric radiation transfer to produce an estimate of true surface reflectance on pixel-by-pixel basis. These models are handicapped by the fact that they are basically assuming flat terrain (2 geometric degrees-of-freedom).

The only commercially available atmospheric modelling package to include the four geometric degrees-of-freedom (x,y,z, and scan angle) is ATCOR-4 (Richter & Schläpfer 2002). The scan angle dependence of the atmospheric correction functions is an important feature for the airborne sensors, such as HyMap, which have large FOV up to 60^{o}–90^{o}.

As demonstrated in this report (Appendix 1), the ATCOR-4 program package has been successfully used for the processing of the HyperGreen 2002 data.

Considering the often rugged terrain conditions and climatic characteristics, it is -based on the experience accumulated in this project - highly recommended to use an atmospheric modelling package which takes the four geometric degrees-of-freedom into account when transforming the sensor radiance data to surface reflectance data.

Spectral ground truth

The present project demonstrates the importance of spectroradiometric field measurements as a reference and quality control for the airborne data acquisition. Even a limited, well-conducted acquisition of high quality spectral ground truth provides data, which greatly enhances the potential and quality of products from HS image processing. Ideally the field spectroradiometric work should be done concurrently with the airborne HS data acquisition whereby selected homogeneous targets (´pseudo invariant fields') are measured during the HS scanner overflights.

Data processing and IT-resources

Returning to the issue of turnaround time for results, it can be stated that for a production situation where large areas of ground are being analysed using the HS data and looking for the presence of a mineral or mineral combinations, it is of importance to be aware of the time and computing requirements necessary to accomplish the task. The experience gained in this project makes it possible to give some guidelines concerning this.

Key issues for the efficient processing and analysis of the HS data are the performance of the used workstation in terms of CPU speed and memory (RAM) and the size of online disk storage. Moving and converting the HS data cubes from and to backups is time consuming and should be avoided.

Processing speed considerations are here based on computing in Windows NT environment with 1.6 GHz CPU speed and 1 GB RAM. It is highly advisable that the processing facilities have a minimum of 2 GB RAM and CPU speed 1.6 GHz or faster. Processing the data on modern 64 bit Unix workstation architectures is likely to further increase the processing speeds.

Processing of the airborne HS data can be conveniently divided into two major steps: a) preprocessing and b) hyperspectral data analysis

Preprocessing of data

Pr-processing of the HS data cubes comprise parametric geocoding and atmospheric correction. These procedures require considerable disk storage space. One line kilometre of HyMap data (ephemeris and DEM data included) occupies 26.5 megabytes (MB) of disk storage. The necessary pre-processing steps generate a number of intermediate work files and many of these must be available for the succeeding processing steps. In order to work efficiently one must reserve on line disk storage, which is at least eight times the size of the radiance data. This implies that the pre-processing of one kilometre flight line data requires 212 MB of online disk storage. The computing time is 3.5 minutes/km. The number of man-hours needed to organise and control the processing steps are estimated to 4.5 minutes /km.

If for instance 1000 line kilometres of HyMap data are to be pre-processed under the premises described above, one should have a minimum of 212 GB disk storage, use 58 hours CPU time and 75 man-hours to accomplish the task assuming a smooth process with no unexpected problems.

Analysis of prepared hyperspectral data

The amount of man-hours and processing time is highly variable depending on the selected analysis method. From a computing point of view the SAM method used in the present project is fast. The results from the SAM have to be controlled and evaluated interactively, which typically takes 1.5 minutes/km. Applied to the above scenario of 1000 line km survey, it would take additional 25 man hours to evaluate the SAM results.

Summary of conclusions

A high-resolution (5 x 5 m nominal pixel size) airborne hyperspectral survey was conducted in West Greenland in 2002 covering approximately 7500 km^2 of where previously a number of kimberlite bodies, in some localities diamond-bearing, had been discovered.

Spectral characteristics of the kimberlitic rocks were established by a field spectroradiometric survey which was conducted concurrently with the airborne survey.

Experience from the field spectroradiometric survey demonstrated that the mapping of the kimberlitic rocks is to be based on the detection of Fe-rich serpentine, phlogopite, carbonate minerals and talc using their characteristic absorption features in the short wave infrared spectral region (2.0–2.5 μm).

The detection of the kimberlite and related rocks by using the hyperspectral data shares the general limitations of optical sensors, i.e. targets must be visible and the illumination conditions reasonable. The detection is further constrained by the small size of the potential targets (typically one or a few image pixels in diameter) and their relatively subtle diagnostic spectral characteristics. Weathering, although predominantly mechanical in nature, clearly enhances the spectral response of kimberlitic rocks.

The spectral correlation between the ground truth data and the apparent surface reflectance data from the atmospheric correlation programs such as Flaash, ATREM and HyCorr was very poor.

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 results from such a processing technique (based on ATCOR-4 program) yielded reflectance data, which were in a reasonable agreement with the ground truth data.

The field spectra of the kimberlitic rocks in West Greenland are remarkably uniform. The Spectral Angle Mapper (SAM) method was used for comparing the image spectra to the selected, characteristic kimberlite field spectra.

The spectral mapping, apart from locating a number of known kimberlite occurrences, generated numerous further potential targets for a field follow up programme.

Recommendations for future work

The hyperspectral image analysis described in this report covers approximately 30% of the area of the 2002 airborne survey leaving much of the potential kimberlite prospecting area untouched. The following immediate recommendations emerge from the experience of the present project:

- *Kimberlite mapping of the 2002 HS survey area not yet covered by the detailed elevation model should be carried out immediately.*

The work should encompass pre-processing and image analysis of the HS radiance data as outlined in the present report. The critical issue for the pre-processing is the availability of high-resolution DEM data, which should have an original spatial resolution 16 x 16 m or better.

- *Follow up field work of the kimberlite targets outlined by the present HS data analysis should be carried out in 2004. Any high priority targets, which could be defined by the processing of the rest of the data should be visited, if possible*

To establish the real success rate, as well as the actual nature of the targets produced, the limited field follow up should be carried out at selected locations, preferably using a light-weight portable spectroradiometer. The main objectives of such a field campaign would be to tune the efficiency of this method and establish its limitations.

Acknowledgements

This project was financed by the Bureau of Minerals and Petroleum, Government of Greenland.

We fully acknowledge the professional skills of the HyVista team (Terry Cocks & Peter Cocks) and the Provincial Airlines, Halifax, Canada crew (Darcy Kellergrew & Paul Penny) for the airborne hyperspectral data acquisition.

Viljo Kuosmanen and Jukka Laitinen, Geological Survey of Finland and Uwe Schäffer, Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, Germany are thanked for the enjoyable collaboration in the field and their professional skills which ensured the high quality of the field spectroradiometric data.

The manuscript benefited from comments and criticism by Leif Thorning.

References

Cocks, T., Jenssen, A., Stewart, I., Wilson, I. & Shields, T. 1998: The HyMap Airborne Hyperspectral Sensor: The System, Calibration, and Performance. *Proc. 1st EARSeL Workshop on imaging Spectroscopy* (M. Schaepman, D. Schläpfer & Itten, Eds), 6-8 October1998, Zurich, EARSeL, Paris, 37-43.

Clark, R.N., Swayze, G.A., Gallagher, A., King, T.V.V., & Calvin, W.M. 1993: The U. S. Geological Survey Digital Spectral Library: Version: 0.2 to 3.0 mm*:* U.S. Geological Survey, Open File Report ***93-592***, 1340 p.

Goetz, A.F.H., Kindel, B., Ferri, M. & Guttmann, E. 2003: Atmospheric Correction of Hyperion and AVIRIS Data, Relative Performance of Four Different Radiative Transfer Models (Abstract). 3rd EARSeL Workshop on Imaging Spectroscopy, 13-16 May 2003, Oberpfaffenhofen, Germany

Jensen, S.M., Lind, M., Rasmussen, T.M., Schjøth, F. & Secher, K. 2003: Diamond Exploration data from West Greenland. Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/21** 50 pp. + 1 DVD.

Secher, K. & Larsen, L.M. 1980: Geology and mineralogy of the Sarfartôq carbonatite complex, southern West Greenland. Lithos **13**, 199–212.

Schläpfer, D. 2003: Parametric Geocoding, User Guide, Version 2.1, ReSe and RSL, Zurich.

Tukiainen, T., Krebs, J.D., Kuosmanen, V., Laitinen, J. & Schäffer, U. 2003: Field and Laboratory reflectance spectra of kimberlitic rocks, 0.35–2.5 μm, West Greenland, Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/43**, 25 p.

Doc: Appendix 1 Atmospheric correction .doc

Appendix 1: Atmospheric correction

Introduction

This appendix contains a slightly expanded description of the investigation of atmospheric correction.

The objective of any optical sensor is the extraction of physical earth surface parameters such as reflectance, emissivity and temperature. To achieve this goal, the influence of the atmosphere, solar illumination, sensor viewing geometry and terrain information must be taken into account.

Several models have been developed for atmospheric corrections: ATREM, HATCH, ACORN and FLAASH are the most widely used. The latter two are commercially available. These programs attempt to infer such parameters as amount of water vapour, distributions of aerosols and scene visibility from their "imprint" on hyperspectral radiance data. These properties are then used to constrain highly accurate models of atmospheric radiation transfer to produce an estimate of true surface reflectance on pixel-by-pixel basis. These models are handicapped by the fact that they are basically applied to flat terrain (2 geometric degrees-of-freedom).

The only commercially available atmospheric modelling package to include the four geometric degrees-of-freedom (x,y,z, and scan angle) is ATCOR-4 (Richter & Schläpfer 2002). The scan angle dependence of the atmospheric correction functions is an important feature for the airborne sensors, such as HyMap, which have large FOV up to 60^{o}–90^{o}.

The quality of the apparent reflectance data from these atmospheric modelling techniques is being widely discussed (for instance Goetz *et al* 2003). They seem to deliver satisfactory results in some terrain and climate combinations. The fact that these techniques do not require terrain elevation models makes them an attractive alternative for the projects constrained with time and other resources.

It was a tempting starting point for the present project to assume that the apparent surface reflectance data, which was one of the deliverables from the HS contractor, could satisfactorily fulfil the quality requirements for the atmospheric correction of the HyperGreen 2002 data.

