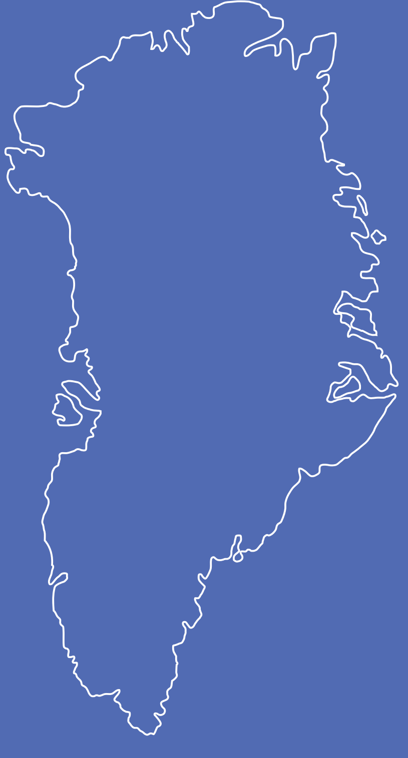
DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE **RAPPORT 2020/3**

Remote Sensing in Greenland

Overview of selected remote sensing activities, related to mineral resources in Greenland, 1979–2019

Leif Thorning, Bjørn Thomassen & Sara Salehi



GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
DANISH MINISTRY OF CLIMATE, ENERGY AND UTILITIES

G E U S

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G E U S

In memoriam Tapani Tukiainen

Our friend and colleague – known to one and all as ‘Tapsa’ – died 11 January 2016 in a tragic drowning accident during a holiday at Tenerife. His ashes were spread over the lake Pielinen at his beloved cabin in eastern Finland by his widow and daughter.

Tapsa was born 27 May 1951 in the mining town Outokumpu, eastern Finland. His father was a mine carpenter and as a teenager Tapsa followed his father's daily work in the mine helping with all sorts of practical jobs. He thereby gained a keen interest for manual labour. Although born into a Finnish-speaking community, he chose to study geology at Swedish-language Åbo Akademi, from where he graduated in 1979, well conversed in that language. Throughout his life, Tapsa showed a keen interest in languages, for example, Greenlandic fascinated him.

Tapsa joined the Geological Survey of Greenland (GGU) in 1978 working on a uranium-prospecting programme in South Greenland. From here, his mathematical gifts gravitated him into the world of computers and data processing; he ended up with the official title 'senior research scientist' at the reorganised Survey (GEUS). In this capacity, he was the driving force in the Survey's development of remote sensing capabilities, and in this field, his sudden death has left a noticeable vacuum. Tapsa was active in all aspects of remote sensing from advanced processing over laboratory spectra studies of rocks and minerals to field operation management of airborne surveys in a large EU funded project. He applied different types of remote sensing techniques in various geological investigations. Concurrently with this, Tapsa continued field work in Greenland where his remarkable talent for geological observation was put to good use.

Tapsa's total lack of snobbery and well-developed sense of humour gained him many friends at the Survey. Thus, asked about his command of the French language before a conference in France, he answered with a grin: café noire! Coffee drinking was indeed one of his passions and he left a trail of coffee mugs behind him in Copenhagen offices and corridors. At the same time, Tapsa had a very independent mind, like a force of nature, difficult to tame or discipline, and this could create problems in a relatively streamlined State organisation like GEUS. He was hard-working, often staying in the office into late evening running computer calculations, but he was also a time-optimist who rarely said 'No' to new assignments. This created certain deadline problems, but any friction did not deter him from taking on new projects.

During the years in the office in Copenhagen and in Greenland field camps, our collegiate relationship to Tapsa developed into genuine friendship. A very amiable and helpful person, Tapsa was a man of few words. Stuffed in a small 2-person kitchen tent on a rainy day in Greenland, brewing coffee on the hissing primus stove, the relief trick was to ask him questions about the Finnish–Russian Winter War 1939–40. Deeply marked by the stifling experience that his family had suffered, this got him going. Tapsa could also be rather absent-minded. For example, when collecting a rock sample during a traverse and putting it in his rucksack, he discovered that other samples lurked. His negligence of the previous day triggered the simple comment: "Ups, I thought it was a bit heavy this morning". Tapsa was a big, practical fellow but finesse was not a core competence. Thus, when camping in Greenland, he could not bother to keep the door flap of his sleeping tent closed all day to keep mosquitos and black flies out, with the result that herds of the irritating creatures waited for him at bedtime. He solved the problem by placing two primuses burning full throttle in the tent: he simply closed the door and waited outside for five minutes. Afterwards, there were no cleaning procedures; the carcasses became an integral part of camp life.

Life is so much more tedious without Tapsa – we sorely miss him.

Bjørn and Leif, May 2018

Contents

1. Abstract

The use of Earth Observation data from satellites and aircraft has been a tool for many years in GGU/GEUS' work related to mineral resources exploration in Greenland. Since the start in the late 70'ties and until now, there have been many projects utilising various datatypes from different platforms for many purposes. Over the last ten years, emphasis has shifted to hyperspectral remote sensing data, often with the addition of LiDAR data. More recently, projects with hyperspectral scanning of near vertical cliffs from vessels at sea, helicopters, drones and fixed stations on the ground have been the main thrust of development.

This report briefly reviews a few general concepts related to remote sensing methods as a background for the presentation of a collection of case stories from Greenland. Remote sensing results and maps have been an integral part of most major projects over the last fifteen - twenty years. The emphasis of this report is on the variety of methods and products available through GEUS' activities in this subject.

The status of hyperspectral work is briefly assessed and some likely trends for the future use of hyperspectral data are pointed out, including such endeavours as new hyperspectral surveys and more experimental local registration of hyperspectral data of near-vertical cliffs, recorded from helicopter or fixed positions on the ground.

GEUS personnel have access to all case stories and the data behind them are stored on accessible internal departmental storage devices. Selected examples of case stories may later be included in the publicly available Greenland Mineral Resources Web Portal, and subject to successful financing of the development, it is expected that the Greenland Mineral Resources Portal will offer the public possibilities for download of some types of remote sensing surveys and interpretation results.

2. Introduction

Given the vast, exposed landscapes of Greenland, the advantages of using observations from aircraft and satellites are obvious. The last 30–40 years has seen a steady international development of better and better data, from analogue aerial photography to a variety of digital data from different Earth Observation Platforms, and the development of computing capacity have allowed use of more and more advanced methods. Today, remote sensing is a mature discipline influencing many branches of the earth sciences. This report presents selected results from remote sensing case stories from Greenland, within the regime of public contributions to mineral exploration, obtained by the Geological Survey of Denmark and Greenland (GEUS – until 1995 GGU). Earth observation methods have been used in Greenland for many other purposes related to e.g. glaciology and climate but this report deals only with optical remote sensing projects related to mineral exploration, geological mapping, and regional assessments of economic mineral potentials. Results from GEUS public classical airborne geophysics projects, such as Aeromag and AEM Greenland, are not included here. The objective of this report is to present illustrative examples of application of remote sensing in Greenland, thereby documenting how past activities in GGU/GEUS forms the basis for further developments in the field of mineral exploration and mapping. It is an account of GEUS' active involvement in remote sensing in Greenland over nearly forty years.

The report has been written for an audience of earth scientist, mostly geologist, well versed in geological issues in Greenland and aware of remote sensing principles but without detailed knowledge of the methodology and its potential. The illustrations have been selected to show how remote sensing data have been used in Greenland in geological research and mapping, especially in relation to the exploration for mineral resources.

In chapter three of the report, a few key concepts and definitions are described very briefly, assuming no prior knowledge of remote sensing but sketching a theoretical background for the understanding of the case stories. It is by no means a complete description, but selected references provide access to a more detailed understanding of the complexities in remote sensing. In chapter four, the remote sensing workspace environment at GEUS is briefly described, including the methods and avenues used for the presentation of results internally in GEUS' project groups and externally to outside interests.

Chapter 5 contains case stories of how remote sensing has been used in projects in Greenland by GGU/GEUS. Chapter 6 contains a 2020 status, with a view to the trends for future use of multi-source and multi-scale remote sensing that probably will become increasingly important, as illustrated by the activities in the field in 2016 and 2019, where hyperspectral imaging combined with photogrammetry using side-looking scanning from a helicopter, boat or from sites on the ground were tested. Acknowledgements and references are in chapters seven and eight.

3. Some key concepts

The definitions, concepts, methods and other background information described in the following subsections do in no way make up a complete description of remote sensing. Only items relevant for the case stories in the subsequent sections have been included and they have been sketchily described. The descriptions are non-mathematical, although actual use of many of the methods is based on advanced mathematics and statistics. Some of the case stories in section 5 contain additional background information on the methods, when needed. There are many good textbooks available. A fairly recent one, available on the Internet, is by Richards (2013), which gives an excellent, detailed, mathematical overview of most aspects of remote sensing processing and interpretation.

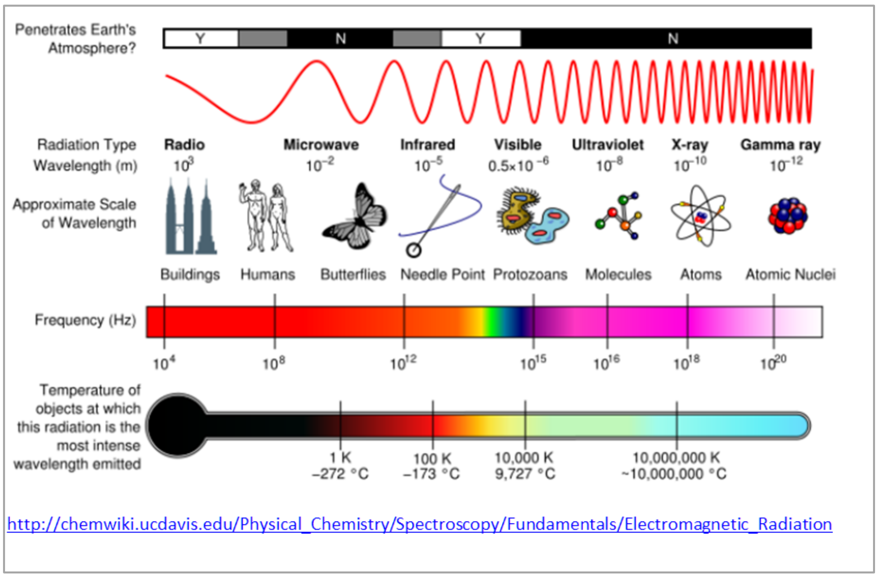

Figure 1. *The electromagnetic spectrum – with indication of types, scales and temperatures.*

3.1 The electromagnetic spectrum

The media for working with remote sensing is the electromagnetic spectrum, see Figure 1. The spectrum of electromagnetic radiation reflected from a surface is the combined result of the original source for the incoming light, the changes to this light moving through space and air, and changes happening at the point of reflection from the surface. For any material, the energy of solar radiation reflected, absorbed or transmitted, vary with wavelength as does the precise processes affecting the radiation. Thus, any material will exhibit a variation over wavelength, i.e. have a spectral signature, see Figure 2, which can be recognised and used to show the presence of certain materials at the surface observed from the Earth Observation Platform, land instrument, aircraft or satellite. In most cases, corrections are necessary to compensate for the specifications of the instrument package and the loss of energy during transmittance and reflection, before advanced methods required to bring out the desired geological information can be applied.

Looking more closely at the range of wavelengths of interest in earth observations of the surface of the earth, some specialised nomenclature is often employed in remote sensing, see Figure 2.

Different materials have different spectra. Assuming it is possible to register a good recording of the spectrum of radiation emitted from a surface, it is therefore possible from the spectrum to determine what the material of the surface is composed of. In Figure 2 (upper panel) is shown just four examples: soil, vegetation, AL-OH mineral, and water, but spectra is known for many more materials, including minerals and rocks (Roger *et al*. 2007). Many different methods can be applied to define and investigate the relationship between a given spectrum, or mix of spectra, and the geology, on a pixel-to-pixel determination.

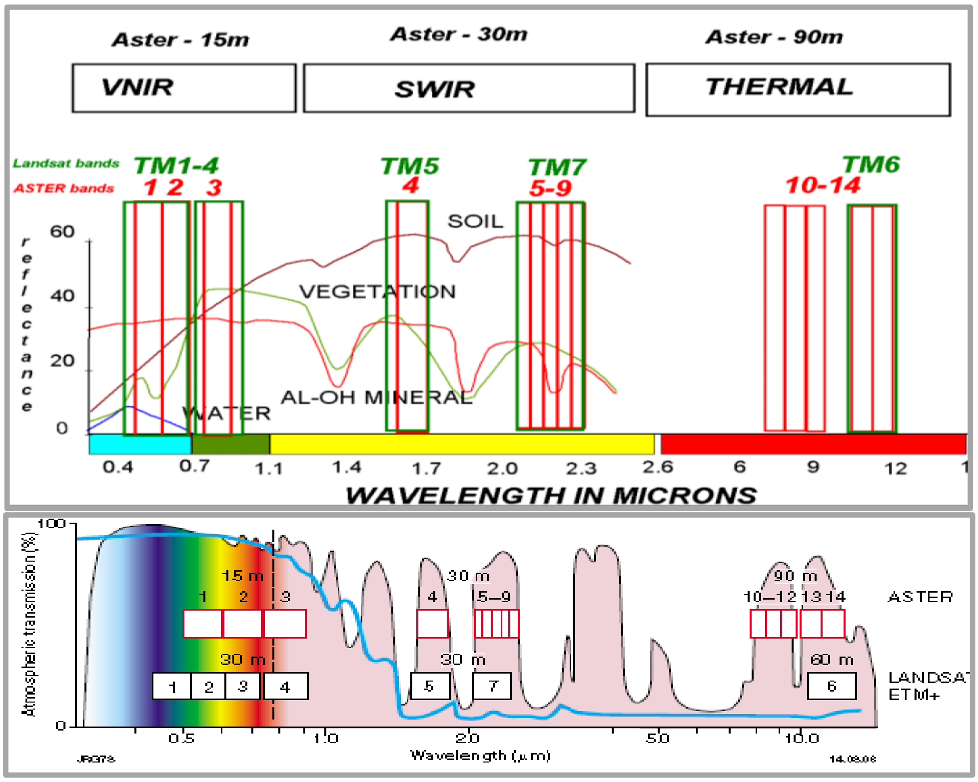

Figure 2. *Sensor specifications of two commonly used satellites, i.e. Landsat and Aster. Upper panel: in remote sensing, special names are often used for different ranges of the spectrum. VNIR = Visible- Near Infrared, including visible light (cyan bar); SWIR = Shortwave infrared; TIR = Thermal infrared. Aster stands for Advanced Space borne Thermal Emission and Reflection Radiometer. Note that Aster data have different spatial resolutions in the different spectral ranges. Lower panel: similar plot, showing more clearly the position of visible light and showing the different atmospheric absorption bands, see explanation in text. Note how the recording bands of the satellites are suited to parts of the spectrum with minimal absorption in the atmosphere. Source: NASA<http://asterweb.jpl.nasa.gov/images/spectrum.jpg>).*

3.2 Radiance, absorption, emission and reflection

A spectrum measured from an observation platform, be it a satellite, an aircraft or an instrument on the ground, exhibits the combined (measured or calculated) result of many different processes and events involving the incoming radiation (the entire electromagnetic spectrum, not just visible light), its path to the surface, and processes happening at the interface and on the path back to the observer. Four concepts are important to understand:

Spectral radiance: is the radiance per unit wavelength received from a surface; the units (SI) are Watt per steradian per square meter per meter or more commonly in remote sensing Watt per steradian per nanometre (W $sr^{-1}m^{-2}nm^{-1}$). This is a vector, i.e. it has a direction and a size.

Absorption: is the process whereby part of the incoming electromagnetic energy is absorbed by the material in the surface at different wavelengths, and turned into internal energy, *e.g.* thermal energy, instead of being reflected from the surface. This is a scaled parameter. It should be noted that quite small 'wriggles' in the spectrum caused by this are meaningful.

Reflection: is the process whereby a part of the incoming light (incident energy) bounces off (reflected energy) the surface and is redirected to the sensor. Some of the reflected energy may originate from specific processes happening at the surface (the laws of reflectance and reaction to different molecular bonds, type of surface, roughness, etc.) and show an effect from the absorption. Plotted relative to wavelengths, this is *the reflection spectrum*, which shows the small variations in the spectrum paramount with respect to the determination of minerals.

Emission: is the process whereby energy due to atomic or molecular transitions between electron energy levels is emitted as photons from the material of the surface. These events can be triggered by incoming radiation or they can happen without any external trigger. Plotted relative to wavelength, this makes up an *emission spectrum*. In remote sensing, this is especially important when dealing with the thermal bands.

There are good description of these and associated physical issues in most standard books on remote sensing or physics; the following relies on http://hyperphysics.phy-astr.gsu.edu referring to the human body to aid in understanding of (1) the energies involved and (2) how different parts of the electromagnetic spectrum have very different effects upon interaction with matter. For low frequency radio waves, the human body is quite transparent. Moving upward through microwaves and infrared to visible light, the absorption becomes stronger. In the lower ultraviolet range, all the UV from the sun is absorbed in a thin outer layer of skin. Further, up into the x-ray region of the spectrum, the body becomes transparent again, because most of the mechanisms for absorption are gone and only a small fraction of the radiation is absorbed, but the process now involves more violent ionization events. Thus, it is true for all types of material that each portion of the electromagnetic spectrum has quantum energies appropriate for the excitation of certain types of physical processes in the atoms. The energy levels for all physical processes at the atomic and molecular levels are quantized, and if there are no available quantized energy levels *with spacing matching the quantum energy of the incident radiation*, then the material will be transparent to that radiation, and this will pass through.

In the case of real data recorded empirically in nature, many such processes are active simultaneously, and the explanation for small details in a recorded spectrum over the range used in remote sensing is complicated to unravel; careful corrections of the spectrum is required to take care of unwanted effects from the system and ambient environment, before a real interpretation in terms of material properties can be attempted. Especially important for remote sensing purposes is the absorption taking place in the atmosphere, because it at certain wavelengths (see Figure 2) limits the amount of energy reaching the surface. These bands of 'atmospheric absorption' are therefore of limited interest in geological remote sensing.

3.3 Satellites, aircrafts and instruments

Measurements of ambient radiation from the surface of the ground are carried out from several types of platforms. From cameras sensitive to the full spectrum or certain parts thereof, to hyperspectral scanning devises on the ground, on aircraft or on satellites. The underlying physical principles are the same and the same image processing methods can be used on the data, though there are differences in the resolution. An overview of satellites can be found e.g. at https://en.wikipedia.org/wiki/Remote_sensing_satellite_and_data_overview. Equipment for airborne use relies on similar instrumentation, e.g. the spectrometers from Specim (Spectral Imaging Ltd, Finland) and HyMAP (Integrated Spectronics Pty Ltd, Australia), which GEUS has used in Greenland.