To assess the applicability of the approaches producing apparent surface reflectance data, the quality of the HyCorr reflectance data was checked at two localities where spectroradiometric field truth data (Tukiainen *et al* 2003) are available. It was important that the surface expression of the reference targets was considerably bigger than the pixel size of the image data. The following localities were used:

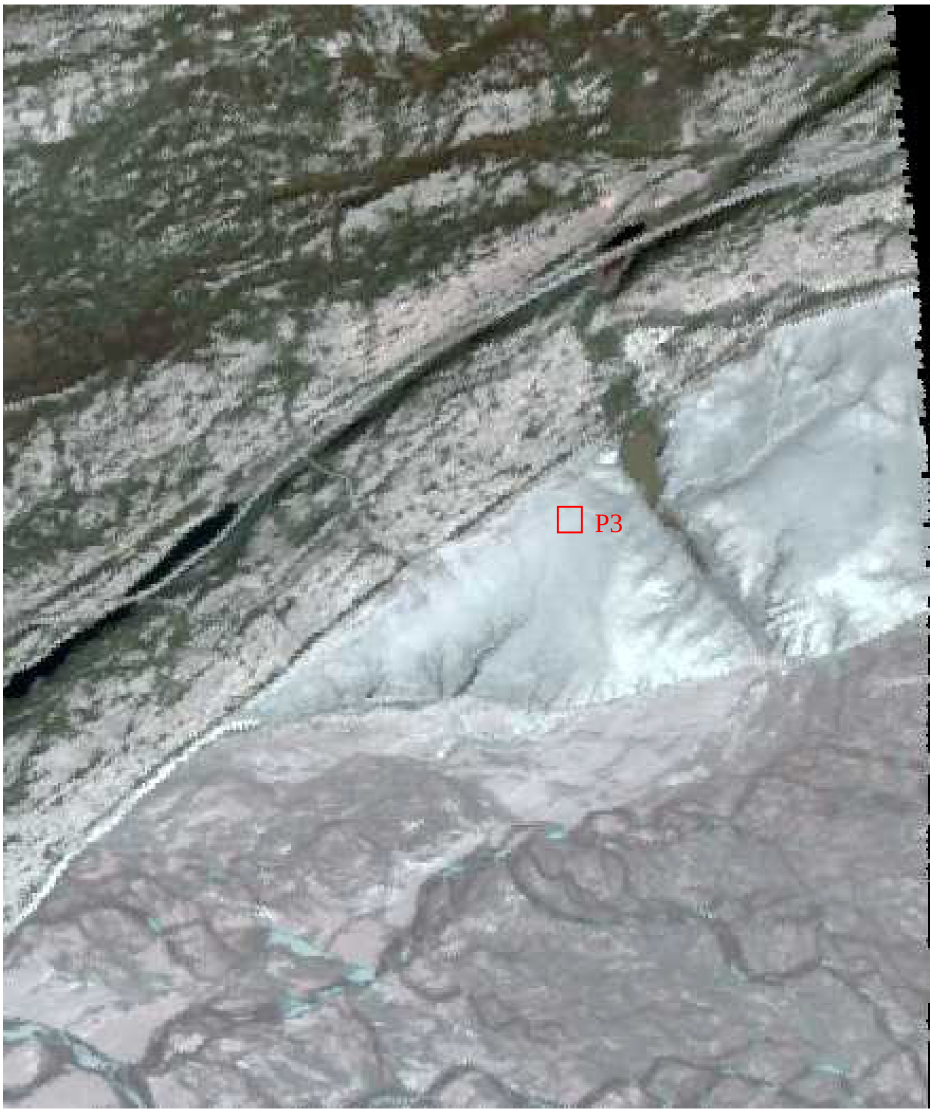


Figure 1. *Locality P3 on the silt formation (light grey) in the vicinity of Kangerlugssuaq airport. Background map: colour composite of HyMap data, natural colours.*

Locality P3 (Figure 1):

An old airstrip in the vicinity of Kangerlussuaq airport. The locality is a part of a major flat area composed of silt deposited in an ice-dammed lake. The locality was measured both in sunlight and using a tungsten-halogen lamp. For location and details see, Tukiainen *et al* (2003).

Locality K8 (Figure 2):

A major well exposed subvertical kimberlite dyke with abundant kimberlite weathering material. The size of the roughly oval-shaped exposure is ca 40 x 10 m. The locality was measured using a tungsten-halogen lamp. For location and details, see Tukiainen *et al* (2003).

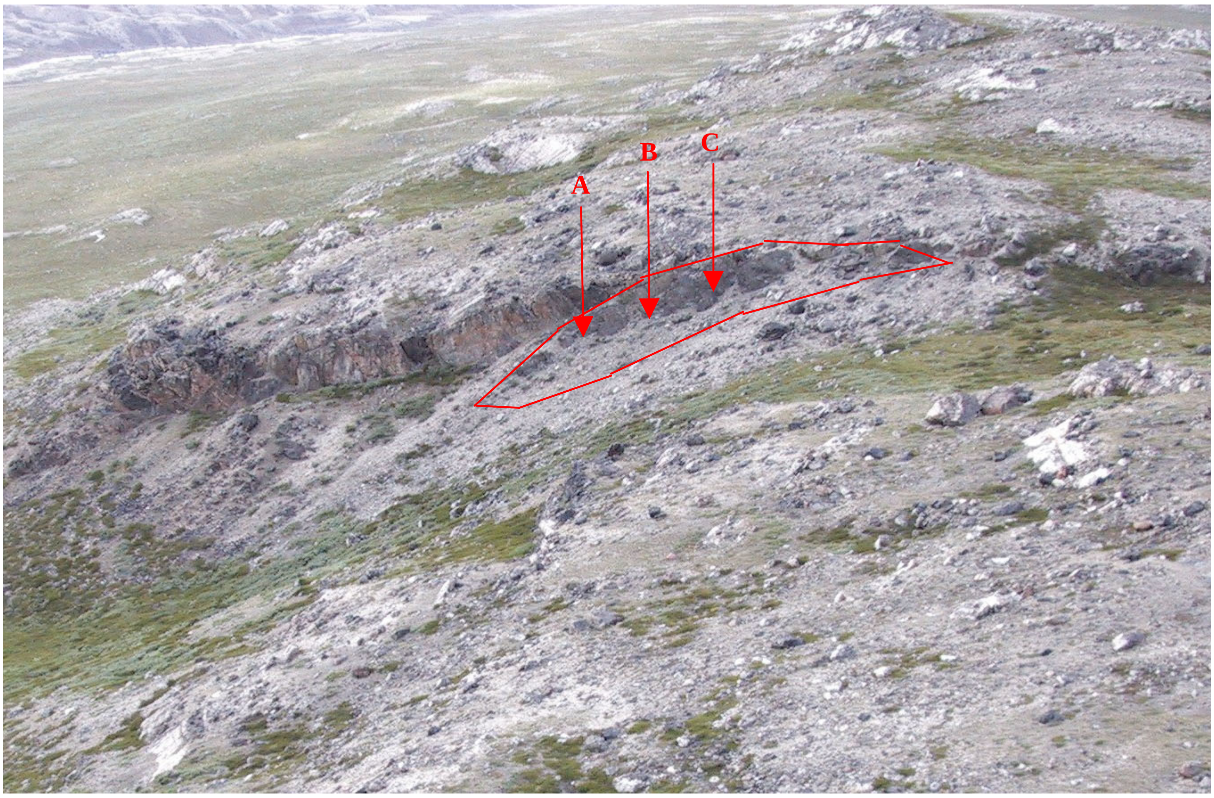


Figure 2 *Locality K12 ("Big Dyke") seen from the east. Lateral distance between the points A & C is approximately 30 metres. The outcrop and the area with abundant weathering products are outlined.*

The correlation between HyCorr reflectance data and field truth data in both localities is poor. The 'smooth' appearance of the HyCorr data can be probably related to some spectral polishing technique. To what extent the polishing has obscured the real spectral absorption features, is not known.

The Flaash – program package (ENVI) was tried as an alternative to generate apparent reflectivity data. The results from the locality P3 (Figure 3) are disappointing: the data are noisy and correlate badly with the ground truth data. Spectral polishing of the Flaash-processed data would generate data very similar to those from HyCorr.

The conclusion that must be drawn from the present project is that programmes such as HyCorr or Flaash failed to produce apparent surface reflectance data of sufficient quality. This is to a large extent due to the rugged terrain of West Greenland.

The good correlation between the ATCOR-4 processed reflectance data and ground truth data is clearly seen in both localities. The subtle absorption features beyond the 2.3 μm are seen in the ATCOR-4 processed data (Figure 4), whereas HyCorr processing has virtually removed them.