3.3.1 Sensors and data types

There are many sensors used for remote sensing from satellites or aircraft, and many more are being developed for specific and general purposes. An overview can be found at this source: https://earthdata.nasa.gov/user-resources/remote-sensors. Both passive and active sensors are in use and it is not possible to go through them all here. The passive sensors rely entirely on the reflected sunlight (e.g. spectral imaging systems), whereas the active sensors use a controlled source to send out the signal and then record the returned signal (e.g. radar and LiDAR). Today, all sensors are highly dependent on digital systems and produce enormous amounts of data, and a very significant development of new sensors, and combinations of sensors, is taking place internationally.

3.3.2 Spatial and spectral resolution; data cubes

The development of hyperspectral data based on many hundred observations distributed over the spectrum has made it possible to define spectra in detail over a target area. Conceptually, the term hyperspectral data cube is often used. Instead of just a conventional RGB view of the area in question, a data cube containing tens to hundreds of narrow bands is acquired using such sensors (Figure 3). Thus, a section 'horizontally' through the cube exhibits the view of the target area at a specific wavelength. Looking at just one row of pixels in that view, a profile over the area can be obtained (b in Figure 3). A 'vertical' stack of just one pixel from each view will produce the spectrum exhibited of that pixel of ground surface. Characteristic spectra of a particular rock type exposed at the surface can be produced by combining the spectra from all pixels falling within the polygon defining the area of the rock type on the ground.

The spatial resolution of these data is determined by the size of the pixel, either as measured from aircraft or satellite or as calculated by interpolation. The resolution of open source satellite data is usually from 10 to 90 meters but can be better in new and commercial satellites. Airborne data can be down to a few meters, and data recorded on the ground or from drones can be at centimetre scale.

The spectral resolution depends on the number of bands recorded by the instrument carried by an aircraft or satellite or used on the ground in the field or in the laboratory, i.e. from less than ten bands to several hundred bands. Ideally, as many bands as possible are desired, because that corresponds to a more detailed digitization of the reflection spectrum curve and its small features. A characteristic feature in a spectrum related to certain minerals or certain processes (e.g. oxidation levels) can be fine events such as the deepening of a local minimum, or a slight shift of the minimum position across wavelength. In other cases, only a few bands are used to define certain rations characteristic of minerals.

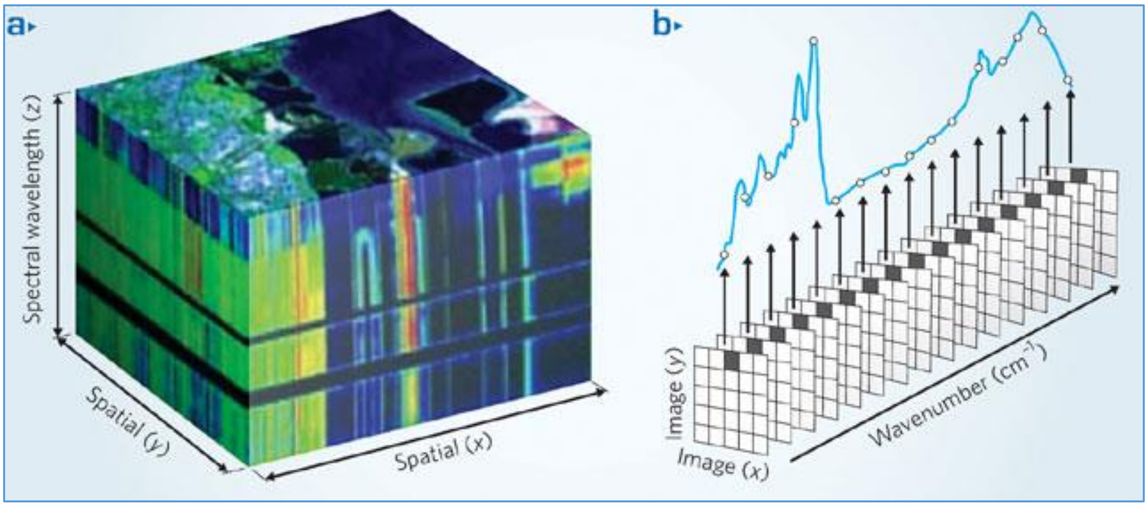

Figure 3. *Hyperspectral data cube. Illustration taken from Bannon (2009) on [http://www.nature.com/nphoton/journal /v3/n11/full/nphoton.2009.205.html.](http://www.nature.com/nphoton/journal/v3/n11/full/nphoton.2009.205.html)*

3.3.3 Corrections to data (pre-processing)

Before any remote sensing data can be used for interpretation through advanced mathematics, the registrations must be corrected in ways depending on which sensor and what scale is used. This is for all practical purposes done on a pixel-by-pixel basis and may involve resampling. The first set of corrections usually has to do with the characteristics of the instrumentation and observation platform, and the purpose is to make the data as independent of the platform as possible. The second set of corrections is aimed at removing unwanted effects of the presence of atmosphere and the effects of the geometry of the position of the platform with respect to the ground surface. In general, the purpose is to obtain corrected values that are as close as possible to what would have been measured on the ground under more controlled conditions. This step can also involve **re-projection** to a desired geographic projection.

Instrumentation errors arise from a number of characteristics of the different sensors used within each band and between the bands, such as their relative calibration, transfer characteristics, non-linearity, residual electronic noise in the sensor (dark current or offset), and the variation of gain of the sensor across wavelengths. In satellites, some sensors deteriorate over time, and this may result in shifts at quality of data recorded after a specific date. Because the sensors within a given band and from band to band can have slightly different characteristics, striping across the scene can often be the result. The magnitude of these types of data errors depend on how many sensors are used. Sometimes black lines or single pixels (no data) can mar an image because a sensor has failed completely. All of these errors result in variations in relative brightness, and different techniques are available to correct for this.

The ambient environment in **the atmosphere** influences the character of the radiometric data. Corrected for instrumental errors, the recorded or calculated spectrum is the product of the original light (the sun), the effects created during its path through the gasses and dust particles in the atmosphere and the reflection at the surface, see Figure 4. The energy emission, **the spectral irradiance**, from the sun is dependent on the wavelength; it is measured in Wm^{-2} and describes how much power density is available from the emitter, the sun, varying across the range of wavelengths. **The radiance** is the power density scattered from the surface into cones of the half-space above the surface and this is measured in $Wm^{-2}r^{-1}$.

In a very clear atmosphere, the only scattering would be **Rayleigh scattering** because of the molecules in the air. In the real world, another type of scattering related to larger particles such as smoke or haze must be expected (**aerosol or Mie scattering**). Both types are dependent on wavelength. Finally, the atmosphere will **absorb** some of the energy; carbon dioxide, ozone, and water attenuate the incoming radiation strongly in some wavelengths.

There are several corrections for all these effects. A model of the atmosphere must be defined for the area in question, to determine the transmittance of the signal paths, and the sky- and path radiance. Based on this, the atmospheric corrections can be calculated if also the system characteristics and geometry (e.g. position of sensor relative to topography) of the measurements are taken into account. These corrections will, if successful, improve the spectral and spatial resolution very significantly. The corrections sometimes include the effects of shadow and different sun angles with respect to the topography on different scenes. In Greenland, far to the north and in many regions with alpine terrains, these often-time-consuming corrections are important.

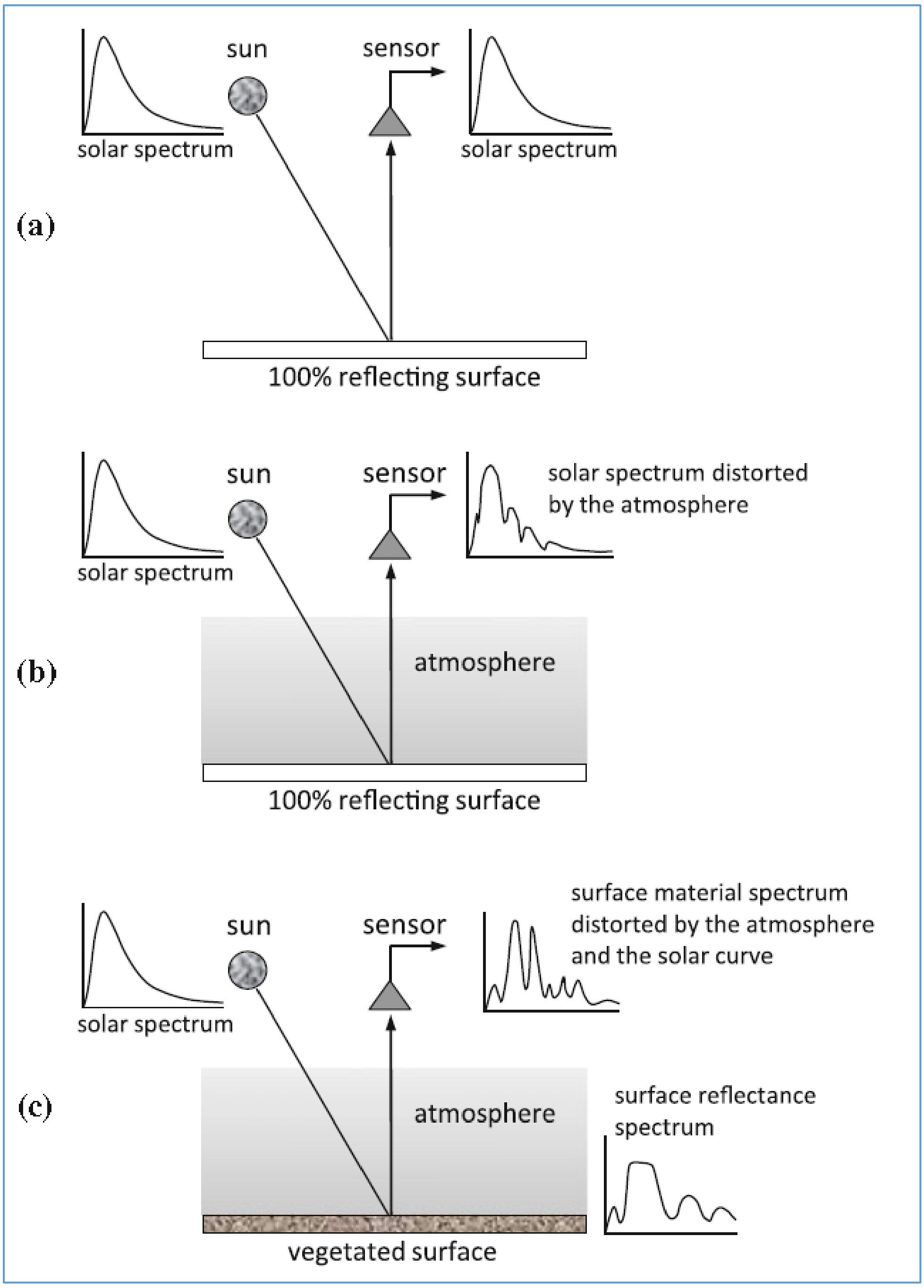

Figure 4. *From Richards (2013), figure 2.3. Illustrates how the original spectrum from the sun (a) is reflected from an ideal surface through the atmosphere (b) and the further effects from a surface with absorption due to the material covering the surface (c).*

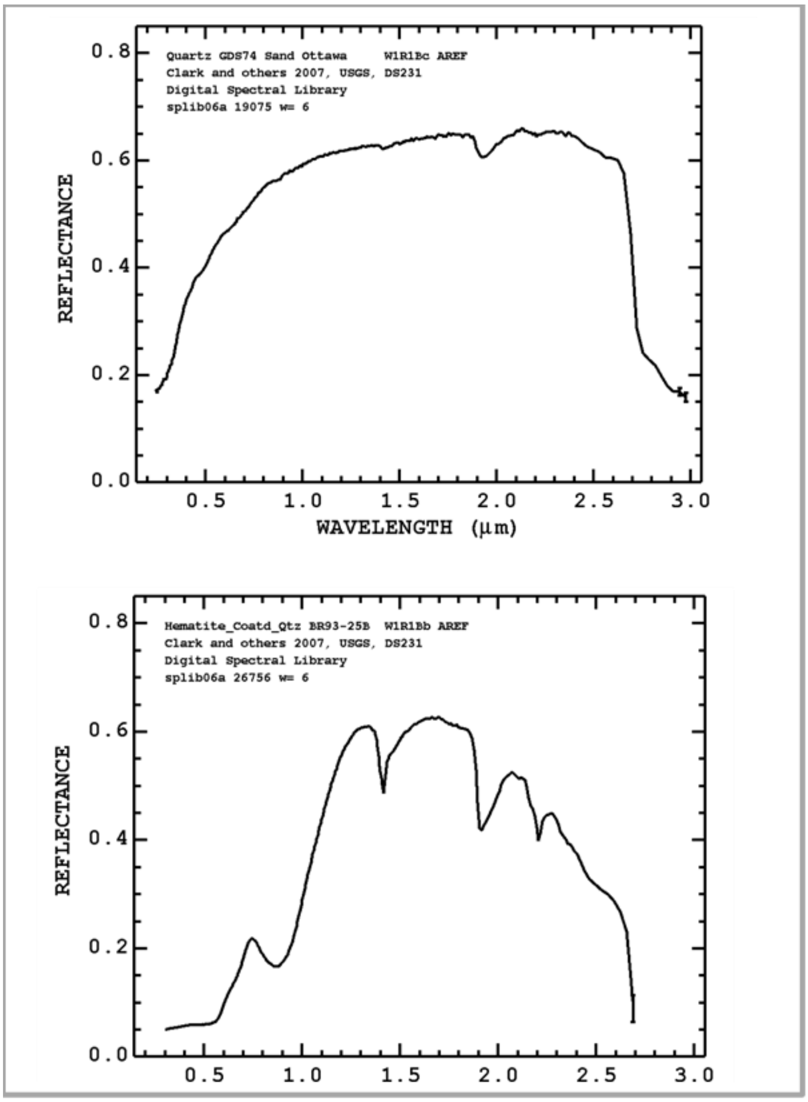

Figure 5. *Two examples of spectra showing how geologically meaningful phenomena may express themselves in spectral data. The local minima are indicative of absorption of energy into the material. Lower panel: Quartz with a thin coating of hematite. Upper panel: pure quartz. In nature, there is often a mix of spectra to sort out, and it is not always as simple as here, but there are various ways of separating several spectra from different material, even when present within the same pixel. From Clark et al. (2007).*

3.4 Spectral libraries

In order to interpret remote sensing data, especially for multi- or hyperspectral data, knowledge of the reflection spectra of a large number of materials is essential. In relation to geology, this includes all minerals, rocks, soil mixtures, etc. If the object of study is vegetation, the target spectra are from different grasses or trees, different plant species, and state of the plants; in urban mapping it is e.g. soil use, building materials and roads. In relation to the earth sciences, the effects of lithology, surface expression, composition, alterations and structures are evaluated.

USGS (United States Geological Survey) and JPL (Jet Propulsion Lab), and many others, have measured the spectra of many minerals and rocks in the laboratory in order to be able to compare them with spectra measured/calculated in nature, *i.e.* outside the laboratory. Various collections of such spectra in digital format are called spectral libraries and one of the most well-known is the USGS Spectral Library containing the spectra of some hundreds of different minerals and rock types, and some forms of vegetation. These are easily found using http://speclab.cr.usgs.gov/spectral-lib.html, the USGS Digital Spectral Library web site.

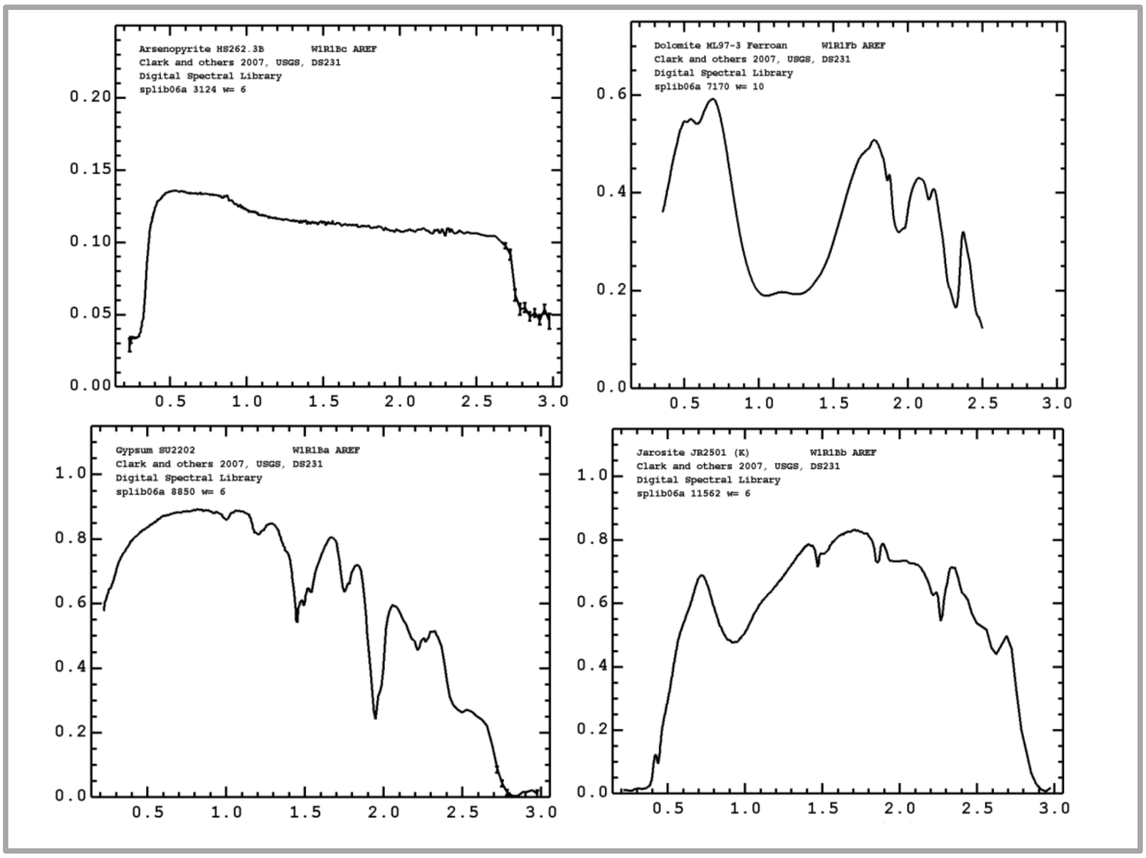

Figure 6. *Examples of spectra from USGS Digital Spectral Library, Clark et a.l. (2007): arsenopyrite, dolomite, gypsun, jarosite. Axes as in Figure 5.*

Digital access to this and other libraries is built into most hyperspectral programme systems for processing and interpretation, such as e.g. ENVI, and can be used from appropriate software environments, but the libraries can also be browsed directly on-line. Figures 5 and 6 give examples of laboratory measurements of spectra. When trying to identify spectra from the real pixels of hyperspectral data from nature, there can be much more noise present, or the spectrum can be a mixture of different spectra from different materials, see section 3.7.