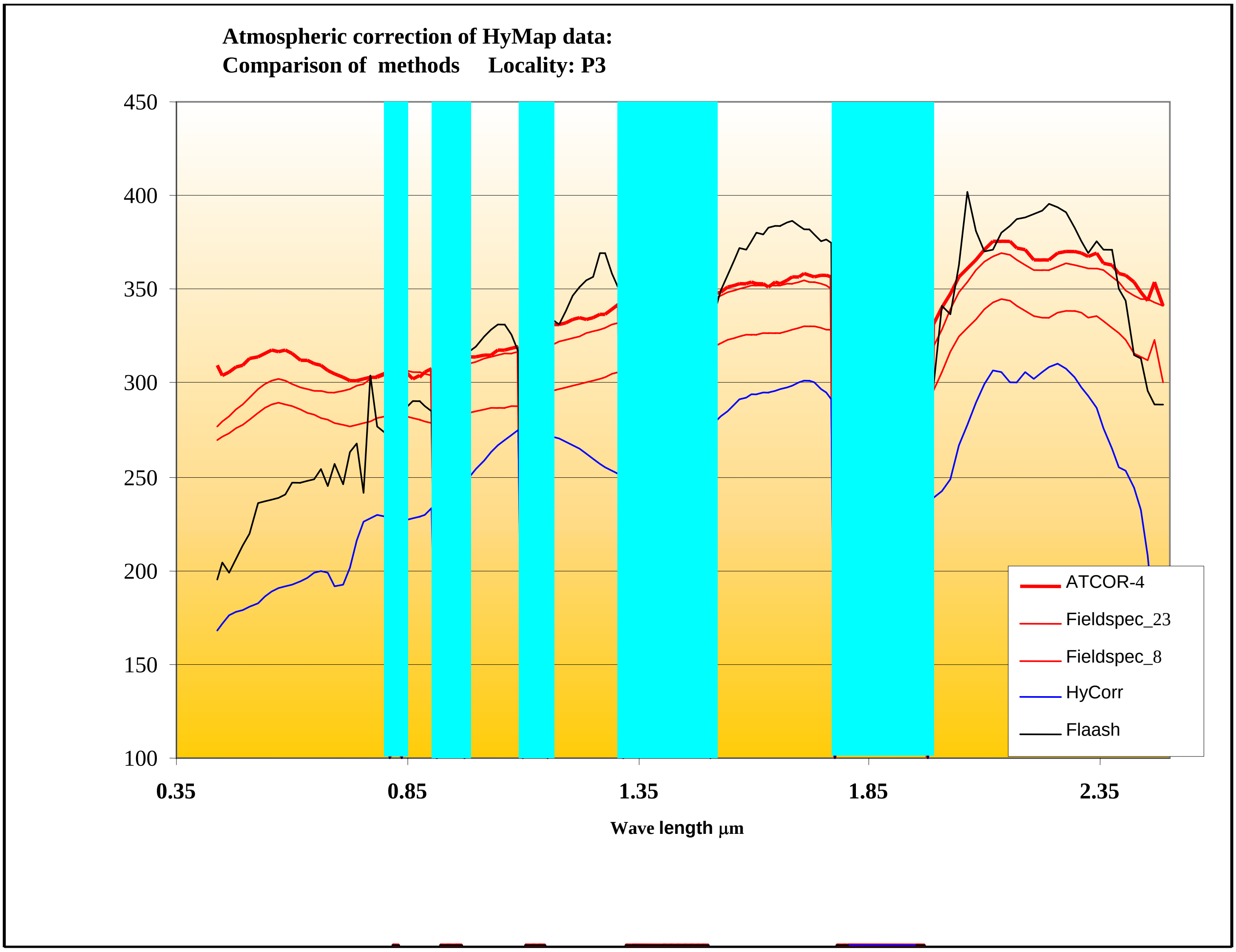
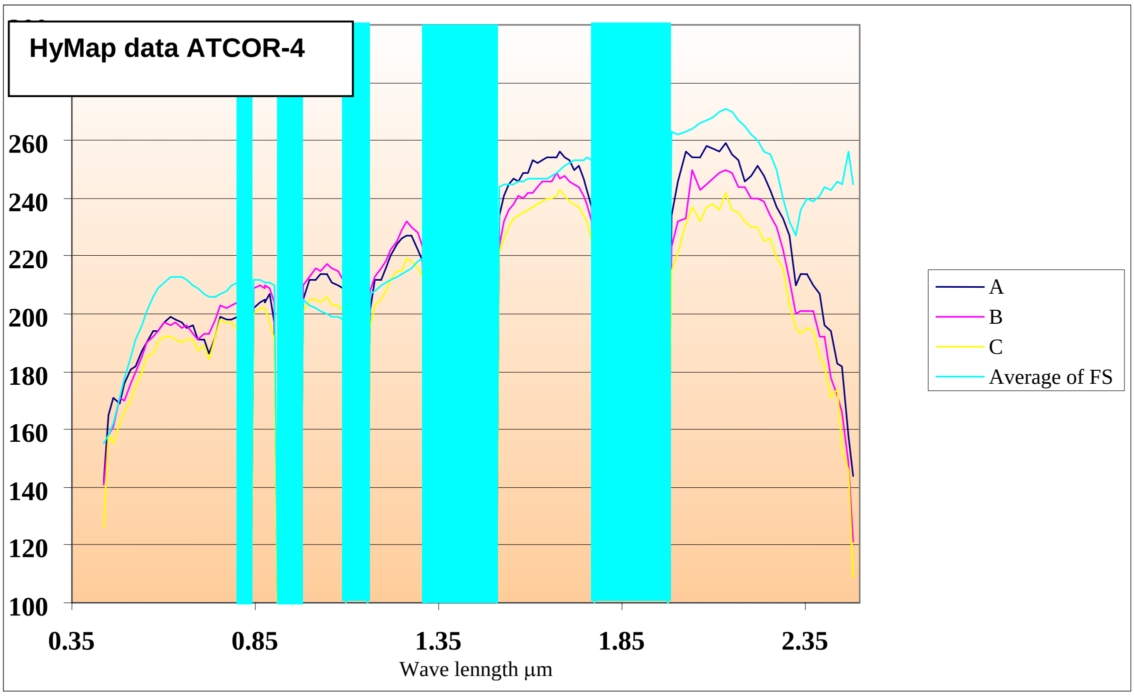


Figure 3 *Field spectra of homogeneous silt measured under sunlight (Fieldspec_23 & Fieldspec_8 resampled to HyMap bandwidths) and HyMap surface reflectance spectra produced by ATCOR4, HyCorr and Flaash. Locality P3*

Atmospheric correction

Digital elevation model

The general GEUS DEM for West Greenland has been calculated from the 1:100 000 scale topographic data, and it is as such not accurate terrain reference for the 4 x 4 m resolution.



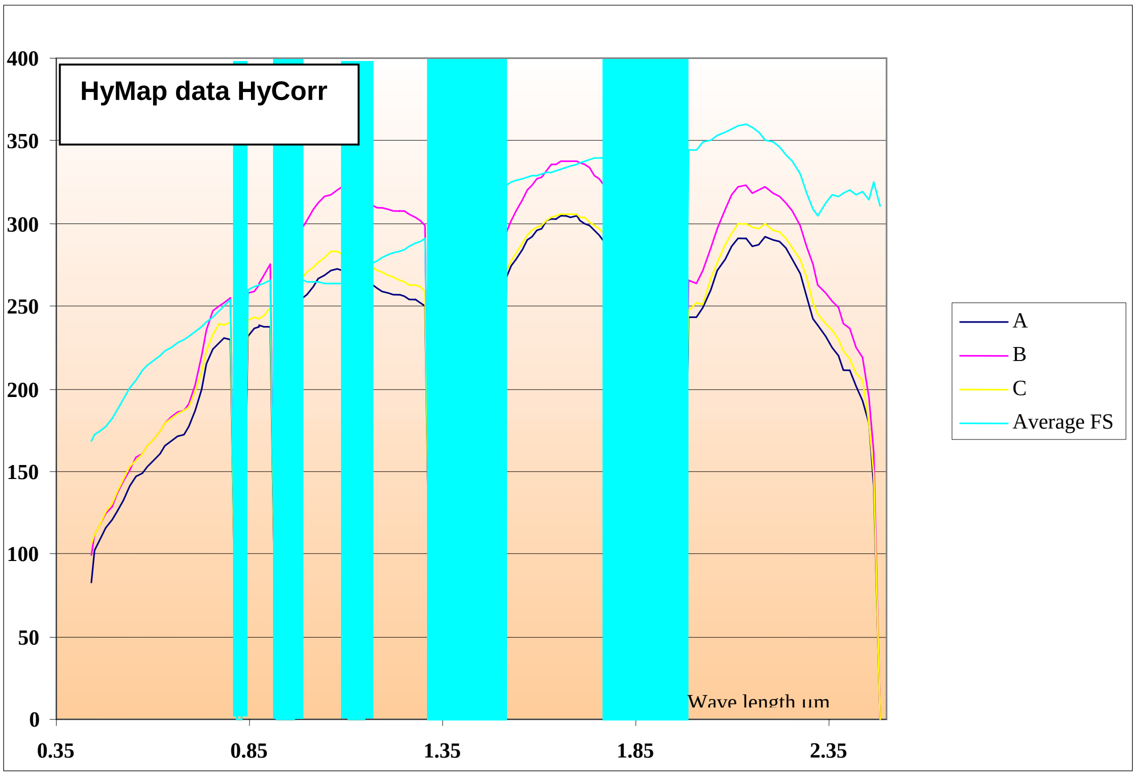


Figure 4. *Field spectra of kimberlite measured using a tungsten-halogen lamp (Average_FS, resampled to HyMap bandwidths) and HyMap surface reflectance spectra (A,B & C) produced by ATCOR-4 and HyCorr . Locality K 12 ("Big Dyke")*

HS image data. To evaluate the capabilities of the ATCOR-4 in a more appropriate way, a new more detailed DEM was produced at GEUS photogrammetric facilities.

The new DEM was generated from the scanned 1:100000 stereoscopic aerial photographs. It was anticipated that this imagery could generate a DEM with a 16 x 16 m spatial resolution. The 16 x 16 m DEM was resampled to 4 x 4 m resolution using bilinear interpolation. To reduce the speckle noise in the DEM, applying a median filter (over 4 points) produced the final DEM.

Parametric Geocoding

The HS image data were geocoded using the PARGE software (Schläpfer 2003). The new DEM and the flight line ephemeris data enable the parametric approach for geocoding. Apart from generating an orthoscopic geocoded image, the PARGE system also generates slope and aspect files and angular output for use in the ATCOR-4 program.

Atmospheric correction for rugged terrain

The ATCOR-4 program package (Richter 2003) was used to convert the HyMap radiance data cubes to surface reflectance data. The ATCOR-4 algorithm for rugged terrain was used. The processing details and steps for this algorithm are:

- During the calculation of the visibility index map DEM information (elevation, slope, aspect, skyview factor) is taken into account.
- The retrieval of water vapour map has to include the terrain elevation.
- The empirical BRDF (across-track illumination effects) correction is based on the local illumination map (local solar zenith angle) derived from the slope, aspect and shadow channels.
- Retrieval of the spectral reflectance cube consist of the steps:
  a) Three iterations for terrain reflectance
  b) Empirical BRDF correction depending on illumination map
  c) Adjacency correction
  d) Spherical albedo correction

The equation depends on all DEM information, maps of visibility index, water vapour, elevation and scan angle.

The adjacency and spherical albedo correction are not performed for spectral bands beyond 1.5 μm, since these effects are negligible for long wavelength bands.

Processing parameters

Aerosol type

The Rural model was chosen, 3000 metres above sea level with water vapour column 2.0 [g/cm^2] from sea level to space. Altitude-interpolated atmospheric files matched to the flight level were calculated for each flight line.

Maritime aerosol type or mixed rular/maritime options may give better results for the coastal areas. Furthermore, higher values for the water vapour column may be justified for the areas adjacent to and/or dissected by fiords.

In-flight calibration

In-flight calibration experiments are done to check the validity of the laboratory calibration. The aircraft environment is different from the laboratory and it may have an impact on the sensor performance. The in-flight calibration assumes that the spectral calibration does not chance, i.e. the centre wavelength and the spectral response curve of each channel are valid as obtained in laboratory.

The in-flight calibration of the HyperGreen 2002 data was based on the single (bright target) option in ATCOR-4 using the field spectroradiometric data from the locality P3 (Figures 1 & 3).

References

Goetz, A.F.H., Kindel, B., Ferri, M. & Guttmann, E. 2003: Atmospheric Correction of Hyperion and AVIRIS Data, Relative Performance of Four Different Radiative Transfer Models (Abstract). 3rd EARSeL Workshop on Imaging Spectroscopy, 13-16 May 2003, Oberpfaffenhofen, Germany

Richter, R. 2003: Atmospheric/Topographic correction for Airborne Imagery, ATCOR-4 Users Guide, Version 3, 2003*. DLR* – German Aerospace Center, DLR-IB-564-02/03., 67 pp.

Schläpfer, D. 2003: Parametric Geocoding (PARGE), Users Guide, Version 2.1. ReSe Applications Schläpfer, WilSG & Remote Sensing Laboratories University of Zurich, Wil SG, 166 pp.

Tukiainen, T., Krebs, J.D., Kuosmanen, V., Laitinen, J. & Schäffer, U. 2003: Field and Laboratory reflectance spectra of kimberlitic rocks, 0.35 – 2.5 μm, West Greenland, Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/43**, 25 pp.

Appendix 2: Spectral library

Tukiainen, T., Krebs, J.D., Kuosmanen, V., Laitinen, J. & Schäffer, U. 2003: Field and Laboratory reflectance spectra of kimberlitic rocks, 0.35–2.5 μm, West Greenland, Danmarks og Grønlands Geologiske Undersøgelse Rapport **2003/43**, 25 pp.

EXCL. CD-ROM

Field and laboratory reflectance spectra of kimberlitic rocks, 0.35 to 2.5 micrometers, West Greenland

Tapani Tukiainen, GEUS
Johan Ditlev Krebs, GEUS
Viljo Kuosmanen, GSF
Jukka Laitinen, GSF
Uwe Schäffer, BGR

CONTENTS

Introduction

Project background

Project Hypergreen 2002 of the Geological Survey of Denmark and Greenland (GEUS) conducted a hyperspectral (HS) airborne survey in West Greenland in 2002. The Bureau of Minerals and Petroleum (BMP), Government of Greenland financed the project. HyVista Corporation, Australia was selected as the contractor for the airborne survey using the company's HyMap hyperspectral scanner, manufactured by Integrated Spectronics Pty, Ltd, Australia.

The prime objective of the airborne HS survey is to assist the mapping of the kimberlitic rocks. The earlier investigations have demonstrated that some of the kimberlites in West Greenland are diamond-bearing, which has made the region an important target for diamond prospecting.

To establish the spectral characteristics of the kimberlitic rocks of West Greenland, a field programme was carried out to measure spectra from selected kimberlite occurrences. Accurate spectral ground truth from the known occurrences of kimberlitic rocks is of crucial importance for the development of image processing procedures for the mapping of kimberlitic rocks.

The field work was carried in the period 1st of July – 30th of July 2002. The activities were based on Kangerlussuaq International Science Support (KISS) facilities at Kangerlugssaq.

The most important means of transportation during the fieldwork was a helicopter - chartered on *ad hoc* basis from the company Grønlandsfly. Limited fieldwork could also be carried out by car in the surroundings of Kangerlussuaq airport.

The scope of this report is to provide (1) a technical description of the essentials of the data collection and (2) the spectral database with descriptive and geolocation information.

Personnel and responsibilities

Experts from Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Germany and Geological Survey of Finland (GTK) were invited to carry out the field and laboratory measurements. The field staff comprised the following persons:

Uwe Schäffer	BGR	01 – 22/July 2002	Research scientist
Viljo Kuosmanen	GSF	04/July - 01/Aug 2002	Research scientst
Jukka Laitinen	GSF	04 – 16/July 2002	Research scientist
Johan Ditlev Krebs	GEUS	01- 30/July	Research assistent
Tapani Tukiainen	GEUS	03/July – 11/August 2002	Project leader

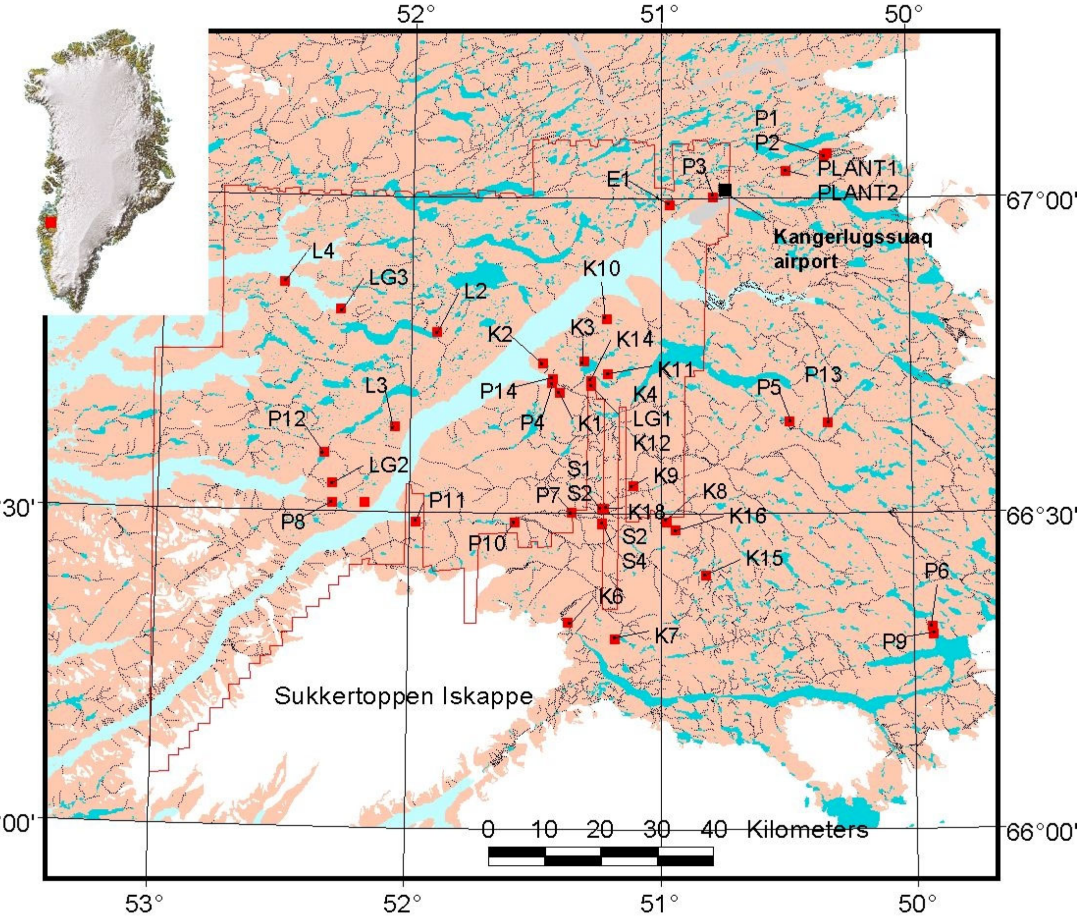


Figure 1. *Field localities where spectroradiometric measurements were carried out. The area covered by the airborne hyperspectral survey is indicated by the thin red line. Code for sites are: K = kimberlitic rocks, L = lamproitic rocks, LG= local geology, S=rocks of the Sarfartoq carbonatite complex, P=pseudo invariant fields, Plant=vegetation, E=environmental.*

Figure 2. *The biggest kimberlite exposure (K12) with abundant weathering material seen from the East. Insert: close up of the dike.*

Measurement localities

The 44 measurement localities (Fig. 1) fall into seven categories:

Kimberlite (K):

Field measurements were carried out in 18 localities. The visited occurrences vary from thin, some decimeter wide dykes or sheets to a major c 3 meter wide dyke (locality K12, Figure 1. andFigure 2.). Rock exposure is a rule poor, some of the localities are merely *in situ* block fields.

Lamproite (L):

Lamproitic rocks occur in the western part of the area. Size and rock exposure conditions are similar to the kimberlites.

Local geology (LG):

Spectral characteristics of the country rocks; gneiss, amphibolite, mafic dykes, anorthosite, etc. were measured at some localities.

Sarfartoq carbonatite complex (S):

The major rock types of the Sarfartoq carbonatite complex: carbonatite (sövite, beforsite), fenite and pyrochlore enriched rocks were measured in four localities.

Pseudo invariant fields (P):

The airborne imaging spectrometry data is normally offered to the client by the operator as ‘at sensor’ radiance which has to be transformed into ground reflectance. Therefore spectral measurements on large ‘standard reflectance panels’’ on ground level are needed for downward calculation of radiance and to transform it into ground reflectance. In practise, large homogenous, flat fields, such as sand dunes, homogenous rock outcrops are chosen and prepared for these purposes. Wulder et al. (1996) call them ‘Pseudo Invariant Fields’ (PIF’s). The PIF’s are practically ideal if they fulfil the following requirements (Kuosmanen et al 2000):

- A PIF must be approximately a Lambertian surface
- Internal spectral reflectance should be smooth, no sharp absorption features
- Internal reflectance content of each PIF is as constant as possible. Sun illumination must be uniform on the PIF surface. These are checked by consecutive measurements from different locations on the PIF, before and after overflight.
- Minimum size of PIF is 3x3 pixel sizes
- Minimum number of PIF’s is two, light (over all wavelengths) and dark (over all wavelengths)
- The PIF’s are optimally located if they lie in the centre of the flight line.
- The PIF area must be distinguishable from its background. A clear spectral signal (e.g. a car) can be placed in the neighbourhood.
- Sun irradiance on each PIF is measured during the overflight
- A helicopter camera photo from each PIF is of great help, when a reference pixel is searched from HyMap data.

Fourteen PIF localities – mainly homogeneous, vegetation free exposures of alluvial material were selected from the HyperGreen survey area. Most of the above requirements were met in all chosen localities. However, due to complicated flight execution and actual instrument availability, irradiation measurements during the overflight were not possible.

Environmental (E):

Spectra from selected localities with an oil-contaminated surface layer were cursorily measured in the vicinity of the abandoned military radio antenna facility at Kellyville (E).

Instrumentation and methods

FieldSpecFR instrument specifications and set up

The specifications for the portable spectroradiometer FieldspecFR used for HyperGreen 2002 measurements are summarised in Table 1.

Table 1. *Specification for FieldSpecFR*

Parameter	Specifications
Spectral Range	350-2500 nm
Spectral Resolution	3.0 nm @ 700 nm 10 nm @ 1400 & 2100nm
Sampling Interval	1.4 nm @ 350-1050nm 2.0 nm @ 1000-2500nm
Scanning time	100 milliseconds
Detectors	One 512 element Si photodiode array 350-1000 nm Two separate, TE cooled, graded indexInGaAs photodiodes 1000-2500 nm
Input	1.4 m fiber optic (23° field of view) Optional foreoptics available
Calibration	Wavelength, reflectance, radiance*, irradiance*. All calibrations are NIST (NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY) traceable (*radiometric calibrations are optional)
Noise Equivalent Radiance (NeDL)	UV/VNIR 1.4 x 10^{-9} W/cm2/nm/sr @700nm NIR 2.4 x 10^{-9} W/cm2/nm/sr @400nm NIR 8.8 x 10^{-9} W/cm2/nm/sr @2100nm
Notebook Computer	Pentium processor, 800 MB hard disk, 16 MB Ram, 3.5" floppy disk drive, battery, AC power supply
Weight	7.2 kg

The fore optics (optical lenses in front of the scanner used to set the effective angle of incidence) for radiance measurements of the Spectralon reference panel (measured for irradiance determination) and target measurements under sunlight were as follows:

- GTK instrument: bare fibre (e.i. 23 degrees field of view (FOV))
- BGR instrument: fore optics resulting in 8 degrees of FOV

Makita contact probe and lamp was used for contact measurements of the targets. Type of fore optics is mentioned with all measurements in the HyperGreen spectral database.