3.5 Accessory data: Photography, LiDAR and RADAR

For proper corrections of hyperspectral data, detailed knowledge of the terrain is needed, in the form of a digital elevation model, which today can be produced accurately and fast, sometimes from the satellite data themselves (e.g. the Aster satellite, which has a special channel recording overlapping views of the surface). When measurements are done from aircraft, it is now common that normal aircraft radar, special radar, and special LiDAR systems (**L**ight **D**etection **a**nd **R**anging) record the distance to the ground and some properties of the ground surface. These data are used to produce very accurate DEM (**D**igital **E**levation **M**odels), which in turn are used to calculate some of the corrections. It is now common practise also to register digital colour photography from aircraft and very high-resolution photo-like images from satellites, but also many details of the LiDAR ground return signal itself (*'*full signal Li-DAR*'*). These types of data are considered scientific data in their own right and are often used directly together with the spectral data in the interpretation process to register the type and character of the surface. GEUS can use the colour photography of vertical or oblique photography in stereoscopic mode for detailed tectonics; some of the recent projects have focused on combined photogrammetric and remote sensing measurements (Salehi *et al.* 2018). If extremely accurate DEM are needed, it is possible to book a satellite radar recording from certain suppliers.

The accessory data also normally include flight information data on altitude, platform accelerations, etc. These data are normally used for the setting up of the digital model of the flight used for e.g. geometrical corrections and are not included in deliveries from GEUS containing value added products.

3.6 Field and laboratory hyperspectral imaging systems

GEUS possesses a model FieldSpec 3 HiRes that can be used in the laboratory and in the field for *in situ* measurements of the spectrum of natural materials (Figure 7). When not in the field, the instrument is set up in a laboratory for spectral measurements of rock samples. Other hyperspectral scanners can be used to produce actual hyperspectral images of drill cores and samples and use these for the identification of mineral grains via their spectra – but such scanners are not yet available at GEUS.

Hyperspectral imaging systems have been used for many purposes. Increasingly over the last ten years, instrumentation has been developed that is small and lightweight enough to be packed into handheld devices the size of a mobile phone or normal ground survey instruments, and are being used together with LiDAR to map out sites, buildings, excavations, caves and build three-dimensional models of these, including types of surface materials. Of special interest for the earth sciences is e.g. when applied in mines, using the hyperspectral properties of the ore-carrying mineral to trace the ore in the country rocks and lay out the best possible drilling pattern to follow the ore, even if the ore is not visible to the naked eye. International developments are strong and focused on small LiDAR and RADAR devices coupled with hyperspectral scanners that can be utilized in self-driving cars, drones and for unique special purposes. This development will probably result in tools that increasingly can be used in geology on site level, for mineral identification, and for small-scale tectonics. A broader use of image scanning on site level is anticipated, adding much to the normal sketches, photos and notes usually taken by a geologist at observation sites. This goes well together with the measurements of actual spectra in nature and in the laboratory; GEUS is involved in activities designed to further the development of relevant methods, see section 6.

Figure 7. *Tapani Tukiainen demonstrates the FieldSpec 3 HiRes spectro-radiometer on Constable Pynt airfield, Central East Greenland, at the start of the field season 2009.*

3.7 Processing resources and timing

The introduction of hyperspectral data in remote sensing has led to a significant increase of already quite intimidating processing time requirements. GEUS' processing of the data from the hyperspectral survey from East Greenland in 2000 proved this, often using days of processing time for single steps on the computers hitherto utilised for the remote sensing work. A more powerful and dedicated server had to be acquired and this improved the situation somewhat, but still the amount of necessary processing time is a factor that must be taken into account, when planning the use of airborne hyperspectral data, in relation to a field mapping programme running over two – three years. Upgrades to even stronger servers will always be worth considering.

Ideally, the products from remote sensing should be made available as early in a geological mapping project as possible in order to let the total plan (and costs) benefit from the results, when going into the field for the first time. Realistically, if the data are collected late in the overall plan, one must be patient and wait for the time-consuming processing to finish before the interpretation results are available. The processing cannot be rushed, because this leads to a risk of errors and the need for re-processing of the data. Errors or wrong choices early in the processing lay the foundation for unsuccessful interpretation down the road. The argument for placing remote sensing surveys and geophysical surveys early in the project is logical and well proven, but it is difficult to accomplish in reality because more traditional planning often is applied.

As a further consequence of this, GEUS has adapted a preference for acquiring data in a stage of processing as close to final data as possible, so that the GEUS processing time (and calendar time before field work) can be dedicated to interpretation and not be totally taken by tedious but still important pre-processing and early stage procession. In practise, this means that GEUS prefers, if possible, to contract for data-ready-to-use just off the aircraft. This cannot always be assured with hyperspectral data, but the international developments indicate that it may soon become generally possible. Satellite hyperspectral data may be purchased at various levels of processing. However, the standard atmospheric corrections done by the supplier often have to be redone more accurately for the alpine, partly snow-covered regions in Greenland, because standard methods have problems in distinguishing between ice/snow and clouds.

There is a strong trend in the development of instruments and methods that will probably help bring down the processing time. Specific, goal-oriented instruments are becoming more common for specific problems, often accompanied with special processing for specific purposes. Hopefully this trend will eventually bring about data, which quickly are ready for interpretation and integration with other types of geophysical and geological data.

4. Using results from remote sensing

The remote sensing maps of many types have become increasingly popular in the geological mapping and mineral exploration projects run by GEUS. In this section, we briefly explain the setup so far adapted for making the use of especially hyperspectral data an integral part of such projects.

4.1 The HSRS environment at GEUS

The maps/data produced from multi- and hyperspectral data are meant to be used in combination with other types of maps/data, such as geological, geophysical and geochemical maps. This all takes place in the digital domain, and for many interpretation purposes, it is necessary to combine information from many different maps and data sets. As for all these types of data, subsequent field work and detailed investigations must be considered an integral part of the interpretation process for remote sensing data.

The processing and storage of hyperspectral data often causes considerable problems, because the amount of data in play for some operations is enormous and can be prohibitive for handling large areas. This cannot be avoided, if advanced remote sensing processing is the objective. Program systems like ENVI are especially constructed to cope with this, but even so total processing time for one operation on one subset of data may occasionally run into days, if the computer used is not sufficiently well equipped; even with strong processing units, it is often a matter of hours for some operations for large data sets, and transport time of data over net installations between different machines is a significant factor. Fortunately, the general technical developments will diminish this problem in the future.

GEUS has optimized the equipment used for the heavy processing, as much as economically possible, using a dedicated server with its own storage devices connected to the GEUS net giving access to departmental data storage space for long term storage. With a reasonable grouping of data, processing times can now be kept to manageable amounts of time. The environment for the image processing is mainly ENVI, assisted by PYTHON for organised processing streams, and associated programmes in a Linux regime, with other special program systems for LiDAR and RADAR. If new, large projects are started, the acquirement of significantly stronger processing units and faster disk systems must be seriously considered to ensure the necessary operability.

The ESRI ArcGIS environment is standard at GEUS for map compilation based on Earth science data from geological mapping and exploration activities in Greenland. The different earth science disciplines are handled by specialised programs and processing flows, and only results needed for the integrated interpretation are passed on to the ArcGIS geodatabases in the form of digital maps and other data files, similar to what is the case for the remote sensing results, see Figure 8. Thus, each geoscience discipline is handled in the most suitable environment, with special hardware and software for the particular task, and only the results, data or maps, thought to have a general interest are shared by exporting them to the appropriate ArcGIS geodatabase, and using them in that environment. ENVI can be used for many of the tasks but demands more user experience and skill than ArcGIS, which is used generally in the department for many other tasks, but based on experience so far, it has proven to be much slower than ENVI, when dealing with ‘big data’.

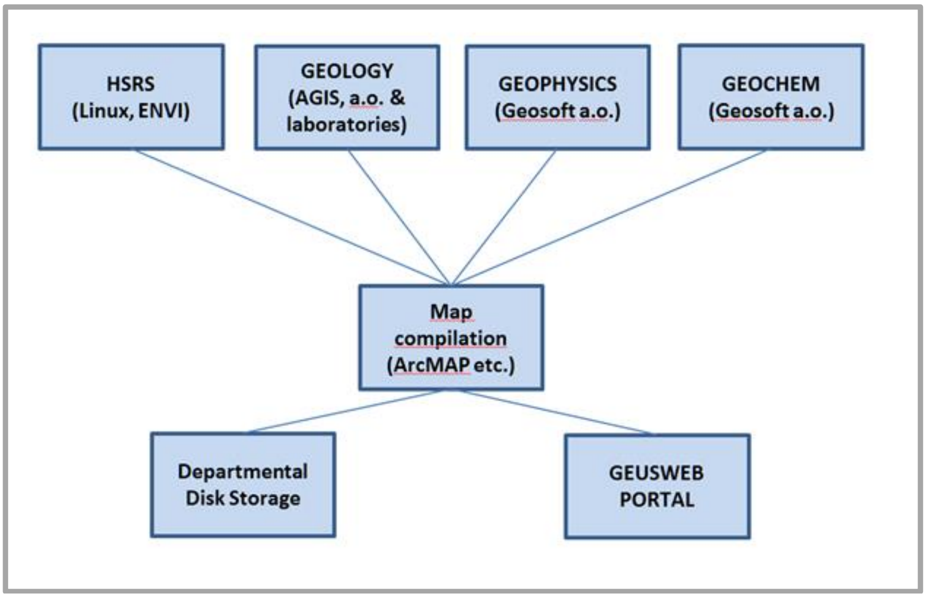

Figure 8. *Principle data flow for the production of geoscience maps; similar but not quite identical for all disciplines. More details for the remote sensing processing are shown in Figure 9 below.*

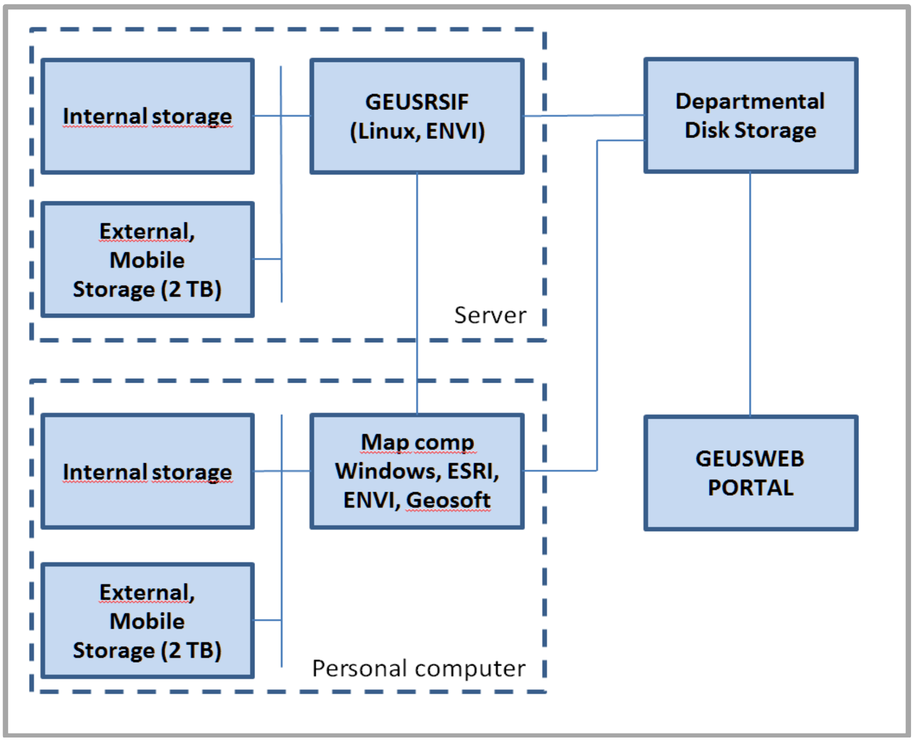

Figure 9. *The workspace or invironment for use of remote sensing data and methods by GEUS personnel. The learning curve for many of the program systems involved is quite steep, but to the extent possible, it is attempted to automate them as much as possible, giving non-expert users a chance to work with the data. In practice, many more software packages*

are used, depending on the researcher working with the data and the specific goal of the interpretation. Considerable own-development of methods and scripts also take place at GEUS.

For a quick look at HSRS map products, pdf-files are stored in the departmental storage area with access for department members.

At the present, because of the overriding problem of storage requirement during remote sensing processing, it has been decided to use mobile disk capacity for intermediate period storage of the work. This is a device (USB3 compatible) with two or more slots, each of which can accommodate a *c*. 2 TB data removable disk. Different projects or regions are allotted the nescessary number of mobile disk, which can be moved between the LiNUX-server and the PCs being used. This is much faster than working over the net presently available at GEUS. The remote sensing work is done by use of programs on the server and/or the PC's for lighter processing, as the case may be depending on size of datasets and type of work being done (see Figure 9). Original data are stored on the departmental data storage devices as read-only source disks and are regularly backed up by the system, ensuring long time security for the data. Final versions of data, e.g. corresponding to maps produced, are also kept on the permanent departmental disk storage.

The new maps or datasets produced during the processing in the compiling or the interpretation phases of the work, are stored on the internal disks of the server or the PC and on the movable disks. They are handled with maximum safety but must be considered more exposed to data failure of one type or another. Finished products, expecting to have a further life of use in other projects, are stored on the departmental disk storage for general use, often as 'layers' in GIS-compilations of many data types from a given locality or region. When the work is finished, the removable disks are used as permanent off-line archival storage for the data.

Compiled data sets of remote sensing data and finished project results will usually be announced over the Greenland Mineral Resources Portal, if data are available for purchase or download, whereas more complicated datasets may demand approaching GEUS for a quote. Presentation on the portal will usually involve showing one or more map products based on remote sensing data and relevant for the geological or technical problems being investigated.

Also, data sets involving many types of geodata will usually be demonstrated on the portal, and datasets may be available for purchase in the form of e.g. Geodatabases (ArcGIS) or as simple files, but these will not contain all the remote sensing data involved in the work, only the selected data belonging to finished maps, or in some cases just the finished maps. Limited image treatment rutines are available in ArcGIS environment, but not with the full range of operations, which are avilable in ENVI.

GEUS scientists working in projects depending (among other data) on remote sensing products may find it useful or even nescessary to view many more intermediate or test products during the progress of the work. GEUS' departmental storage facilities will therefore in the future encompass a directory (read-only), where remote sensing workers will place as many intermidiat or preliminary map products as feasible for internal review only. This is meant for open *internal* forum discussion.

Processing methods and their practical organisation will be constantly under review and adaptation to developments in computer facilities and capabilities.

4.2 Type products from remote sensing work

Through both standard and specialised processing, followed by interpretation using many different methods, the intelligent use of remote sensing data, especially hyperspectral data, will lead to the construction of many different products presenting the **information extracted from the data**. The case stories presented in section 5 of this report bring real examples; here in section 4, an overview is briefly described.

Most of the products are in **map form**, some supported by additional **graphics and tables**. The maps can be **vector- or raster-based** or combinations thereof. The measurements (scanning) taken digitally in the **frequency** range and pixel by pixel **spatially**. Therefore, **colour maps** can be formed by assigning particular frequencies to red, green and blue and plot e.g. the RGB combination, producing a map where the resultant **colours represent different values of parameters**. Using the three wavelengths actually corresponding to the colours red, green and blue will produce what is called a **natural colour map**, i.e. the map will show the surface approximately as the human eye would see it. However, by using other wavelengths or calculated parameters for the three colour-canon slots, other features of the data can be displayed as **false colour maps**, where the colours no longer look like the real surface but represent certain elements or features related to properties of the rocks, e.g. mineralisation. Finally, many methods can 'manipulate' the original values in the frequency window and produce new values which cannot any longer be assigned to specific frequencies but may **enhance specific features that are geologically meaningful**. The 'manipulation' may encompass advanced **statistical and mathematical calculations**, **filtering** in space or Fourier domain, **classification** of pixels, and may include **spatial operators** involving many pixels. Some of the methods applied in **hyperspectral data analysis** are complicated and advanced, and may be able to **directly map the actual material present** in each pixel, thus making it possible to produce - from the same basic data set - e.g. **geological** maps, maps of **soil use**, maps of **vegetation** etc. as different **layers**.

Further exploiting the possibility of three-dimensional displays, the **DEM** (digital elevation model) constructed from the LiDAR data, or by other well-known techniques such as photogrammetry, can be illustrated in different presentations. The DEM surface can be displayed in 3D and draped with many different types of colour maps and place e.g. mineralised sites on **the three-dimensional surface**.

In advanced **integrated geoscience interpretation**, the input layers are not limited to remote sensing data but will include known geology, other geophysical parameters, geochemistry, mapped changes, etc. Such large datasets can only be handled digitally in GIS systems, which is why powerful computational capabilities is one prerequisite for use of the data. The specialist methods of e.g. the image processing system ENVI has the necessary GIS capabilities, but if more refined GIS functions are required it may sometimes be an advantage to shift to e.g. ArcGIS or similar packages. Looking at the entire period from late 70'ties to the present, GEUS has used many different systems.

4.3 Integrating all data types

Since the beginning of the production of the Thematic Map Series (TMS) in the late 80'ties with the first one published in 1990 (Steenfelt *et al*. 1990), the underlying idea has been to collect all relevant data into the same observation system, letting the compilation and interpretation of geoscience data exploit all **different views of nature**. The different 'layers' created as described in section 4.2 can be truly mixed or integrated by mathematically correct methods or by manipulation based on experience. The early projects with remote sensing data were part of the inspiration behind this. In 1990, it was still early days for online digital work and expensive expert tools were needed to do the compilation. Though the compilation of the first Thematic Map Series was in fact done digitally, the publication itself consisted of 57 print-on-demand maps in the same scale and projection, forming the more limited basis for a manual interpretation. The same was the case for the following three Thematic Map Series, see section 5.5. In 1997, the last TMS of Inglefield Land was re-published but then as a digital ArcView-based publication, allowing users direct access to the digital data. Since then it has been the ambition always to publish regional geoscience compilations in digital format. Remote sensing-based products lend themselves easily to this philosophy.