Calibration and units

The following practise for the calibration of radiance, irradiance and reflectance measurements were used:

Radiance and irradiance calibration is in-built in the instrument but it was cross-checked between the GTK and BGR instruments. (Radiance Unit: W/sr•m^{2,} Irradiance Unit: W/m^2).

Reflectance Standard: A Lambertian diffuse 'Spectralon Reference panel' was used as a reflectance standard. This panel is mainly composed of PTFE and it provides 100% light reflectance over wavelengths 400-2500 nm. (Spectralon® is a registered trademark of Labsphere, Inc.).

Reflectance: Reflectance of a surface is the ratio of the radiant energy reflected from a surface to the radiant energy incident on the surface. (Reflectance unit: % or fraction).

Reflection: The process by which incident illumination reacts with the sample and is converted to radiant energy that subsequently travels back away from the sample surface (also see Absorbed Energy). All real reflection involves varying degrees of specular reflection and diffuse reflection.

For more definitions and details see http://www.asdi.com/asdi_t2_sc_glo.html

Illumination conditions

Sun illumination conditions were highly variable during the fieldwork in July 2002 due to unpredictably changing weather. This may affect the HyMap data quality. However, because it was possible to choose and measure several ground truth localities (PIF's) by Makita light, it is expected that satisfactory homogenisation of the HyMap data can be achieved.

Field measurements

Two persons are normally needed to carry out field measurements with one FieldSpecFR instrument. The technical performance of field reflectance measurements is carried out through a repeated sequence of steps after arriving to the target, explained in the following instructions:

1. Open FieldSpec and mount the accessories, turn the instrument on and then the computer on.
2. Choose fore optics according to target distance and size, and illumination needed depending e.g. on sunlight availability.
3. Run 3-sensor calibration & black current determination
4. Choose the savefile number and mode (Radiance Irradiance or Reflectance) of measurements to be stored
5. Run White Reference (WR) if reflectance was chosen in 4
6. Direct the fiber with foreoptics to the target
7. Record the reflectance to the ASD savefile.
8. Transfer the savefile into Excel or ascii for further input into HyperGreen spectral database

Laboratory measurements

Perkin Elmer Lambda 19 laboratory spectrometry

Seventy six selected samples of rocks, debris and soils from different target areas have been chosen for laboratory spectrometry at the BGR Perkin Elmer Lambda 19 laboratory instrument in Hanover. Multiple measurements of kimberlitic and other rock samples with respect to different surfaces underlined the fact that the general reflection signal of dark kimberlites is very weak. Fresh samples of kimberlites (cutted or broken surfaces) reveal a very poor and non-distinctive data set in the reflective range of 400 to 2500 nm.

Distinctive features can be expected from brighter weathered surfaces, which reflect the natural field conditions. For that reason some samples have been measured several times under different conditions.

For simplification, the results and the assessment of signal quality have been differentiated into:

- strong signal,
- distinct signal,
- existing signal,
- weak signal,
- no, or weak signal.

The important specifications of the UV/VIS/NIR Perkin Elmer Lambda 19 instrument are:

- double beam ultraviolet / visible / near-infrared spectrometer,
- PC-controlled,
- Spectral range: 185 – 3200 nm,
- Spectral resolution: +/- 0.15 nm (UV / VIS), +/- 0.6 nm (NIR),
- Sampling slit: 0.05 – 5.0 nm (UV / VIS), 0.2 – 20 nm (NIR),
- Sampling interval: 0.01 nm (UV / VIS).

All measurements have been carried out in the range of 400 to 2500 nm, with a sampling slit of 2.0 nm and samling interval of 1.0 nm.

FieldSpecFR laboratory spectrometry

A set of kimberlite hard rock and powdered samples were also measured by FieldSpecFR in GTK's Remote Sensing Laboratory. These measurements do not significantly differ from those done in the field. Fore-optics for hardrock samples was Bare Fiber with 50 W tungsten-halogen light source and for the powders, the Makita mounting was used.

Spectral database

Overview

To make the data readily available for interested parties, the results of the fieldwork is stored in a Microsoft Excel-file on CD-ROM:

HyperGreen2002_Spectral_library.xls

The spectral database contains references to digital photographs (jpeg - format): these are stored on a directory HyperGreen2002_photos on the CD-ROM.

Table 2. *The structure and attributes of the database:*

Sheet Name	Field name	Values	Comments & descripton
Descriptions	Spectra_Id	BGRnnn GTKnnn	*Unique spectra id*
Descriptions	Date		
Descriptions	GEUS_Sample_#		
Descriptions	Locality	*Locality types:*	*K=kimberlite,* *L=lamproite* *LG=local geology* *P=pseudo invariant feature* *S=rocks types within Sarfartoq Carbonatite complex.* *E=environmental (from Kelly Ville)* *Plant = vegetation*
Descriptions	Measuring method		
		Sun 8 deg	*FieldSpec optic fibre with lens sunlight*
		Sun 23 deg	*FieldSpec raw optic fibre sunlight*
		Lab/Perkin Elmer	
		Lamp & Lab/lamp	*FieldSpec raw optic fibre Tungsten halogen lamp*
		Cos receptor	FieldSpec cosine alpha receptor
Descriptions	Data type		
		Ref	*Reflectance*
		Rad	*radiance*
		Irad	*irradiance*
Descriptions	Distance	metres	*Distance between sensor and target*

Descriptions	Photo	file name	*Digital photo of target*
Descriptions	Latitude	decimal degrees	*Geographical co-ordinate*
Descriptions	Longitude	decimal degrees	*Geographical co-ordinate*
Descriptions	Altitude	metres	*Altitude above sea level*
Descriptions	Collector	initials	*Collectors' initials*
		UW = *Uwe Schäffer*	
		JDK = *Johan Ditlev Krebs*	
		TT = *Tapani Tukiainen*	
		JL = *Jukka Laitinen*	
		VK = *Viljo Kuosmanen*	
Descriptions	Loc_photos	file name	*Overview digital photo of locality*

Sheet	***Column 1***	***Column_2 – Column_n***	
BGR_LAB	Wavelength	Spectra	
GTK_LAB	Wavelength	Spectra	
			Row # 1: Spectra_ID Row # 2: GEUS sample # Row # 3 – 2500 data
BGR_FIELD_1	Wavelength	Spectra	Row # 1 Spectra_ID
BGR_FIELD_2	Wavelength	Spectra	Row # 2 – 2500 data (BGR)
GTK_FIELD_1	Wavelength	Spectra	
GTK_FIELD_2	Wavelength	Spectra	

In addition to the Excel-files a collection of digital photographs are included in the spectral database.

Spectral targets

Pseudo invariant features

Numerous PIF localities – mainly homogeneous, vegetation free exposures of alluvial material were selected for detailed, measurements. Reflectance measurements and the interpreted outliers for one PIF locality are shown in Figure 3. However, due to instrument availabilities the irradiation measurements during the overflight are not available. However, some mid day clear-weather irradiance measurements were done and documented into the spectral database. Spectral variability of the PIF reflectances (Figure 4) is not high, but maybe sufficient for finding 'dark' and 'light' pixels. The reflectance spectra in Figure 4 are averages of measurements for each PIF (outliers excluded).

In a few PIF localities, reflectance was measured both under sunlight and by Makita.
In the locality P3 (Figure 5) reflectance curves from sunlight and Makita measurements fit well in short wave infrared (SWIR) area, which is most important for mineral detection purposes. Differences in visible (VIS) and NIR area are due to the fact that the measurement localities were not exactly the same.

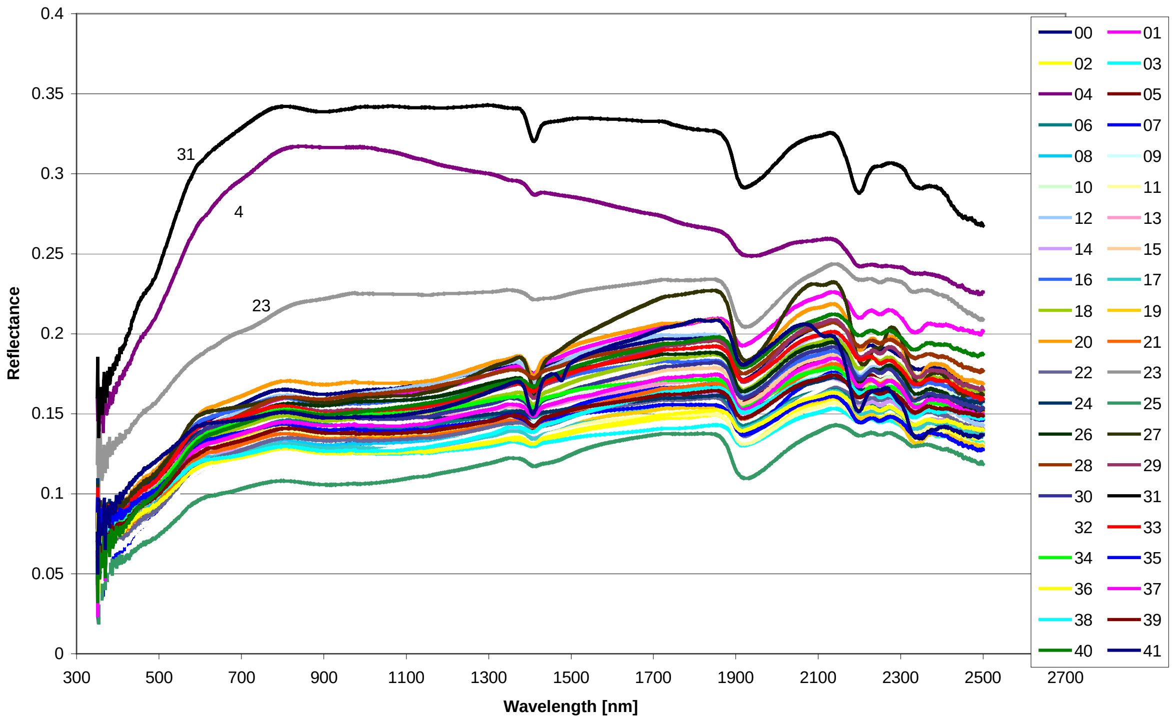


Figure 3. *Individual measurements from the PIF locality P10. The sample numbers 4, 23 and 31 indicates the excluded outliers*.