5. Selected case stories from Greenland 1979–2019

In this section, we have gathered a selection of case stories from Greenland from 1979 to 2019.

5.1 Airborne Daedalus survey, central East Greenland, 1979

The first serious attempt of airborne remote sensing in Greenland took place in 1979 in East Greenland, when this new method of investigation was introduced to Greenland (Thyrsted 1980; Thyrsted & Friedman 1982, 1983). The aim of the project was to test the method in relation to mineral exploration. The project was a joint French-Danish operation between Groupement pour le Developpement de la Teledetection Aerospatiale (GDTA), Toulouse, in charge of the technical work and some interpretation, and GGU, mainly responsible for the geological input. The project was financially supported by the Commission of the European Communities and by the Danish Natural Science Research Council.

At the time, it was still uncertain how successful this would be, but the region gave ample opportunities for testing different terranes, different geology and different mineralisation. Mineralisation targeted was (i) hydrothermal lead-zinc mineralisation associated with Tertiary quartz veins occurring within continental Carboniferous–Lower Permian sediments, (ii) the Carboniferous–Permian sediments from Hall Bredning to Clavering Ø, (iii) pneumatolytic molybdenite mineralisation associated with Tertiary porphyritic granites, (iv) strata bound mineralisation of lead, zinc, barium, and copper in Upper Permian and Triassic sediments (v) strata bound copper mineralisation in late Precambrian sediments (Eleonore Bay Supergroup) and (vi) a scheelite mineralisation, possibly associated with late Caledonian granitic intrusions.

Two multi-spectral scanners were used: a Daedalus DS-1250 scanner with seven channels covered the visible and near-infrared part (0.5–1.1 µm) and a Super Cyc10pe SAT scanner with two channels in the thermal infrared part (8.5–12.0 µm) of the spectrum. The scanner platform was a WWII Boeing B-17 aircraft. Flights were performed at 800, 2500 and 5000 m a.s.l. to test for various resolutions with respect to the size of known mineralisation. At these altitudes the ground resolutions are respectively 2.4 m, 7.5 m, and 15 m for the Daedalus scanner, and 1.4 m, 4.3 m and 8.5 m for the SAT scanner, i.e. fairly detailed spatial resolutions. However, because of technical problems and adverse weather, not all target regions could be flown at all three flight levels.

Data processing took place at GDTA in Toulouse: (1) conversion of analogue data to digital data; (2) correction for systematic distortion; (3) superposition of SAT data on Daedalus data whereby all nine channels can be treated concurrently; and (4) superposition of SAT plus Daedalus data onto topographic maps for selected areas.

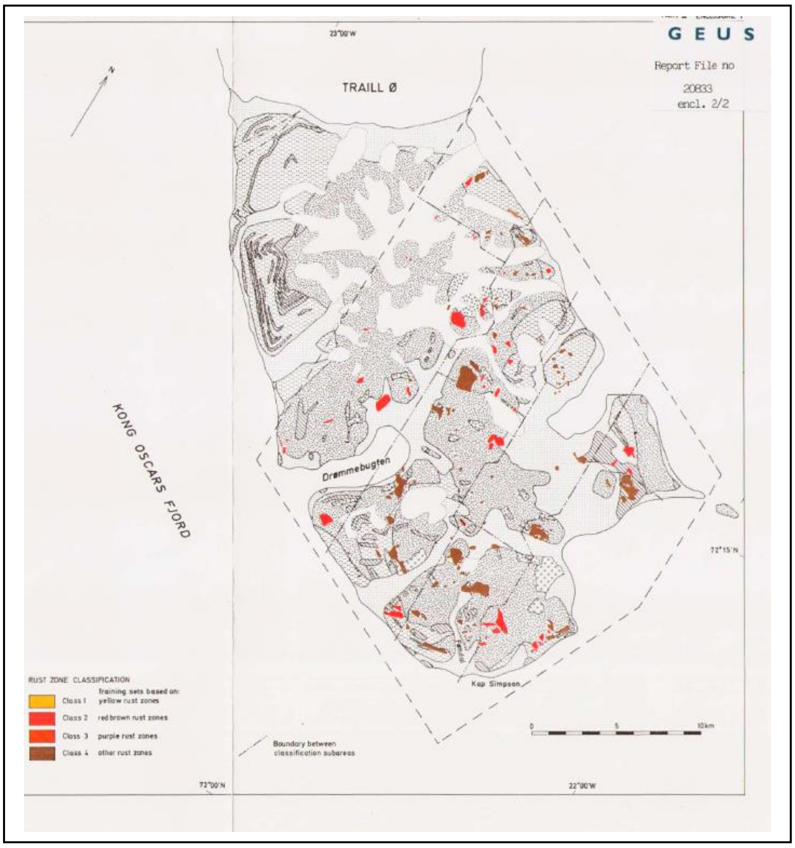

Figure 10. *Results of the 1979 airborne multispectral survey in East Greenland, mapping rust zones on Kap Simpson, Traill Ø. Part of map from Thyrsted & Friedman (1983).*

Though quite early days for remote sensing from aircraft, this project touched many of the subjects still central in multi- and hyperspectral work today. Bad weather, rough flying conditions etc. were a hindrance and the entire planned programme could not be carried out. Many of the methods tried had to be supported by new computer programs constructed in the project; having to work without the easily controllable digital environment of today, resulted in mechanical replacements being used for ground truth, e.g. using photography with filters of coloured glass separating the different wavelengths of the spectrum for comparison with the airborne data. Encouraging results were obtained, see e.g. Figure 10. It could be concluded in the project that (i) rust zones could be located with some accuracy and that the reflection measurements could be used to distinguish different compositions of the rust zones. In some cases, specific mineralogies were suggested by the data. Laboratory measurements of samples enhanced the interpretation of the data in various ways, and characteristic features in the spectre, such as a rapid fall-off of intensity in the region 0.6–0.5 µm related to hematite/goethite pointed to the composition of the rust zone. Primitive classification schemes did give results that could be interpreted. The consensus of the project was an overall positive possibility for use of remote sensing techniques for mineral exploration. Some disappointments were encountered but can today be seen to be caused by the inadequacy of the methods used then, e.g. no use was done of the thermal band. Since then, more detailed and intelligent ways of correcting data have become common. Digital methods are the norm and some of the difficulties encountered then have been eliminated in today's processing of much better data.

5.2 Remote sensing in Uranium Exploration, South Greenland, 1984

This study presented in Conradsen *et al*. (1984) is one of the first attempts to integrate, in the strict mathematical sense of the word, remote sensing data with other types of geoscience data, building on methods later described in Conradsen *et al*. (1992a, b). The remote sensing data were based on four Landsat scenes from which a mosaic was constructed. The processing of the remote sensing data did not bring out any new geological features, but it did outline the already known larger Gardar age intrusions. Several different techniques were tried but cannot be said to bring out significantly new information about an area already studied through fieldwork through many years – the resolution of the Landsat MSS does not really allow that. The study did, however, also look at the integration of other types of data, notably the old aeromagnetic data from the Kryolitselskabet Øresund's mid-sixties survey and geochemistry from regional sample collections; some interesting hints were revealed, e.g. Figure 11 showing a combination of elements, using intensity, hue and saturation for the colour scheme.

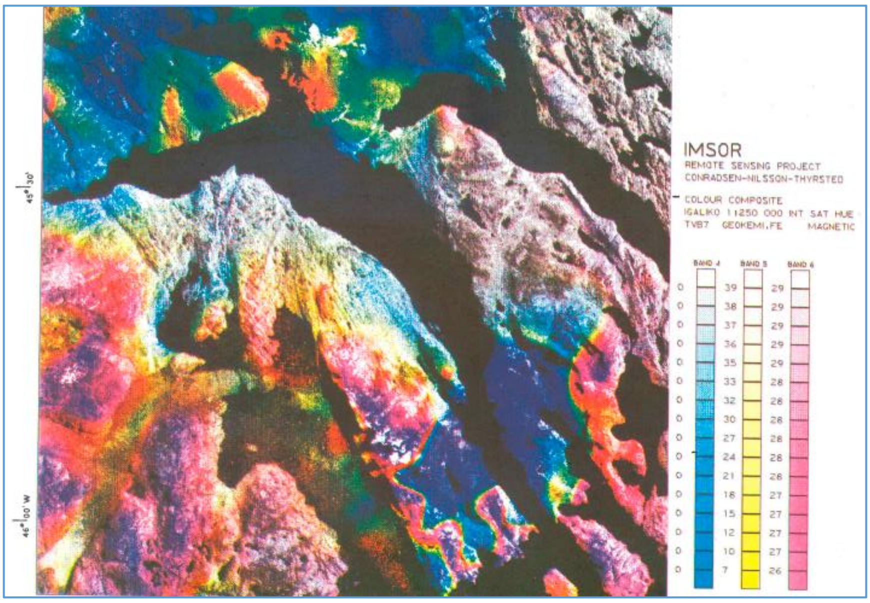

Figure 11. *HIS-image of Ilimaussaq area combining Landsat band 7, aeromagnetic values and kriged values of Fe in stream sediments. The clear delineation of the intrusion comes from the magnetics. Scale: width of map is approximately 50 km. From Conradsen et al. (1984), scanned from the original report.*

5.3 A database of Landsat scenes from Greenland, 1994

As for many other institutions, the event of the first Landsat satellites became the starting point for GGU's use of satellite data. Far from today's excellent data in quality, the early Landsat data were nevertheless titillating enough to maintain expectations. In the seventies, they were mostly used for studies of lineaments, but some GGU personnel were involved in proper image processing and attended the first advanced courses already then.

The greatest success was probably the production of good satellite maps, which was especially beneficial in Greenland where available traditional maps were not that accurate. The DGI institute's fixed geodetic points were available, so the maps produced from satellite data were often more accurate than existing maps. Simple classification schemes allowed some interpretation to be added to the maps.

One problem was encountered repeatedly, when trying to find good scenes from Greenland: the automatic classification schemes for cloud cover could not distinguish snow/ice from cloud and consequently the automatic classification carried out by the data supplier could not be trusted to give a realistic assessment of the usefulness of a scene. The scenes had to be manually inspected via quick-looks and the data tested. Finally, to ensure continued rapid access to good scenes, in 1994 Leif Thorning and Tapani Tukiainen spent a couple of

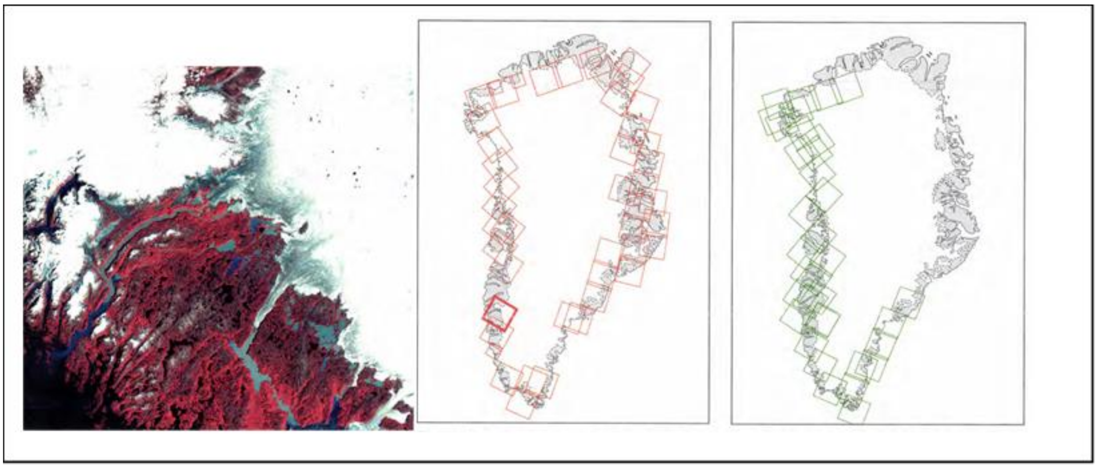

Figure 12. *Left: Example of Landsat TM scene (path 007, row 014 – frame highlighted in centre) and the problem of classifying snow. Centre: Landsat TM scenes originally selected from archives in Kiruna (The seven channel Landsat TM system active 1982 – 1995). Right: Similar for Landsat (The four channel Landsat MSS system active 1972 – 1978). From Thorning & Tukiainen (1995).*

weeks in Kiruna, at the Swedish Space Corporation, going through all then available Landsat and Landsat TM quick looks from Greenland in order to identify a sufficient number of scenes of good quality to cover most of Greenland, see Figure 12 (Thorning & Tukiainen 1995). These became the core of a database of Landsat scenes, which occasionally has been augmented since then and now can be accessed via an ArcGIS interface at GEUS.

Satellite data from modern or upcoming satellites can usually be inspected at special web sites run by the data providers responsible for the given satellite, and thus access to high quality data is easier today. These data will not be incorporated in the Landsat TM collection. Most data producers today offer good facilities for inspection and ordering of satellite data, so there is no need for continued development of GEUS' Landsat Image Database.

5.4 Spot and Landmark, South-East Greenland, 1993–1995

In the first half of the nineties, project GIRS (Geological Information from Remote Sensing) investigated some aspects of using remote sensing in connection with the different phases of a typical GGU regional assessment programme (Tukiainen & Thorning 1995; Tukiainen *et al*. 1993), including a comparison between Landsat TM and SPOT. The target was South Greenland (project SUPRASYD). Project GIRS was carried out in co-operation with Satellitbild, the Swedish Space Corporation. Two sets (standard base maps and maps of extracted geological information) of seven maps were produced by Satellitbild based on SPOT before

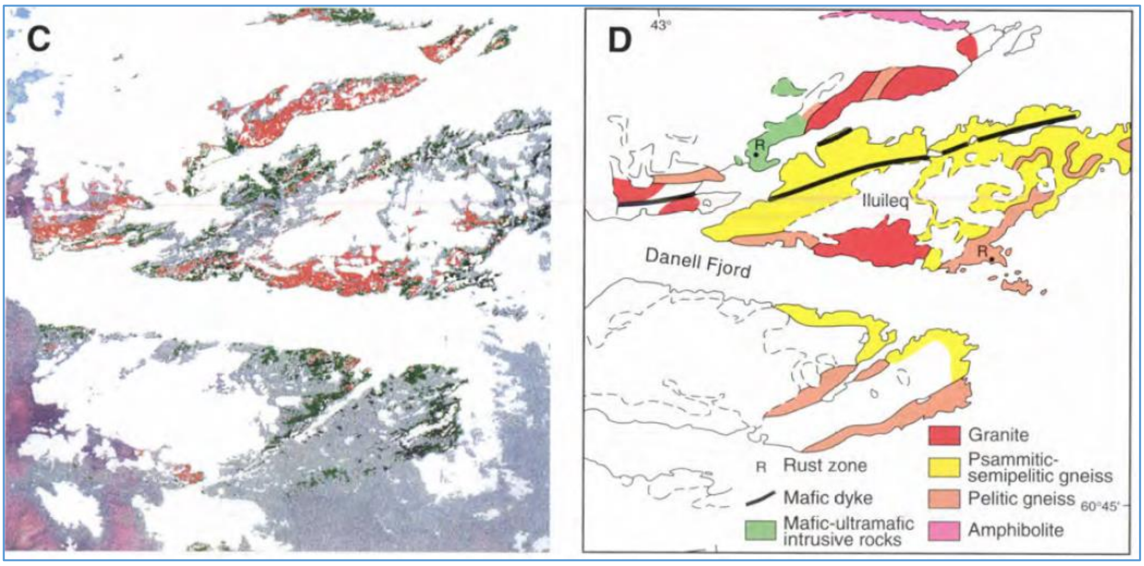

Figure 13. *The best results in project GIRS were obtained using Landsat TM (left). Here from South Greenland in a comparison with observed geology (right). From Tukiainen & Thorning (1995).*

the field season in 1992 and could be assessed during the geological reconnaissance work. The Landsat TM data could not be delivered until after the field work, but were then processed by GEUS and thus the preparations to the field work had to rely on SPOT X, with better spatial resolution (20 by 20 metres), but fewer bands over a narrower range (three bands in the range 0.50 to 0.89 μm). The field work made it clear that the SPOT-based 'geological' maps could not be used with any degree of certainty. The Landsat TM maps produced in early 1993 based on a Principal Component Transformation were much better. Principle components 2, 3 and 4 contain information about the geology, see Figure 13. Briefly, the conclusion of the comparison was that for geological purposes, Landsat TM data were superior although the spatial resolution was inferior compared to that of SPOT. However, the seven SPOT-based maps were at the time the best 'topographic' maps in existence for SE Greenland, because they were new maps based on better spatial resolution and newly checked geodetic points, and the maps could be used successfully in the geological field work. This underlined another aspect of remote sensing data: new and accurate maps could be produced quickly, an important fact for Greenland, where many regions had not yet been mapped topographically with any degree of modern accuracy.

5.5 Thematic Map Series, 1990–1997

Although remote sensing data played a minor role in terms of number of maps per issue, (a series typically comprise some 40–60 different maps), the Thematic Map Series should be mentioned, because the principles and goals developed in the late eighties for these maps became inspirational for the systematic work with remote sensing data. At that time there was still far between desktop computers that could handle the graphics as is common today, GIS systems were heavy programs difficult to use, and colour printing was just becoming feasible, so the thematic maps were produced digitally using the expert tools and the maps, some 40–60 for each region, were then printed and delivered on demand. As the development of desk top GIS, colour printers etc. picked up, it became possible to use a different approach with maps in different layers in an ArcView project file, which the user could print from or use digitally. Therefore, the first four issues were printed maps in a loose leaf system, A4 or A3 size paper: the Nuuk–Maniitsoq area, southern West Greenland (Figure 14) (Steenfelt *et al.* 1990), the Kap Farvel–Ivittuut area, South Greenland (Thorning *et al.* 1994), the Paamiut–Buksefjorden area, southern West and South-West Greenland, (Ady 1995; Ady & Tukiainen 1995), and Inglefield Land, North-West Greenland (Schjøth *et al*. 1996). By then, the accessibility of desktop GIS and other geoscience programs had improved so much that it was thought realistic to depend on purely digital publication; the maps from Inglefield Land was therefore re-issued in 1997 as a digital ArcView file. The print-on-demand Thematic Map Series were discontinued in the late nineties, but the principle (e.g. Ady 1995) has since been applied to many of GEUS' publications of regional geoscience data related to GEUS' mineral assessment projects. In relation to this, several remote sensing maps have been included, allowing remote sensing data to be easily compared with other types of geoscience data in integrated interpretation. The last stage of development has brought the data and maps to the Greenland Portal, which can display all maps released and in give access to the data behind the maps.

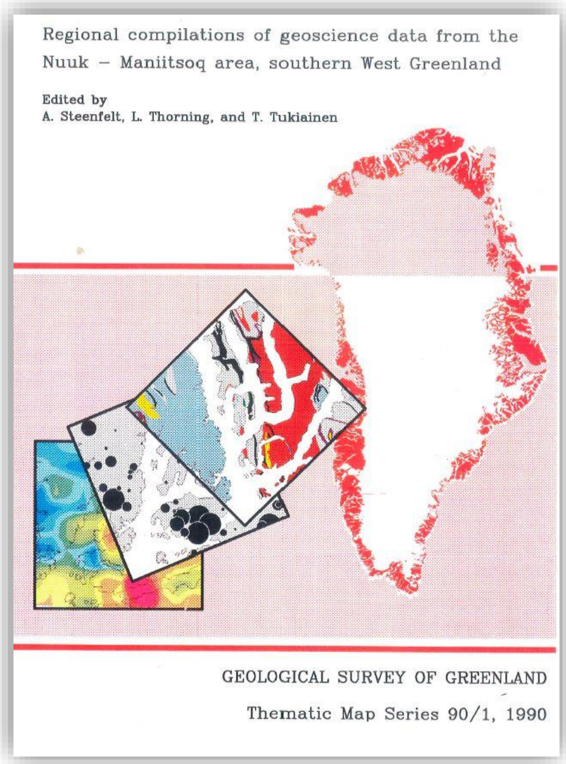

Figure 14. *Principle of thematic maps illustrated on the titel page of the first 'print-on-demand' editon from 1990. This issue contained 57 different maps of earth science data covreing the same area of southern West Greenland.*

5.6 Satellite Image Maps for communes, West Greenland, 1998–2001

In the late nineties, the impressive image maps produced in relation to several of GEUS' projects caught the attention of the public in Greenland. By request, GEUS compiled a couple of natural look images based on Landsat TM data into wall maps of different regions around major communities in scale 1:500,000. These maps probably still adorn walls in several public offices and companies in the area, see Figure 15 for an example. A special version of this map type and three-dimensional views were produced by Tapani Tukiainen for the application for award of World Heritage Site to the Ilulissat glacier and ice-fjord in scale 1:300,000, see Figures 16 and 17. To produce such maps is now a standard operation and it is always done in connection with e.g. mineral resources assessment and other specialised compilations.

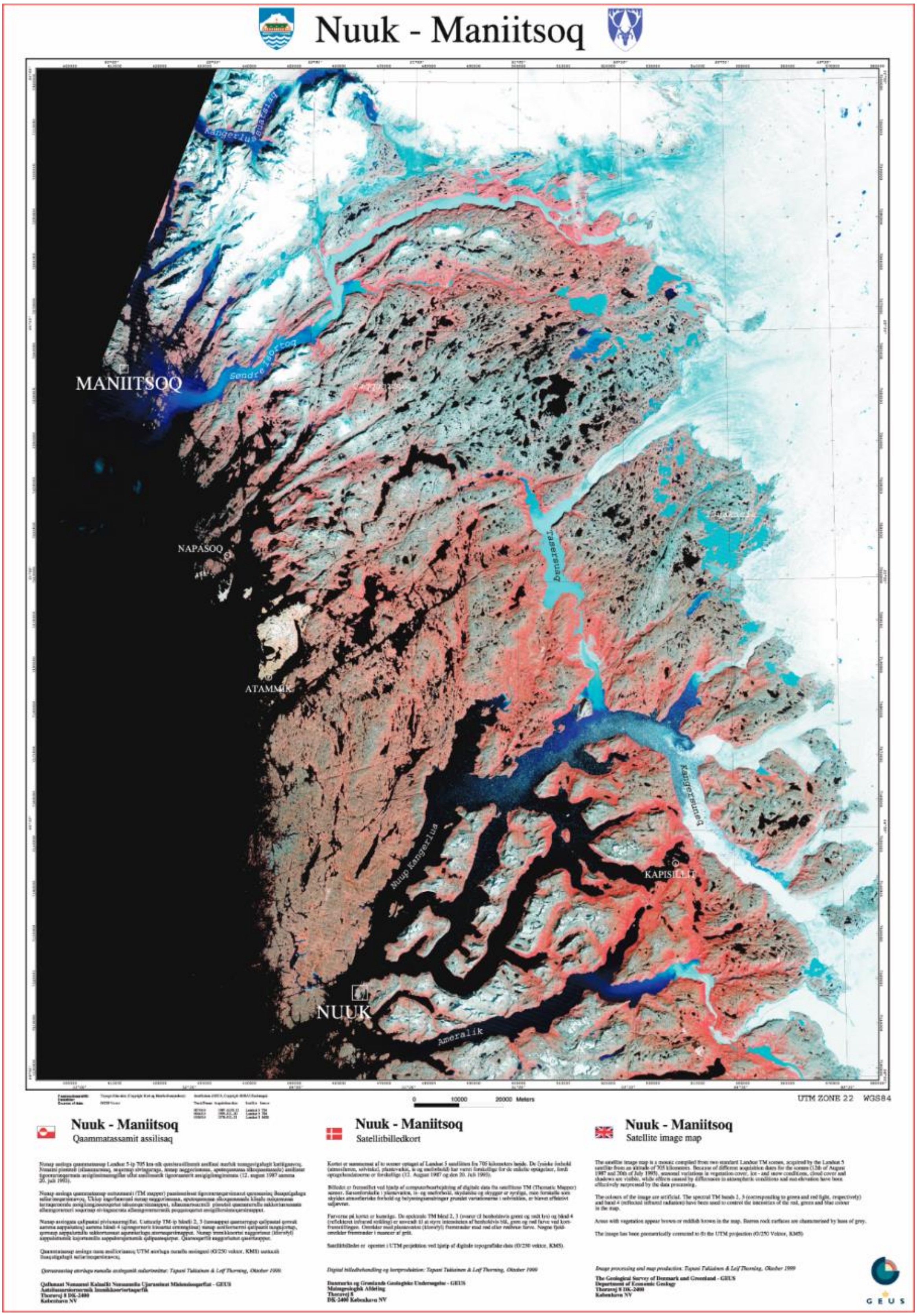

Figure 15. *Example of wall map prepared from Landsat TM data.*

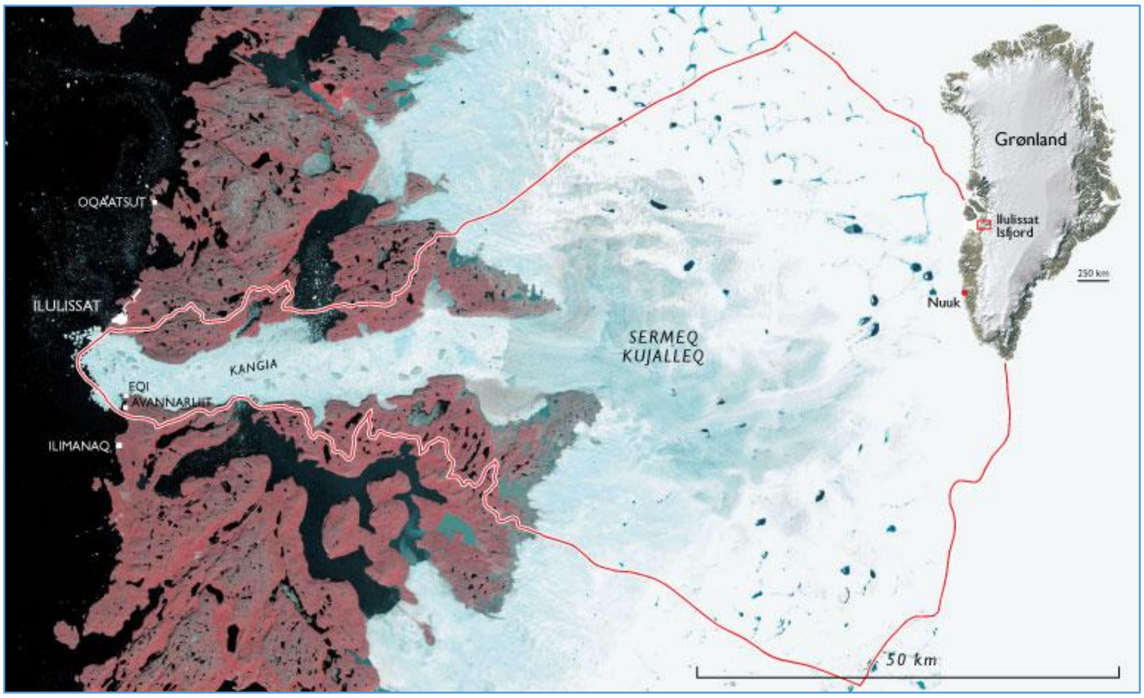

Figure 16. *The satellite image map produced for the World Heritage Site application, Ilulissat ice-fjord, in 2001.*

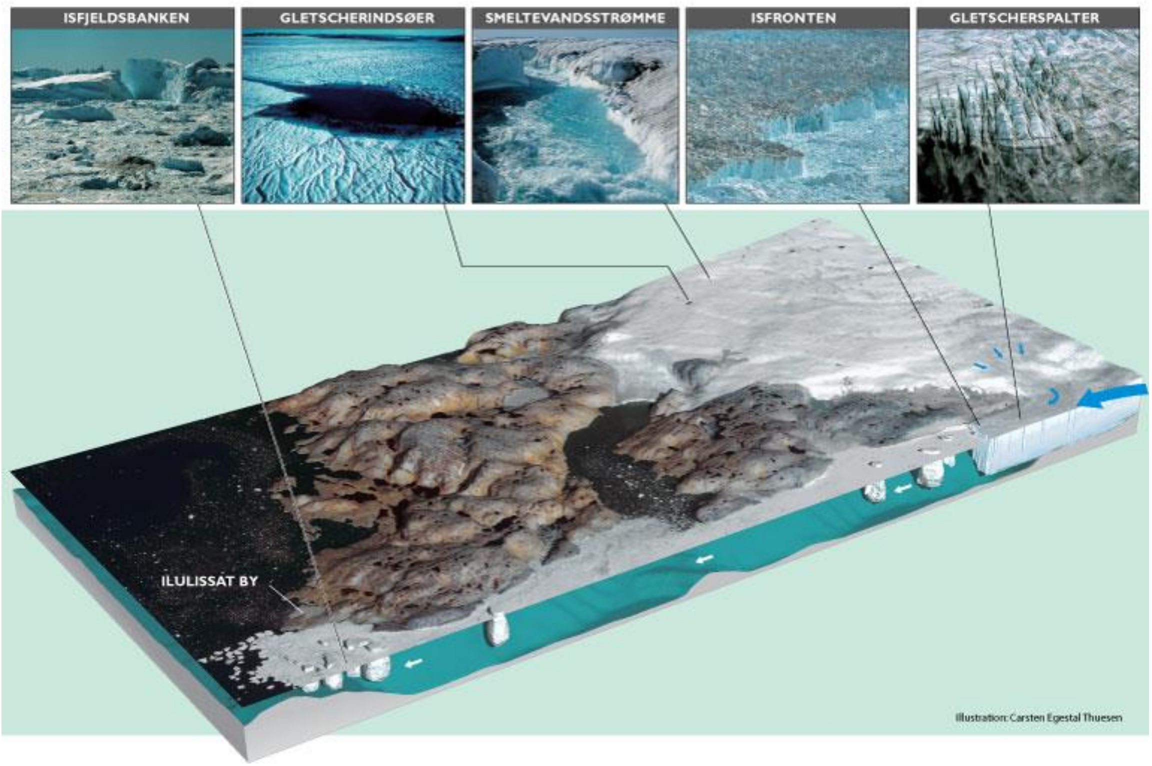

Figure 17. *Three-dimensional rendering of the image draped on a digital elevation model (DEM) produced from Aster data using GI geodetic points.*

5.7 Upernavik 1998, Landsat TM interpretation

The Upernavik 98 project was a one-season exploratory reconnaissance of the mineral potential and drainage geochemistry of the Upernavik–Kap Seddon region, North-West Greenland, supported by the Bureau of Minerals and Petroleum, Government of Greenland (Thomassen *et al*. 1999a, b). The ship-based fieldwork covered the region's coastline stretching for 330 km in a north–south direction. The region is underlain by Archaean gneisses and a major Palaeoproterozoic supracrustal unit (Karrat Group) deformed and metamorphosed during the 1.8 Ga Rinkian orogenesis (Figure 18).

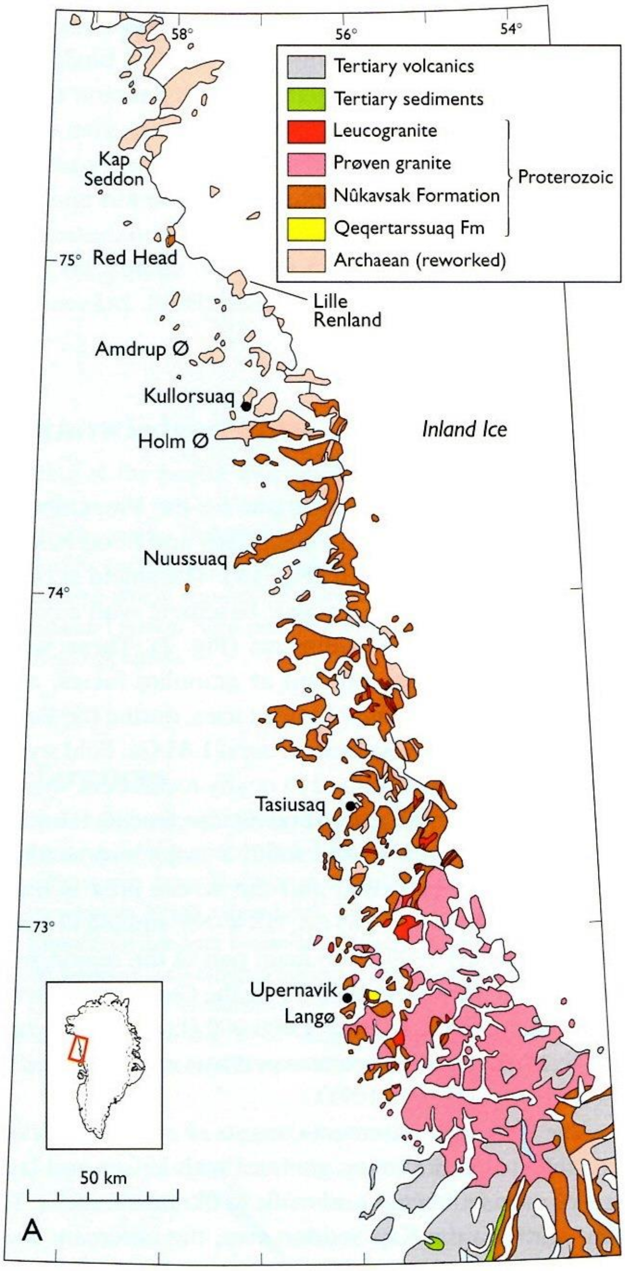

Figure 18. *Geological map of the Upernavik region. From Thomassen et al. (1999b).*

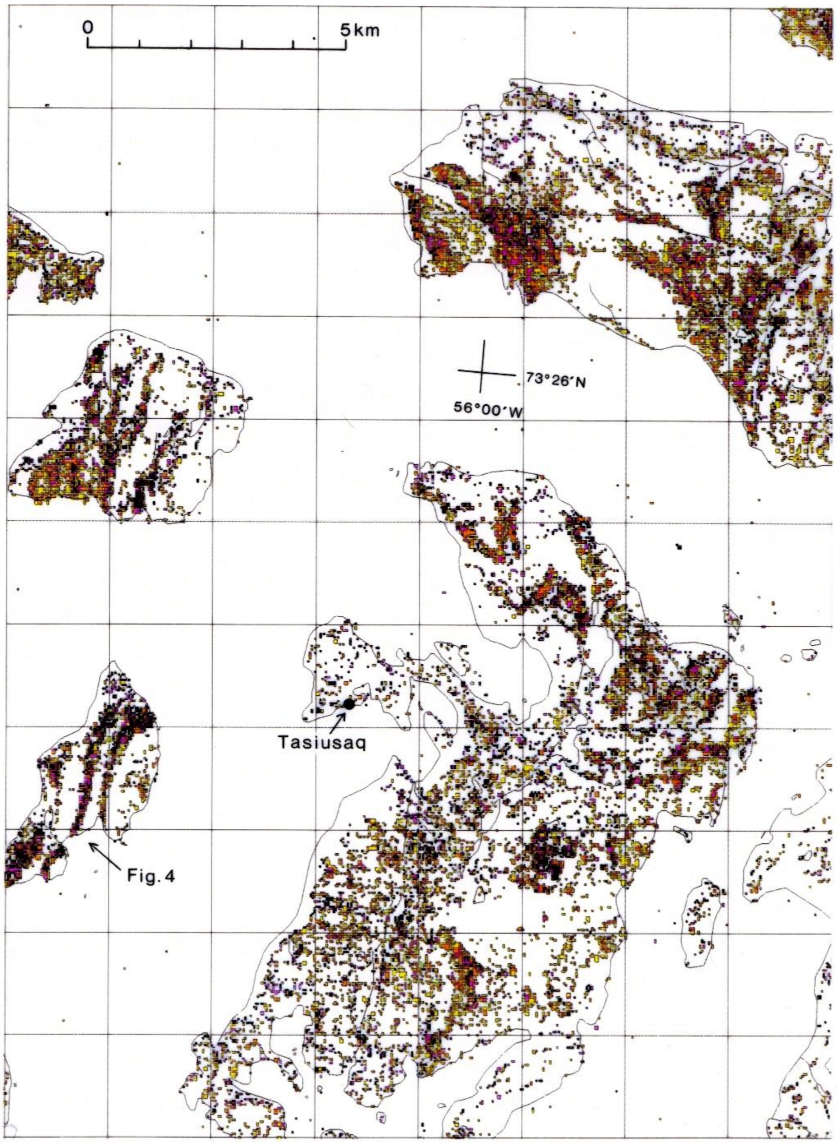

Figure 19. *Colour anomaly map of the Tasiusaq area, near Upernavik. The map is produced from Landsat TM satellite images. Dark colours: strong discolouration, red tones: medium discolouration and yellow colours: weak discolouration. From Thomassen et al. (1999a).*

Before the field season, a remote sensing study of rust zones based on Landsat TM imagery was carried out, and maps at 1:100,000 showing zones of more intense ferric iron staining were produced for use in the planning of the daily traverses (Figure 19). The maps revealed extensive anomalies in Nûkavsak Formation metagreywackes corresponding to conspicuous red and yellow rust zones seen in the field (Figure 20). They consist of conformable, tens of metres thick horizons with enhanced content of biotite, graphite, pyrrhotite and magnetite. Although no signs of base-metal concentrations were encountered, the zones constitute future exploration targets.