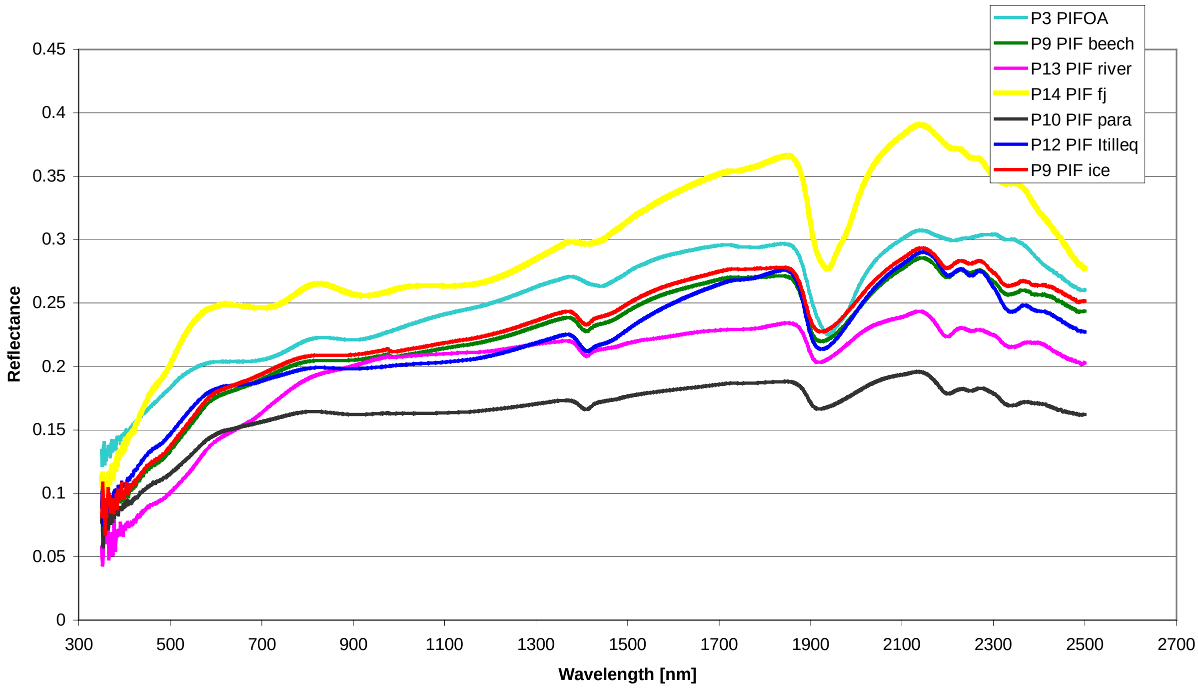


Figure 4. *Average spectral reflectances of seven PIF localities*.

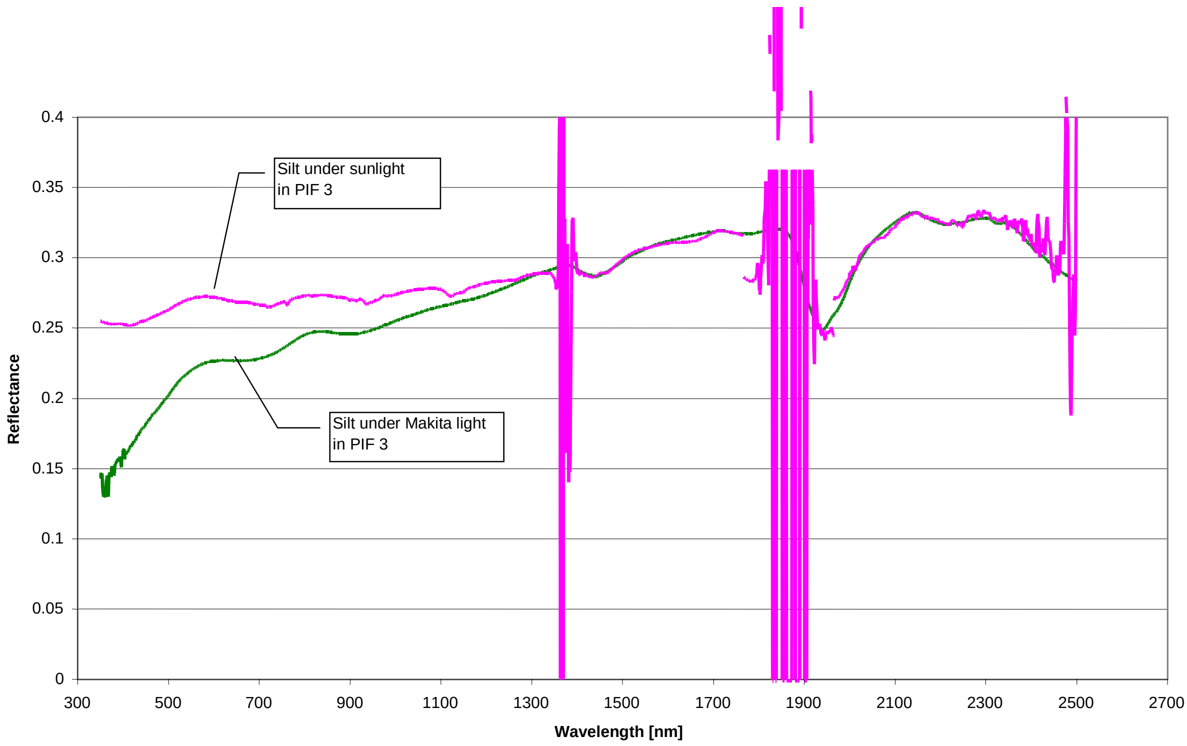


Figure 5. *Reflectance of the silt surface at PIF P3. Differences in the VIS &NIR area are due to slightly different measurement locations.*

Kimberlite targets

The kimberlite targets in the area are frequently covered by a weathering surface. Both the weathered 'soil' cover, the exposed hard rock weathered surface and the unaltered hard broken kimberlite surface were frequently measured (Figure 6).

An average reflectance curve of six PIFs can be regarded as the reflectance of 'bulk bed-rock' in Figure 7. Comparison between the average PIF reflection and the surface expressions of kimberlite in locality K12 gives a rough idea about their spectral separability (Figure 7 and Figure 8).

Kimberlite targets are mafic rocks with flat reflectance curves. The weathering surfaces, however, show tendency to have more vivid spectral appearance than the fresh broken surfaces. The spectral contrast between the weathered kimberlite and the surrounding rocks, as exemplified by the rocks in locality K12, is not great but clearly recognisable (Figure 8).

Comparison of the 'soil' covering the kimberlite and hard kimberlite rock suggests that the 'soil' on the kimberlite bodies seem to be a result of physical weathering rather than arise from chemical change (Figure 9 & 10).

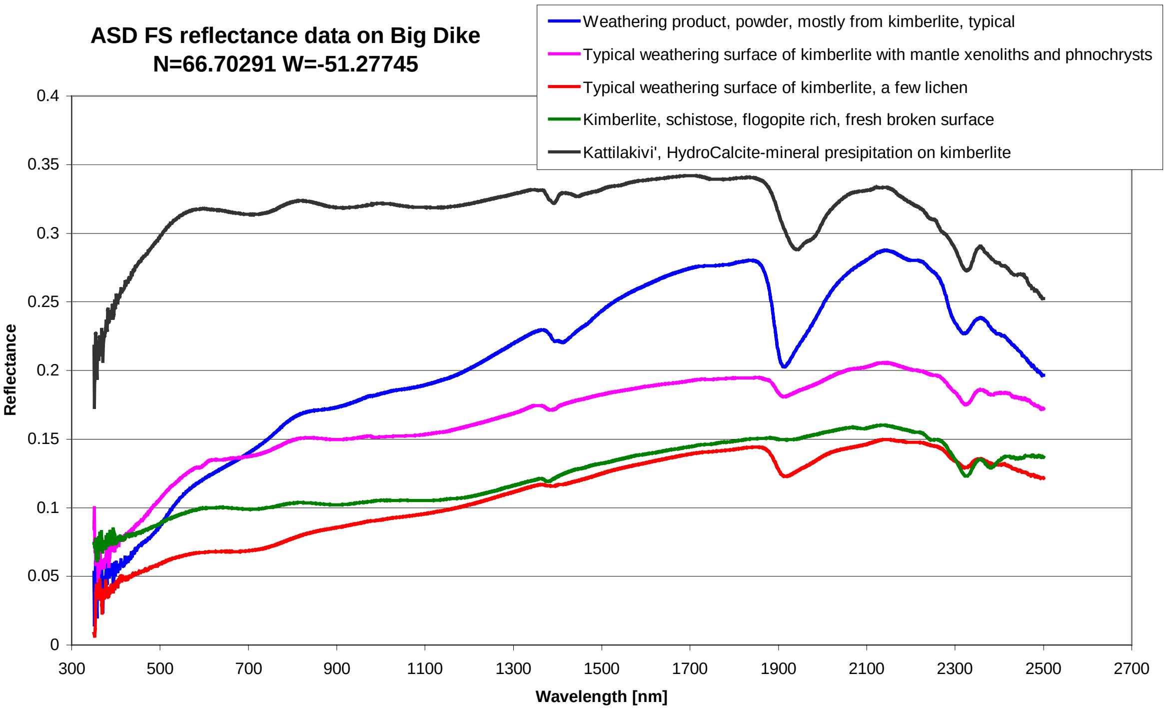


Figure 6. *Typical surface expressions of kimberlites.*

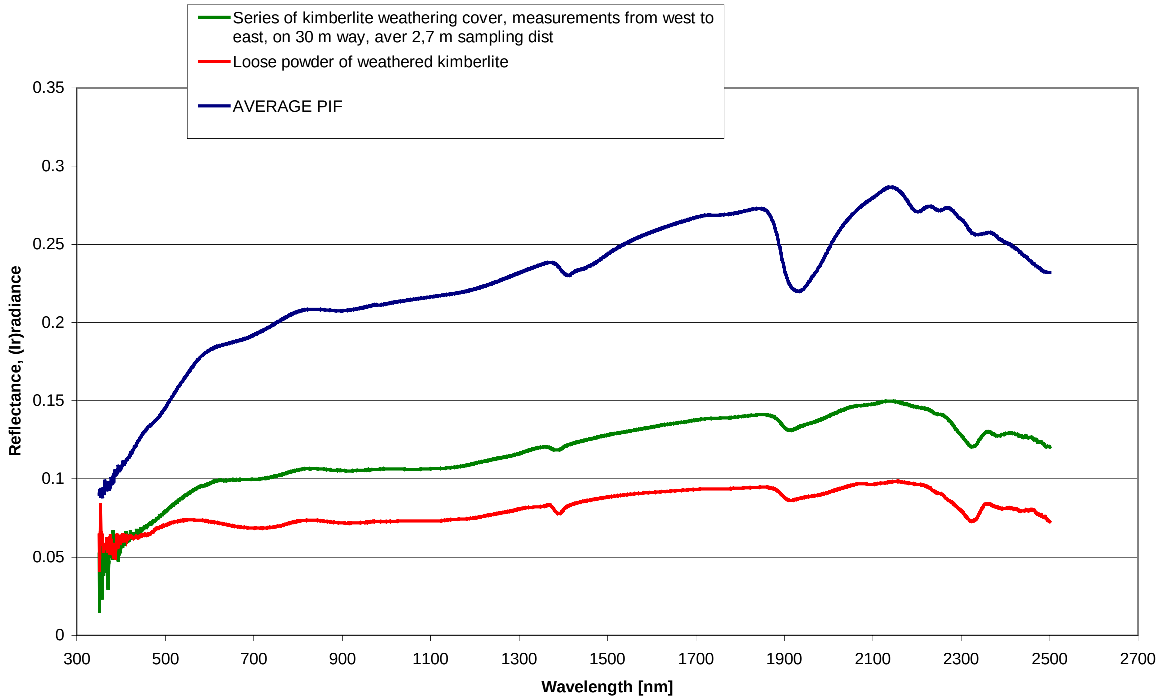


Figure 7. *Surface expressions of kimberlite (two lowest curves) in the kimberlite location K12 and average reflectance of six PIFs.*