A programme of spectroradiometric measurements of rock surfaces was carried out using a GER Mark V Infrared Intelligent Spectroradiometer borrowed from the Musée royal de l'Afrique centrale, Belgium, which provides accurate spectral measurements from 350 to 2500 nm in 704 channels. The objective was to determine spectral characteristics of representative lithologies and various types of hydrothermal alteration. The effect of partial lichen cover on the spectral characteristics of rocks were measured in selected localities. The measurement programme was combined with collection of representative rock samples from each investigated locality. The results of the spectroradiometric survey provided a reference dataset for the processing and interpretation of available multispectral satellite data and future hyperspectral data sets from air- and spaceborne sensors.

Figure 20. *Typical rust zone in the Nûkavsaq Formation metasediments on an island southwest of Tasiusaq. View towards the west; relief is about 100 m; cf. arrow 'Fig. 4' on Figure 19. From Thomassen et al. (1999a).*

5.8 MINEO Hyperspectral survey in North-East Greenland, 2000

GEUS participated in a three-and-a-half-year EU project (under the 'Information Society Technology' Programme 1998–2002; Contract IST-1999-10337: *Monitoring and assessing the environmental Impact of mining in Europe using advanced Earth Observation Techniques*). The project started in January 2000 with the general objective to develop hyperspectral remote sensing methods to measure and monitor mining activities and the pollution of the environment sometimes arising from this. Hyperspectral HYMAP surveys were flown over known mine sites representing different climatic environments in Finland, Germany, Austria, United Kingdom, Portugal and Greenland. GEUS (Tapani Tukiainen) was responsible for the general supervision of the HYMAP surveying programme over all sites and the handling of the data from the Greenland site. Full documentation and data examples of the project can be found at the official web site of the project, http://www.brgm.fr/mineo/.

Airborne hyperspectral measurements were carried out in North-East Greenland with HyVista Corp. as contractor, see Figure 21. A Dornier 228 aeroplane from Deutsches Zentrum für Luft und Raumfart served as platform for the hyperspectral spectrometer and a Zeiss aerial camera. The data acquisition was by a HyMAP^{TM} sensor with 126 bands covering the 440–2500 nm spectral region with a 4 x 4 m spatial resolution (Tukiainen 2001). The MINEO project, which included ground truthing in 2001, was completed in 2003 (Aastrup *et al*. 2001; Tamsdorf *et al*. 2003). Airborne surveying for the HyperGreen project was also carried out in 2000, see section 5.10.

The EU-supported project was in Greenland directed towards mining-related pollution which covered the abandoned lead-zinc mine Blyklippen at Mesters Vig, central East Greenland. Although the reflectance of sphalerite is too low for the mineral to be spectrally identified when alone, its spectral characteristics enable the discrimination of the sphalerite-bearing tailings at Blyklippen. The hyperspectral data using Spectral Angle Mapper therefore proved to be efficient in mapping the distribution of tailings, and alluvium affected by tailings in the surroundings of the mine. Furthermore, the mapping results indicate that considerable amounts of tailings were transported and deposited 8–10 kilometres away from the mine, where the terrain become flatter (Figure 22).

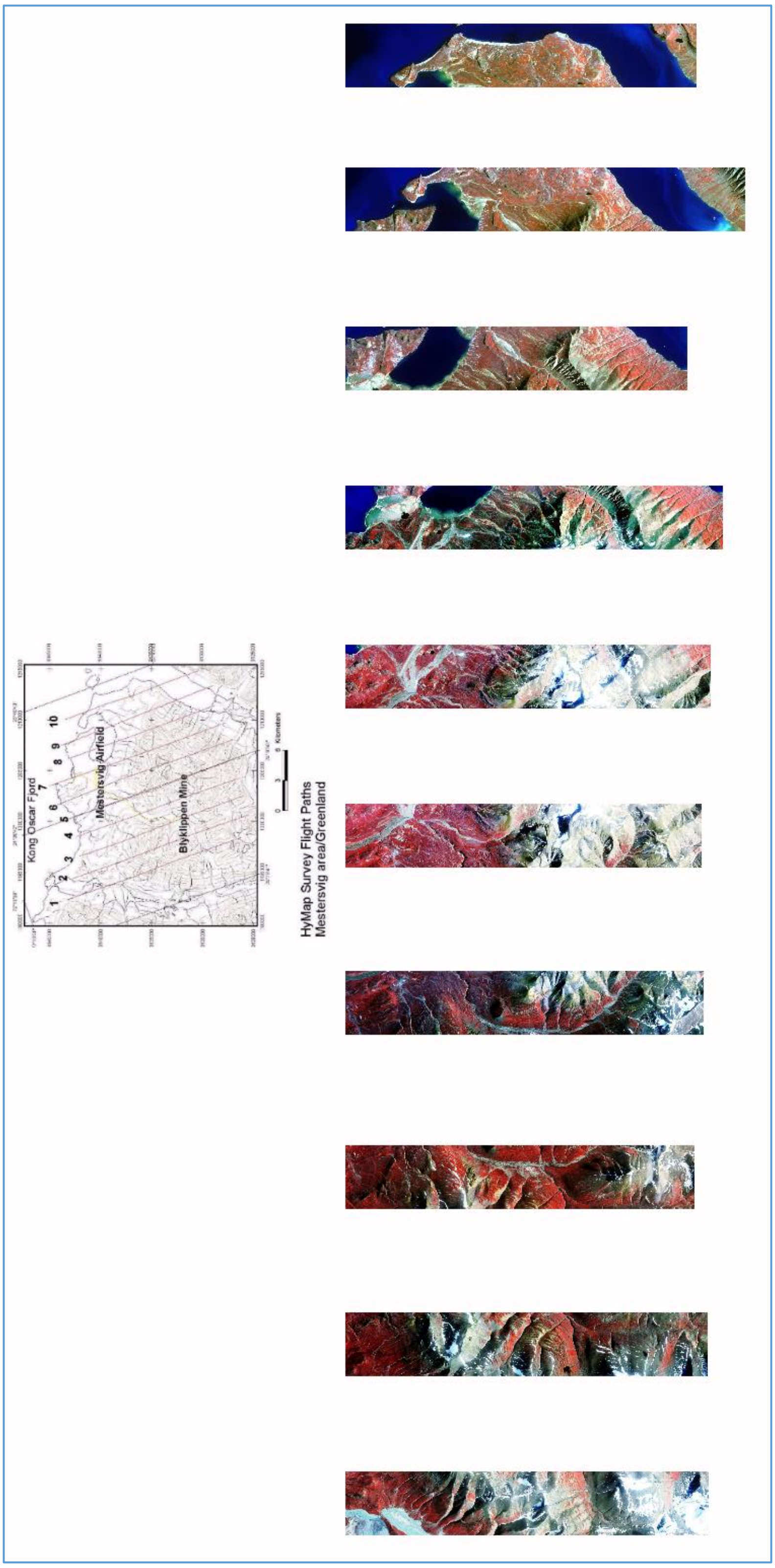

Figure 21. *Quick look of the hyperspectral data from MINEO/Mestersvig Greenland, illustrating the typical form of airborne data from whole flight lines, with overlap between the lines allowing for later merging into a proper map. The figure shows a 'natural look' version of the data over the Blyklippen mine site and surroundings. From the official MINEO web site.*

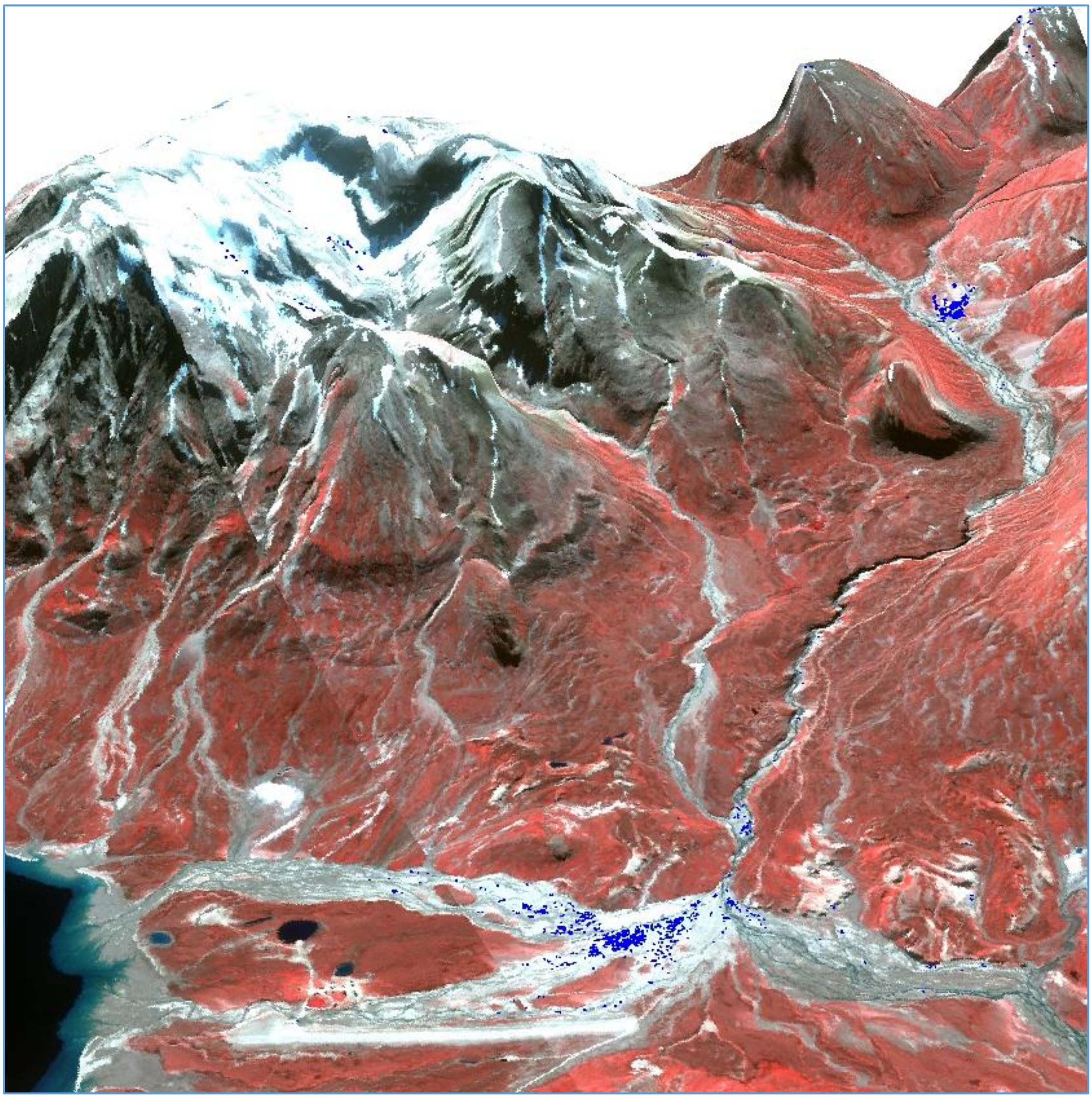

Figure 22. *The tailings and washout (blue) from Blyklippen have been draped on the 3D map to visualise the deposition of material in the lower parts of the riverbed. HyMAP data. From the MINEO home page.*

5.9 Qaanaaq 2001, Landsat 7 interpretation

Project *Qaanaaq 2001,* was a one-season, ship-based reconnaissance of the mineral potential and drainage geochemistry of the 4300 km^2-sized Olrik Fjord–Kap Alexander region, North-West Greenland; it was a joint project of GEUS and the Bureau of Minerals and Petroleum, Government of Greenland (Thomassen *et al.* 2002a, b).

The bedrock of the region is formed of two provinces: an Archaean–Palaeoproterozoic crystalline shield overlain by the unmetamorphosed Mesoproterozoic Thule Basin of sediments and volcanics (Thule Supergroup).

An integral part of *Qaanaaq 2001* was a pre-season remote sensing study aimed at delineating areas of potential economic interest. It was based on four images of Landsat 7 ETM data recorded during the season of minimum snow cover. The intention was to pin-point localities with mineralisation potentials by mapping minerals carrying iron oxides (rust zones) and hydroxyl ions (argillic alteration). Areas with coincident rust coloration and hydrothermal alteration were considered to have a potential for mineralisation, worth a later field check.

Two different techniques were used to map the distribution of iron-oxides (Fe-O), ferrous-iron (Fe^{+2}) and hydroxyl-bearing minerals: (1) standard band ratios and (2) feature-oriented Principal Component Analysis. By combining these dataset, 28 anomalies were registered as targets for field checks. The field work showed that all areas of alteration and/or rust coloration observed in the field were also registered in the processed Landsat data and that 17 of the anomalies were related to mineralisation and/or hydrothermal alteration (Figure 23), the remainder stemming from formational responses. Therefore, it was recommended to apply this method in future reconnaissance projects.

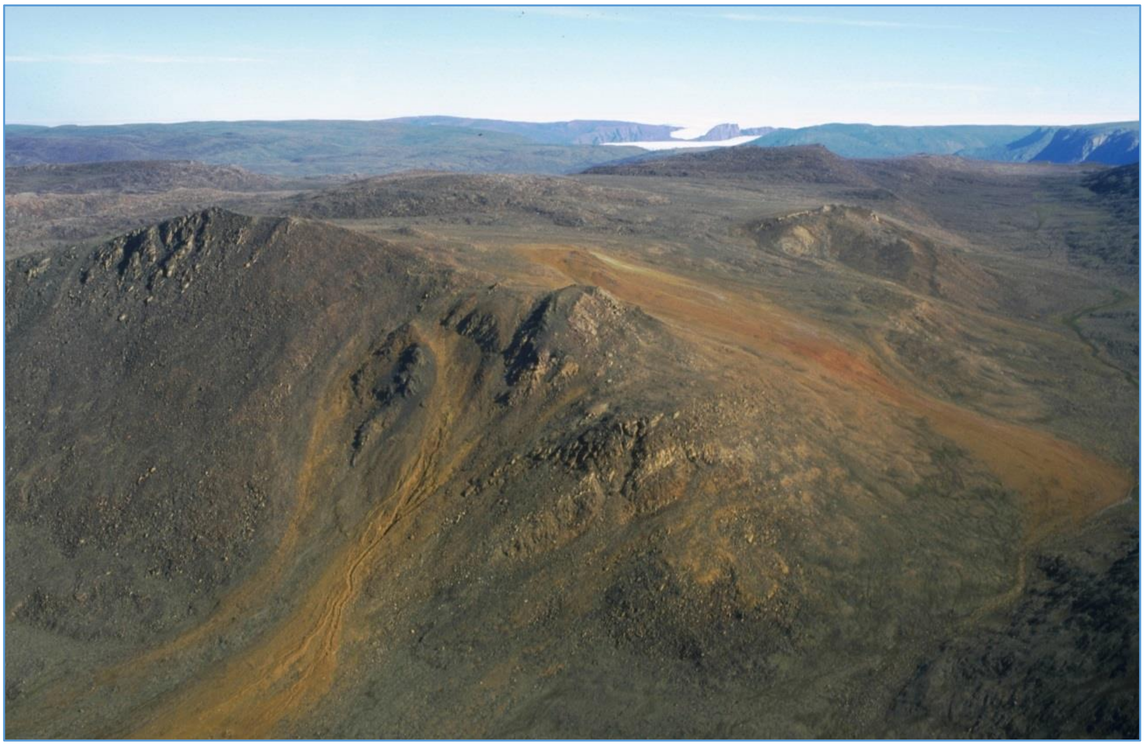

Figure 23. *Site of Landsat anomaly at Mt. Gyrfalcon checked during the Qaanaaq 2001 project. The rusty coloration stems from an occurrence of banded iron formation in the Archaean crystalline rocks. From Thomassen et al. (2002a).*

5.10 HyperGreen and North-East Greenland follow-up, 2005–2009

Exploiting the opportunity of having hyperspectral equipment in Greenland (HyMAP – see section 5.8), several separate surveys were acquired in 2000 in a parallel project (HyperGreen: *Assessing the applicability of high resolution image spectroscopy as a mineral explo-*

ration tool) supported by the Bureau of Minerals and Petroleum (BMP), Greenland Government, covering a number of classic mineralisation sites in central East Greenland (Figure 24).

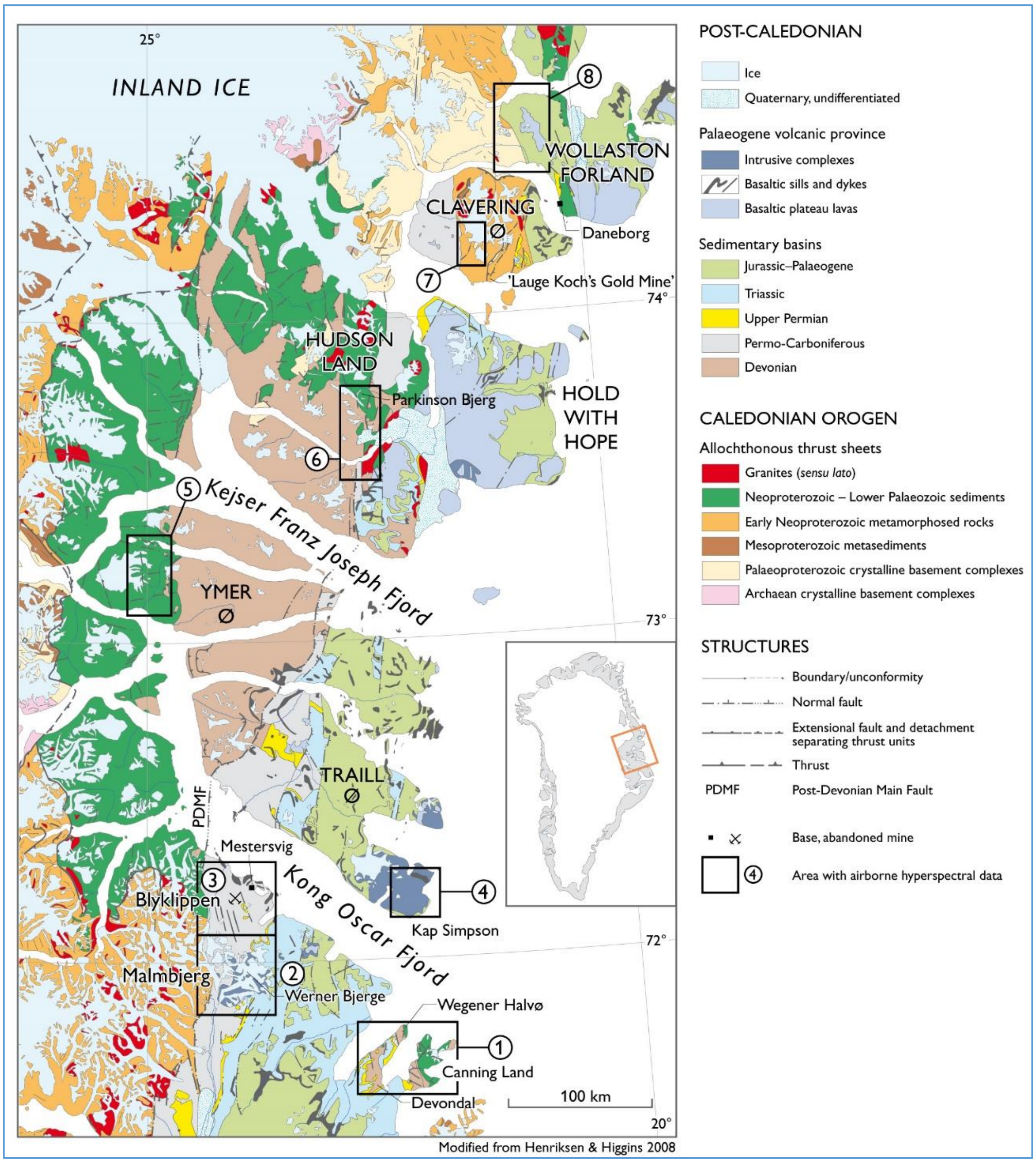

Figure 24. *Geological map of North-East Greenland showing areas covered by airborne hyperspectral data. Modified from Henriksen & Higgins (2008). From Tukiainen & Thomassen (2010).*

The aim was to test the hyperspectral method's suitability in mineral exploration in the different environment of interest in exploration. Airborne hyperspectral data acquired in 2000 were assessed in eight areas underlain by Caledonian and post-Caledonian rocks with known mineral occurrences.

Follow-up ground checks of the HyperGreen airborne data were undertaken in 2005, 2008 and 2009 (Project Hyperøst; Thomassen & Tukiainen 2008; Tukiainen & Thomassen 2010). The work was conducted from fly camps and carried out in co-operation with International Molybdenum Ltd, engaged in the exploration of the Malmbjerg molybdenum deposit, and with other GEUS activities in the region. It comprised geological fieldwork with the registration of spectra of rocks, minerals and their weathering products with a portable spectroradiometer in order to determine their spectral character and to compare this information with the airborne data. In 2005 and 2008, a PIMA II portable instrument was borrowed from other institutions, and for the 2009 season, GEUS purchased an advanced spectroradiometer, model FieldSpec 3 HiRes.

The investigations showed good correlation between the airborne spectra and the field spectra, confirming the quality and stability of the airborne hyperspectral data. In general, sulphide minerals have poor to weak spectral response in the visible and near-infrared (VNIR) and short wave-infrared (SWIR) spectral regions, whereas their alteration products, such as malachite, cerussite, smithsonite and jarosite, are distinctly SWIR-active. However, apart from jarosite, these minerals are virtually non-existent in the region. In contrast, it appears from the study that the hyperspectral detection of typical host- and wall-rock alteration minerals (jarosite, white micas, phengite, kaolinite, dolomite, etc.) provides an effective method to outline exploration targets. Highlights from the survey comprise:

(i) In the Palaeogene Werner Bjerge alkaline intrusive complex (area 2 in Figures 24 & 25), the hyperspectral mapping defined a locality *c.* 1 × 1.5 km in size, which displays many spectral similarities to the nearby Malmbjerg porphyry molybdenum deposit (Figures 26 & 27). This anomaly underlain by Permo–Carboniferous sandstone was found to host a significant number of pyrite- and fluorite-bearing trachytic dykes and sheets enriched in potassium, tungsten, molybdenum and thorium. These rocks may represent the top of a porphyry system with an unexposed granite at a lower level. Likewise, high-temperature potassic alteration and greisen-like spectral signatures on a granite in the north-western part of the Palaeogene Kap Simpson alkaline intrusive complex (area 4) define a new exploration target with potential for porphyry-type mineralisation.

(ii) In the Mesters Vig area (area 3), the airborne data revealed a distinct *c.* 500 m wide zone of pervasive kaolinisation of Permo–Carboniferous arkosic sandstone some three km north-east of the abandoned lead-zinc mine Blyklippen. This could be related to unknown mineralisation of Blyklippen type. On Hudson Land and Clavering Ø (areas 6 and 7), extensive low-temperature hydrothermal alteration with associated epithermal base- and noble-metal-bearing veins along regional lineaments is well seen in the hyperspectral data.

(iii) On Wegener Halvø (area 1), a close association of dolomitisation with Upper Permian carbonate-hosted base-metal mineralisation was confirmed by the investigations, making the hyperspectral dolomite map a valuable exploration tool in this area (Figure 28).

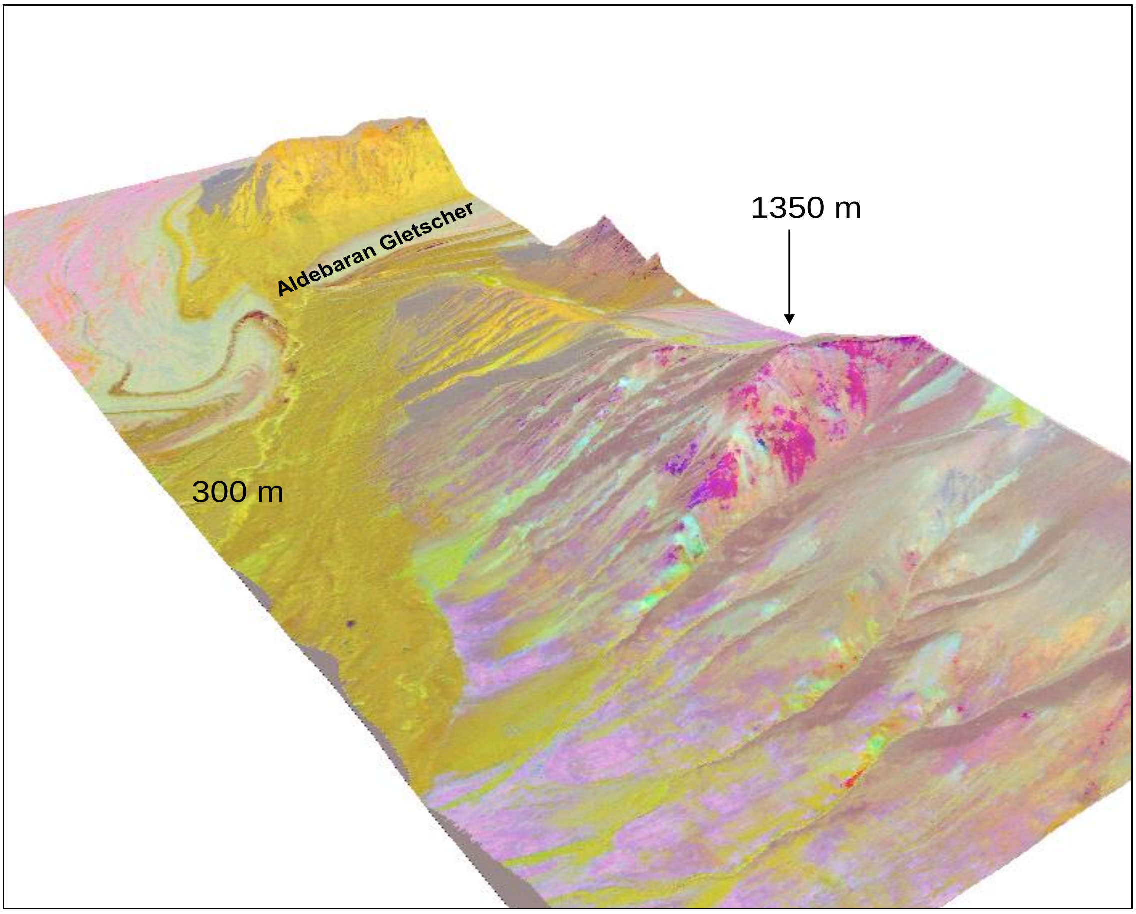

Figure 25. *Hydrothermally altered Carboniferous sandstone 3.5 km south of Aldebaran Gletcher, five kilometres south of Malmbjerg. Perspective view from the south-west of MNF-transformed SWIR data. The area of hydrothermal alteration (iron oxides, muscovite/illite) is outlined by magenta and deep blue colours. From Thomassen & Tukiainen (2008). Could this be a buried Malmbjerg?*

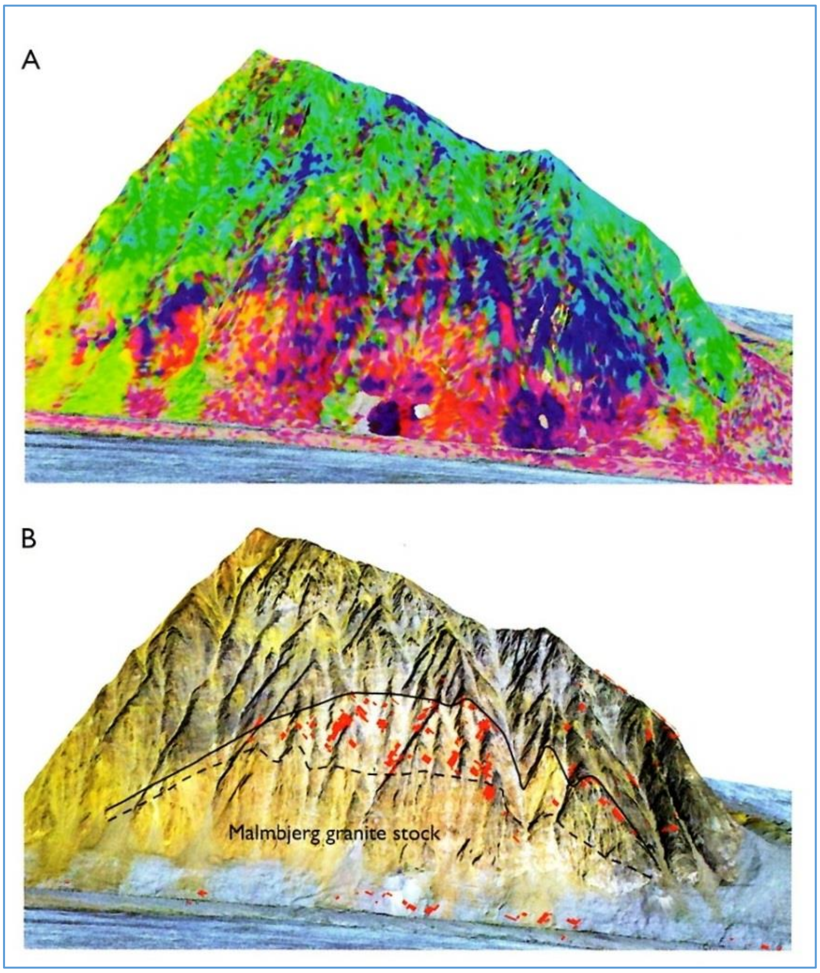

Figure 26. *Upper panel: View from the south-west of the Malmbjerg granite stock. Below: A+B, DTM (digital terrain model): based on Lidar data from International Molybdenum Ltd. (re-sampled at 1 × 1 m resolution), no vertical exaggeration, relief is 500 m. A. MNF-transformed SWIR data draped on the detailed DTM. Note the compositional zoning of the granite stock and intensive high-temperature alteration of the roofing rocks (hues of yellow and orange). B. Orthoscopic Lidar image draped on the detailed DTM. The pixels mapped as topaz/tourmaline-bearing greisen are shown with red. The boundaries of the granite stock are indicated. From Thomassen & Tukiainen (2008).*

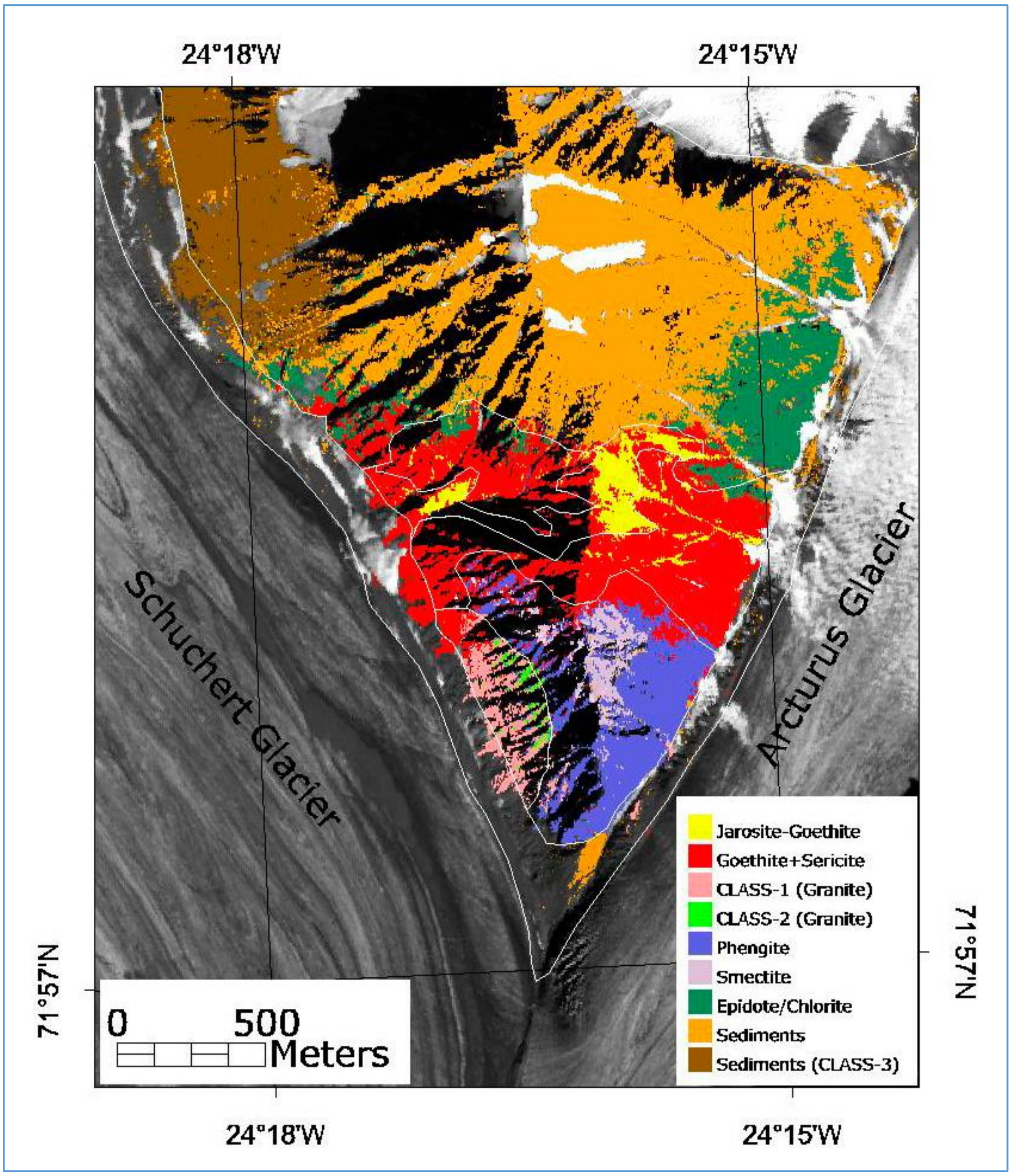

Figure 27. *Classification of rock types and minerals in the Malmbjerg deposit, using the SOM method. From Bedini (2010).*

Bedini (2010) also examined the hyperspectral data from the HyMAP survey of central East Greenland further, using several different classification methods (Figure 27).

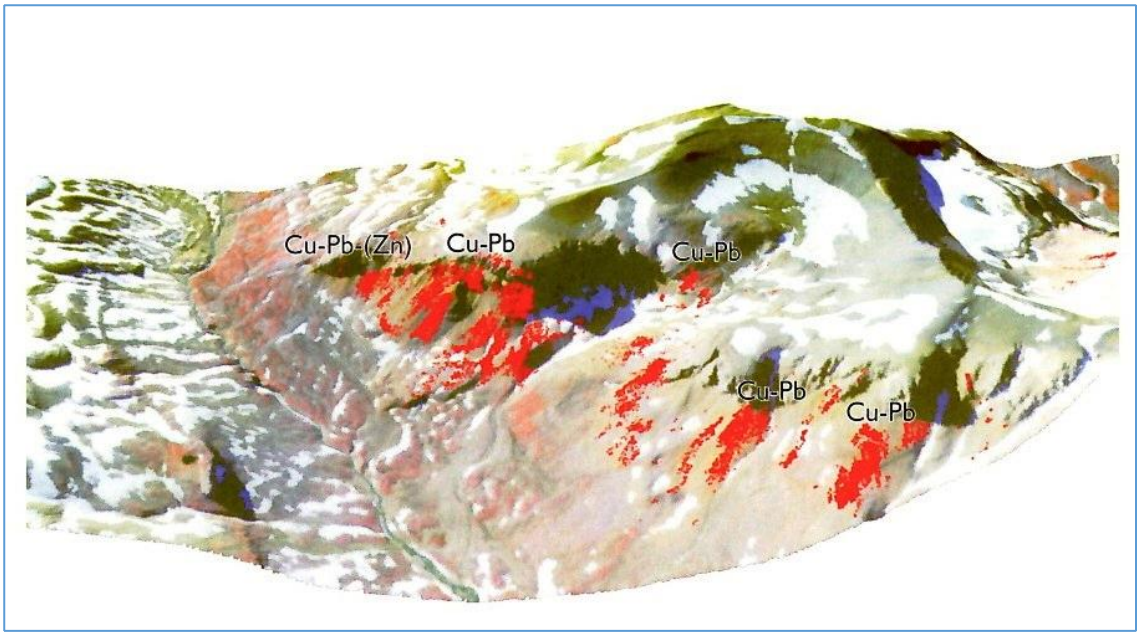

Figure 28. *Top: view from the south-east of Devondal. The lower figure shows dolomitic alteration (red) of Upper Permian limestone draped on a hyperspectral image of the north side of the valley. The scree aprons enhance the surface impression of dolomite. The known occurrences of Cu-Pb-(Zn)-mineralisation are indicated. Background image is a colour composite of HyMAP bands 27(R), 18(G) and 4(B). No vertical exaggeration, relief is 600 m. From Tukiainen & Thomassen (2010).*

5.11 HyMAP hyperspectral survey, central West Greenland, 2002

In 2000, adverse weather conditions over the Ice Cap prevented the aircraft and HyMAP instrumentation from crossing east to west over the Ice Cap, and alternative plans of flying classical mineral occurrence sites in central East Greenland were invoked, see section 5.10. In 2002, GEUS brought the HyMAP instrumentation and crew (HyVista Corporation, Australia) back to Greenland to survey the area of the West coast that could not be surveyed in 2000. The intention was mainly to cover the diamond province of West Greenland. Again, bad weather dominated, and all the flying had to be done in five days out of the fourteen days the instrumentation was available, not always in perfect conditions. The operation in July–August 2002 (project HyperGreen 2002), supported financially by the Bureau of Minerals and Petroleum, resulted in good coverage of approximately 7,500 km^2 of the West Greenland kimberlite province in the Precambrian shield (Figure 29). The HyMAP data acquired have proven very helpful in many projects since then, notably the kimberlite activities in 2003–09, and as late as in the summer of 2016 in connection with new hyperspectral projects, with the focus on mapping of mafic and ultramafic units (Salehi *et al.* 2017b, Salehi 2018b).