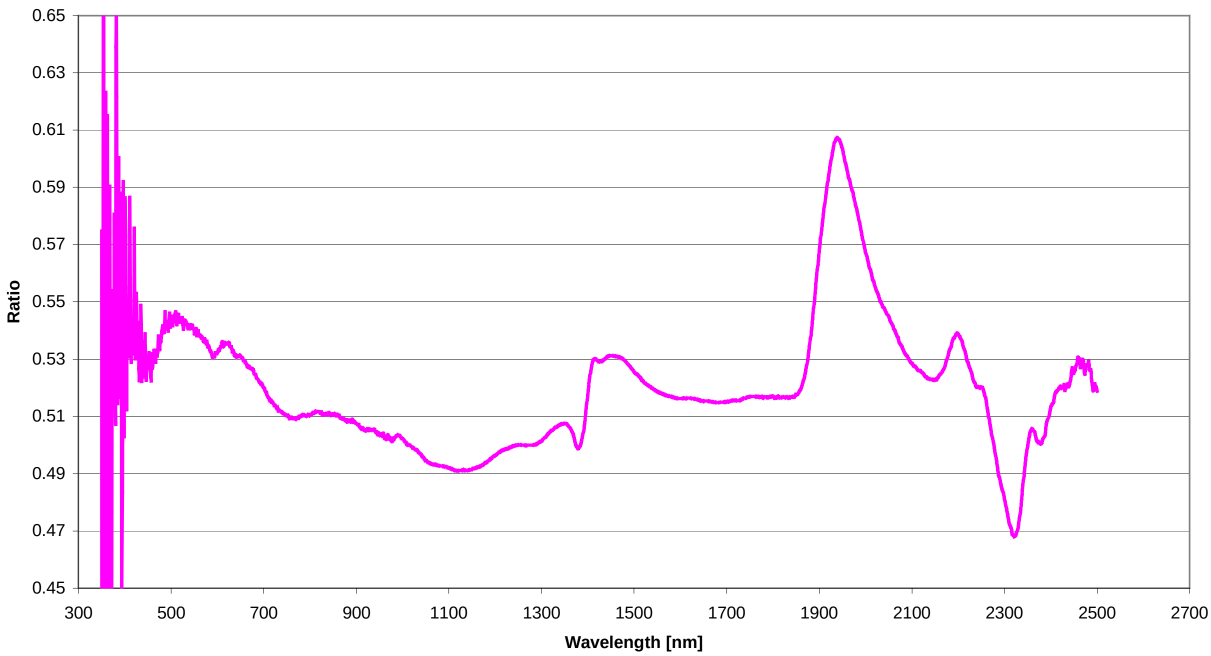


Figure 8. *Ratio between kimberlite suface expression and average PIF reflectance.*

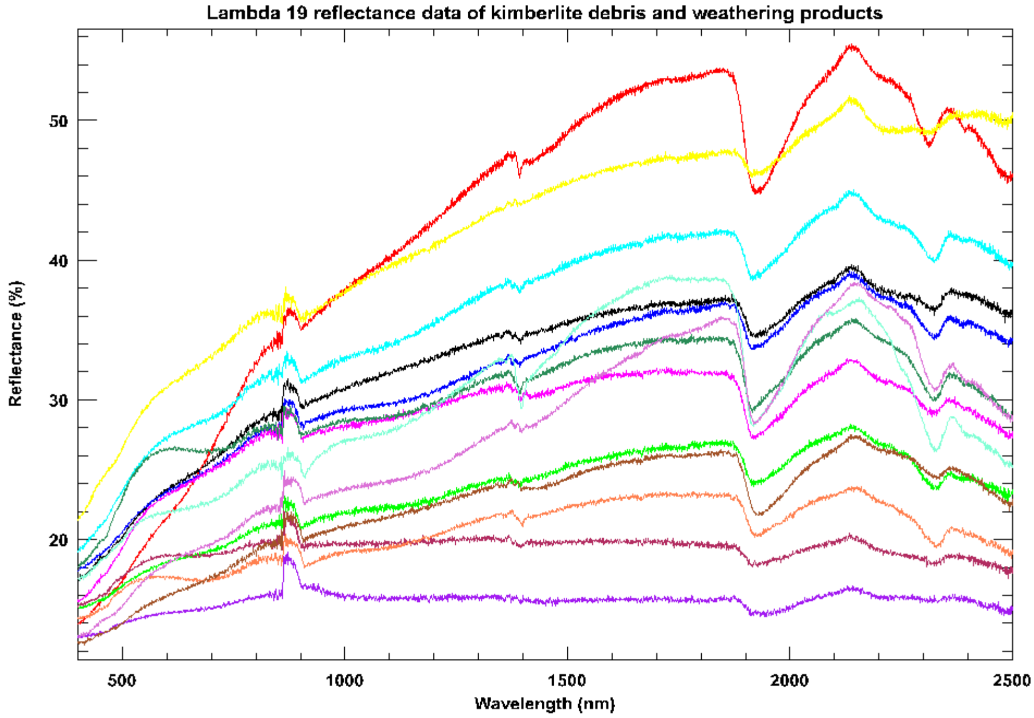


Figure 9. *Reflectance spectra of kimberlite debris, weathered kimberlite and overlying soil.*

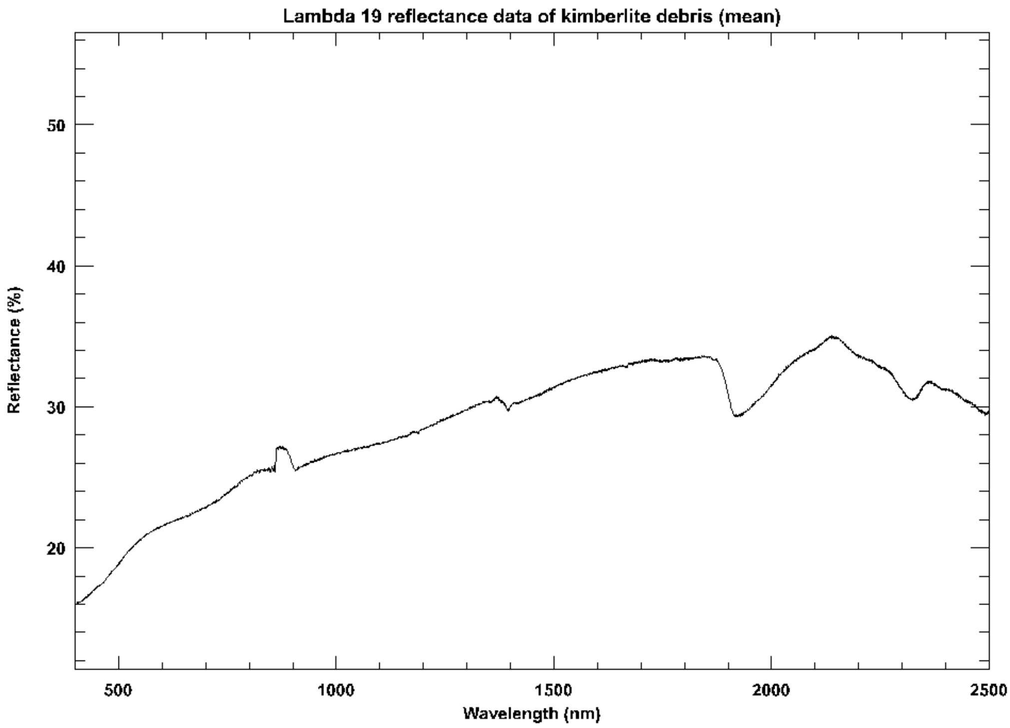


Figure 10. *Reflectance spectrum of calculated mean of crushed and weathered kimberlites.*

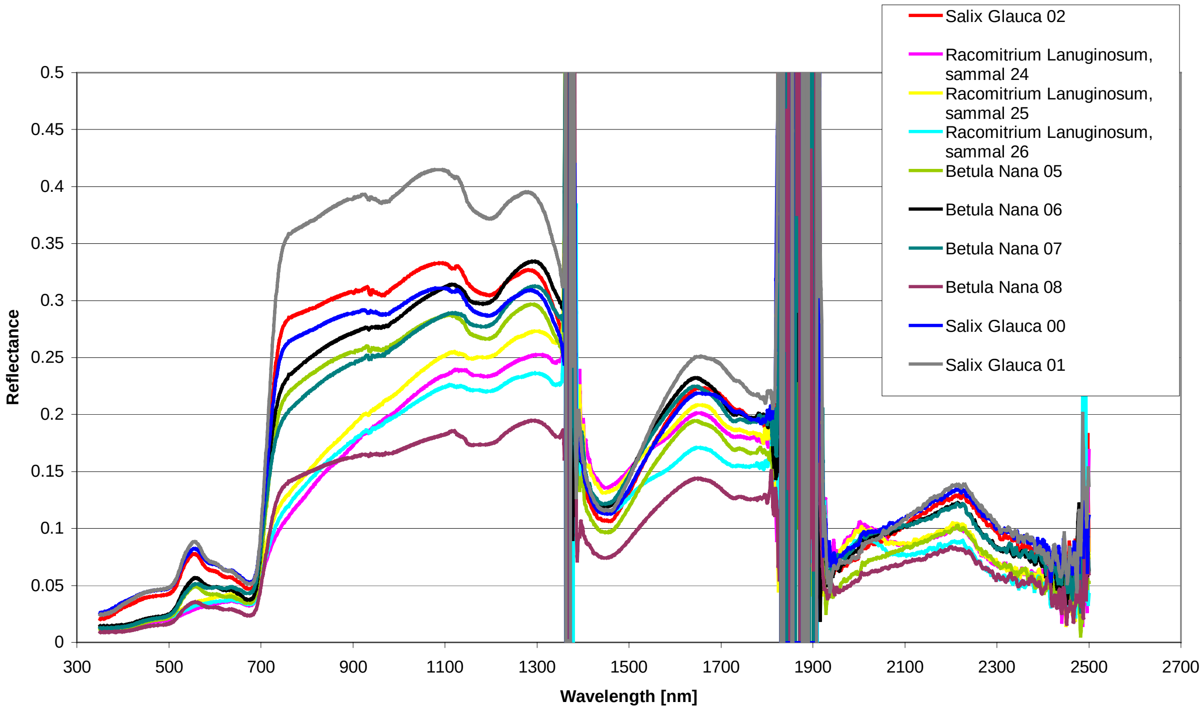
Vegetation targets

Twenty four typical vegetation targets were selected for reflectance measurements under sunlight. The GTK instrument used bare fiber for 'canopy' measurements from a distance of 0.3-1.0 meters.

The following plants were measured (Figure 11):

- Salix Glauca (willow)
- Betula Nana (birch)
- Kobresia Myosuroides (yellow hay)
- Calamagrostis Langsdorfii (green long flourishing hay)
- Racomitrium Lanuginosum (moss)
- Mixed pixel with hay, birch and moss

An orange lichen (Species not identified) seemed to be a typical cover for mafic/dark rocks such as gabbros, amfibolites, peridotites and kimberlites. This lichen occurred seldom on felsic rocks. A set of rock-lichen targets were measured (Figure 11). A typical exposed kimberlite surface is included in the diagram for comparison. Some kimberlite targets seem to



be covered by more flourishing vegetation than the country rock gneises.

Figure 11. *Vegetation spectra measured under sunlight.*

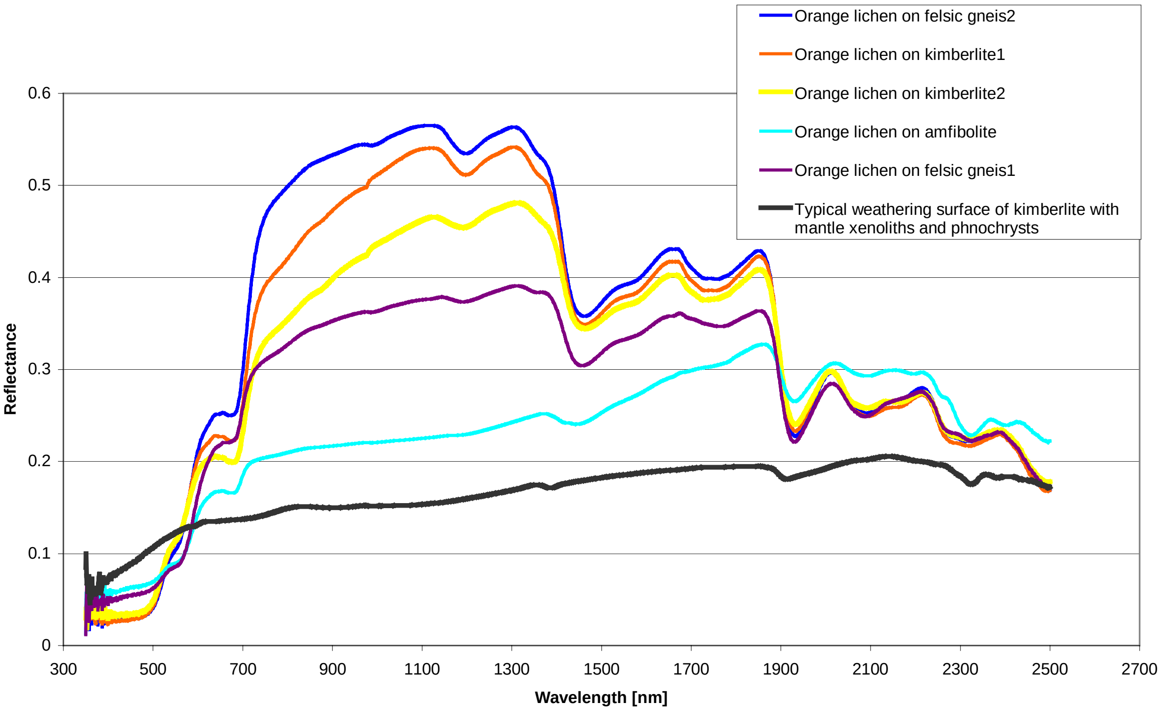


Figure 12. *Reflectances of mafic and felsic rock targets covered by orange lichen near locality K12. The lowermost curve characterises a lichen free, exposed and weathered (hard) kimberlite surface.*

Environmental targets

Reflectance measurements of environmental targets were cursorily measured in the vicinity of the abandoned US Antenna facility in Kellyville. The yard surrounding the facility is contaminated with hydrocarbons used for the antenna power supply station. Figure 13 shows reflectances of the contaminated black soil from the yard. The arrows indicate the typical hydrocarbon absorption features

In the greater area surrounding the yard, remnants of very dark oil spill were detected. Field spectroscopy and laboratory measurements (Lambda 19 at BGR) did not indicate the diagnostic hydrocarbon feature at the wavelength 1730 nm and 2310 nm within the radiance spectra. The reason for that is the very dark surface where nearly total absorption of the measurable reflective spectrum from 400 nm to 2500 nm exists. The “hydrocarbon feature” here is camouflaged due to this physical properties.

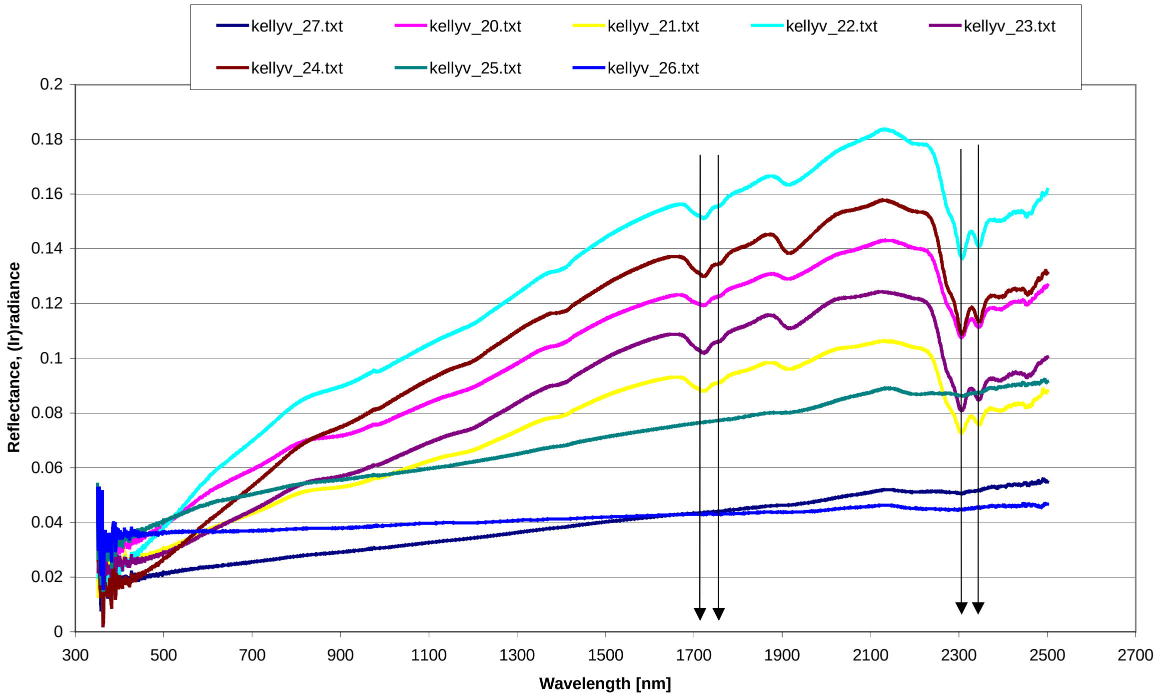


Figure 13. *Reflectances of black contaminated soil around the Kellyville abandoned antenna facility. The arrows indicate diagnostic features for hydrocarbons. –The "hydrocarbon feature" is lacking for the black oil contaminated soil samples (three lowermost flat curves, see text above).*

Evaluation of results

Kimberlite targets, by virtue of their mineralogy, are dark mafic rocks with generally low reflectances with a few absorption features. These features are, however, enhanced on the weathered rock surfaces contributing to a satisfactory spectral contrast between kimberlite and the country rock.

The spectra of the covering soil and hard kimberlite rock suggests that the 'soil' covering the kimberlite bodies seem to be a result from physical weathering rather than from chemical change.

The study area included several excellent sand or gravel Pseudo Invariant Features (PIF's) and a sufficient amount of their spectral characterisation could be recorded for their further use as ground truth for atmospheric corrections of HyMap data.

References

Kuosmanen, Viljo, Arkimaa, Hilkka, Carlson, Liisa, Chevrel, Stéphane, Hyvönen, Eija, Kuosmanen, Eira, Laitinen, Jukka, Rainio, Heikki, Ruohomäki, Timo, Siira, Maarit and Sutinen, Raimo 2000 HyMap-campaign and related fieldwork in Sotkamo, Finland, during summer 2000 for MINEO and HYDO. Geological Survey of Finland, Archive report RS/2000/5, 31 p., 18 appendices.

Höerig, B & Küehn, F. (2000): HyMap Hyperspectral Remote Sensing to Detect Hydrocarbons.- Proceedings of the „Fourteenth International Conference on Applied Geologic Remote Sensing", 206-211, Las Vegas, Nevada, 6-8 November 2000.

Höerig, B. & Küehn, F. (2001): HyMap Hyperspectral Remote Sensing to Detect Hydrocarbons.- Int. Journal of Remote Sensing, Vol 22, No. 8, p. 1413-1422, Birmingham (Taylor & Francis).

Wulder, Mike; Mah, Steven and Trudeau, Daren, 1996. Mission planning for operational data acquisition campaigns with the casi. Proceedings of the Second International Airborne Remote Sensing Conference and Exhibition, San Fransisco, California, ERIM,Vol. III, pp. 53-62.

Appendix 3: Kimberlite mapping results

The mapping results are on the enclosed CD-ROM which contains the following files:

Index map and 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

Classification results from Spectral Angle Mapper (SAM).   Format ArcView shape file
KIMBERLITE_1.SHP
KIMBERLITE_2.SHP
KIMBERLITE_3.SHP

Classification results from Spectral Angle Mapper (SAM).   Format ENVI vector file
KIMBERLITE_1.EVF
KIMBERLITE_2.EVF
KIMBERLITE_3.EVF