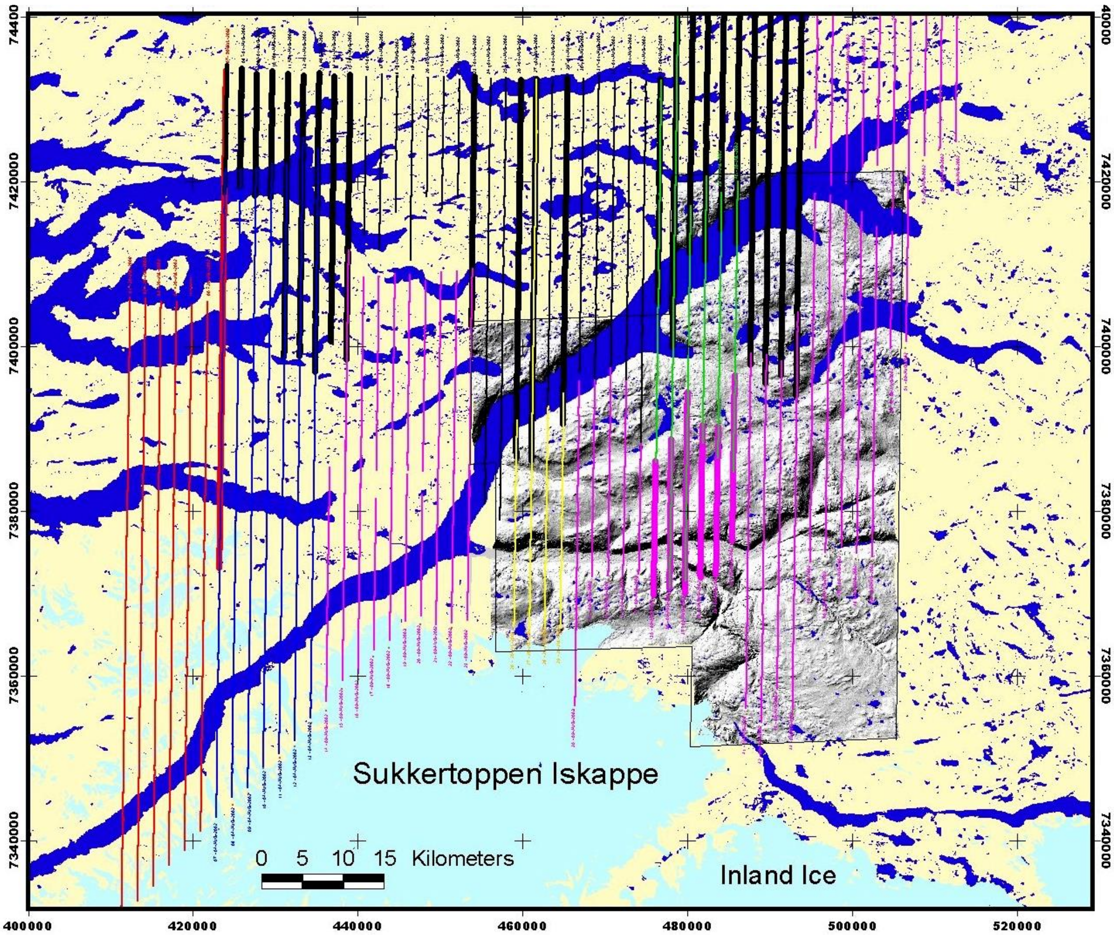

Figure 29. *Coverage of the airborne hyperspectral survey flown in 2002 over the kimberlite province of West Greenland (Tukiainen & Krebs 2004).*

5.12 West Greenland (kimberlites and carbonatites), 2003–2009

The original purpose of the HyMAP survey in 2002 in West Greenland was to provide new data for the then ongoing investigations of the West Greenland diamond province. Many occurrences of kimberlites were known, some of them contained diamonds, but no major pipes had been identified. It was hoped that the HyMAP surveys would reveal if any such structures were present. The results of this work have been reported by Tukiainen & Krebs (2004) and Tukiainen *et al.* (2003), see Figures 30–32.

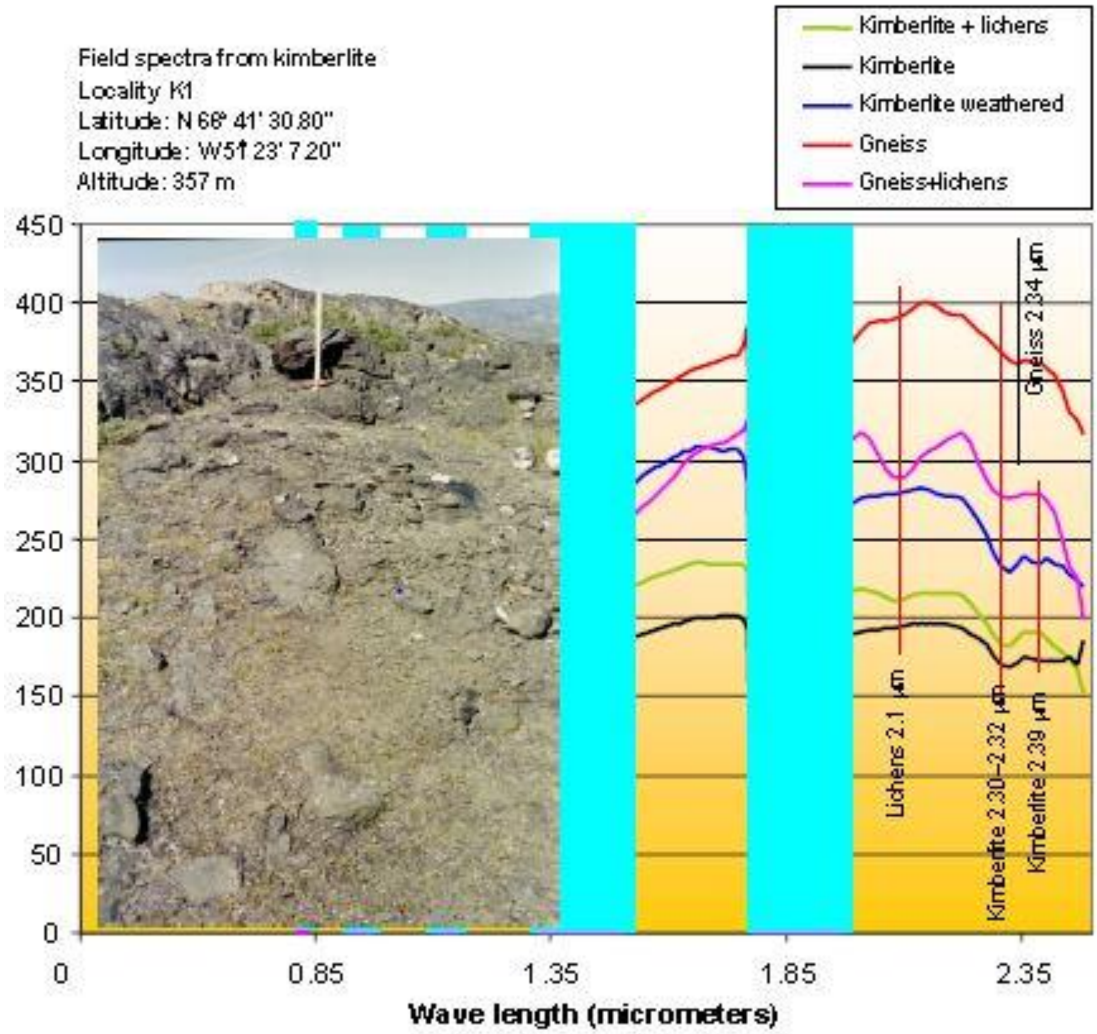

Figure 30. *Field Spectra of kimberlite and gneiss measured under sunlight (spectra resampled to HyMAP band widths) at the locality k1. Note the effects of weathering and lichen cover on the spectral responses. From Tukiainen & Krebs (2004).*

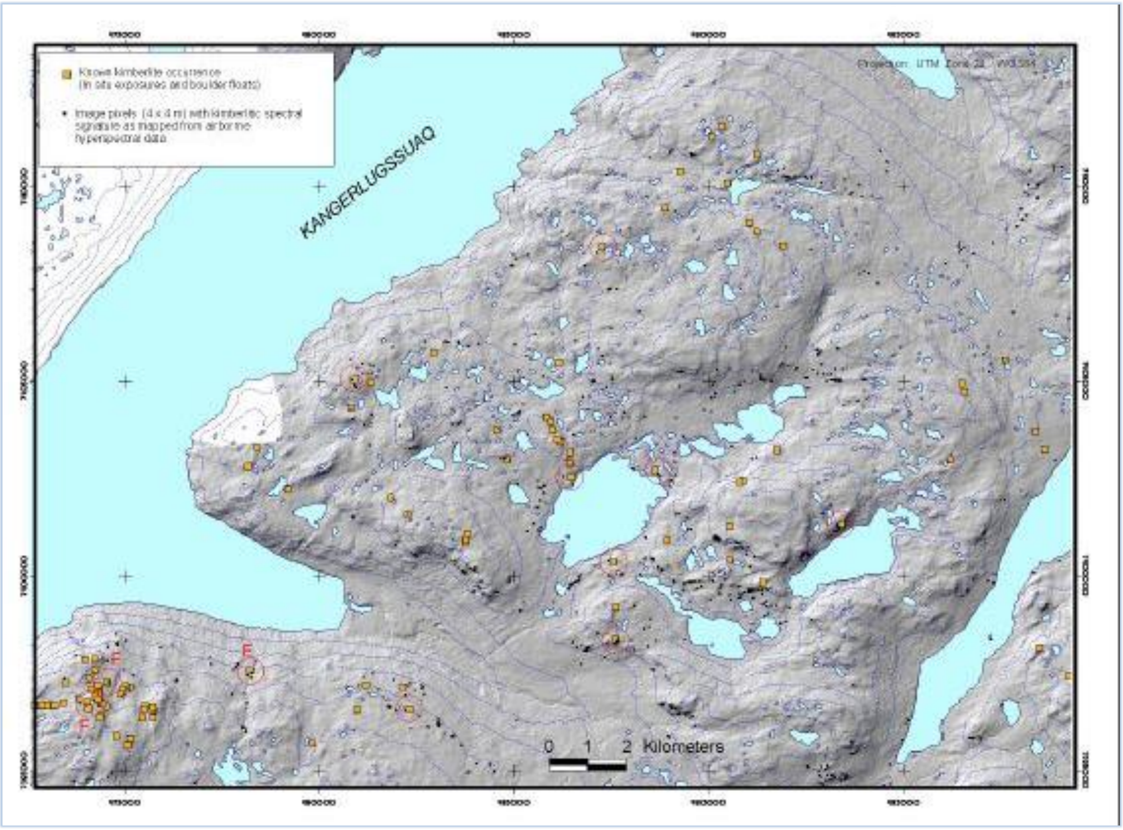

Figure 31. *Results of kimberlite mapping from an area covering parts of subareas 1 & 2. Known kimberlite occurrences (in situ occurrences and boulder floats) are shown on the map. Some known in situ kimberlite occurrences detected by the mapping are encircles with red (F=boulder float). From Tukiainen & Krebs (2004).*

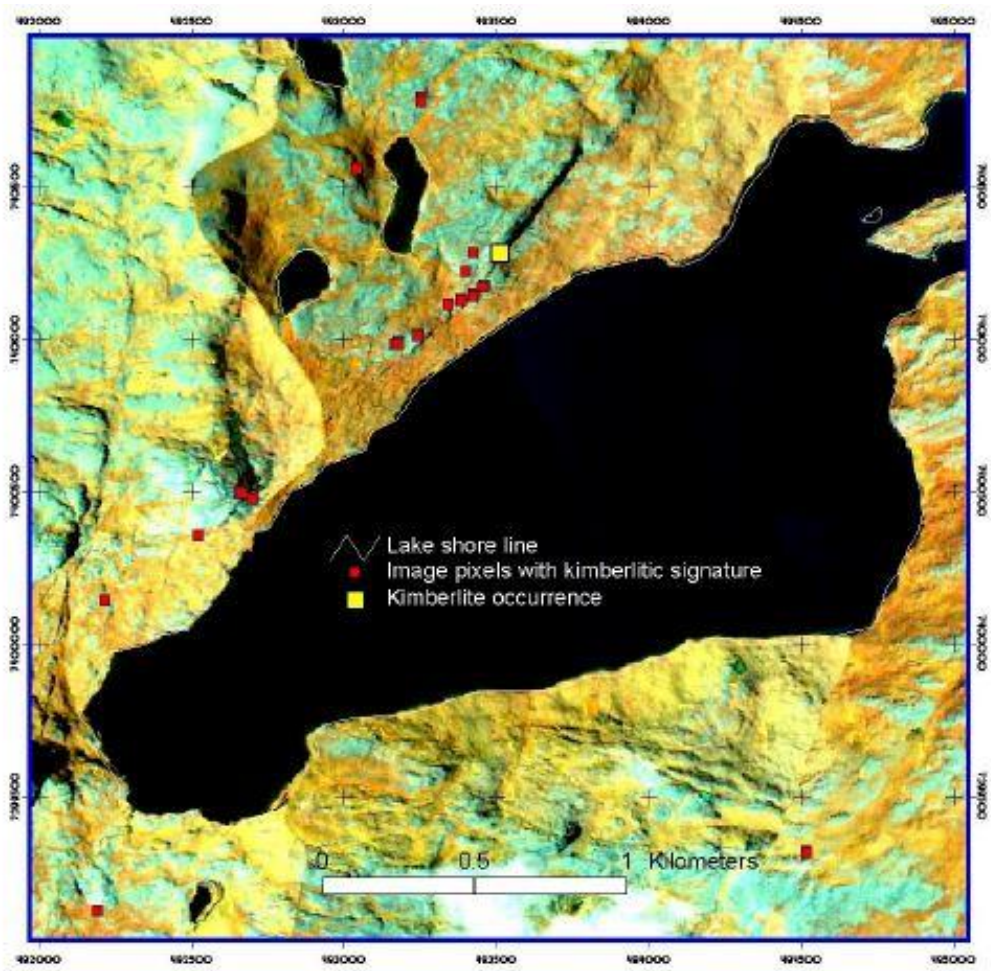

Figure 32. *Typical registration of topographic vector data on the parametrically geocoded HS image data. A know in situ kimberlite occurrence, shown in Figure 30, and image pixels with kimberlite spectral signature superimposed on the image. From Tukiainen et al. (2003).*

The HyMAP data were also used for the mapping of lithologies of the carbonatite complex at Sarfartoq, Southern West Greenland (Bedini 2009). The carbonatite intrusion (Figure 33) occurs where the Archaean gneiss complex to the south meets the Proterozoic mobile belt to the north. The Sarfartoq carbonatite complex was known from aerial geophysical surveys and had been mapped in some detail (Secher 1986) as a core zone composed of dolomite carbonatite and minor søvite (calcite carbonatite) surrounded by a fenite zone and a marginal zone of gneisses frequently altered due to hydrothermal activity. Spectral reflectance measurements showed that the various lithologic units including dolomite carbonatite, søvite, fenite and the marginal alteration zone have distinct spectral reflectance characteristics. The analysis of the HyMAP data was based on an unsupervised clustering algorithm, the Self Organizing Maps (SOM), for the mapping of the main lithology, shown here (Figure 34), and some other methods (spectral mixture analysis) for comparison, see Bedini (2009). The resulting lithological map demonstrates the power of hyperspectral data, showing dolomite carbonatite, søvite, fenite with abundant carbonatite dykes in the outer core, and fenite and hematized gneiss in the marginal alteration zone. The results were compared with field data especially collected to assess the mapping accuracy and proved that the hyperspectral data could be used to better map the outcropping carbonatite lithology.

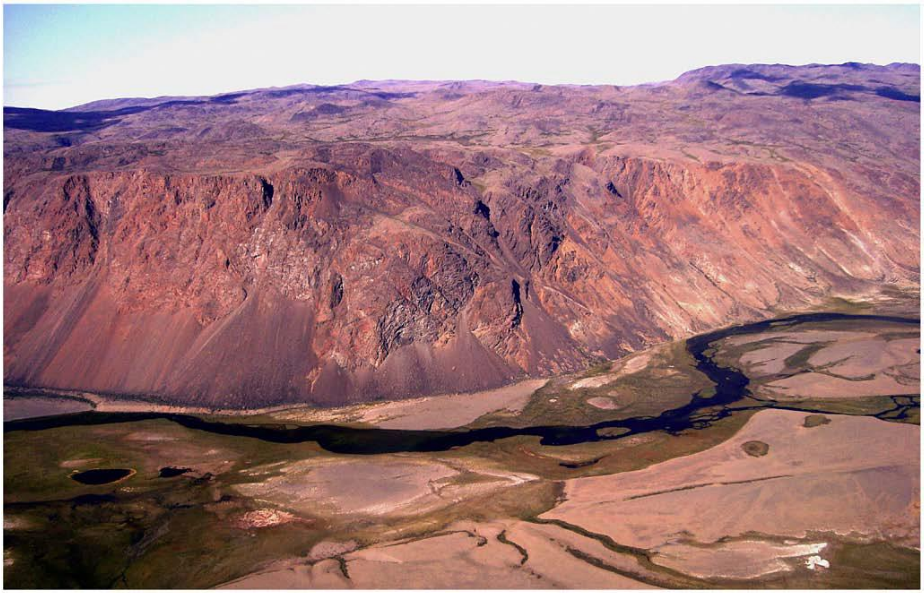

Figure 33. *South-facing outcrop of the Sarfartoq carbonatite complex, southern West Greenland. Height of slope is 400–500 m. From Bedini (2009).*

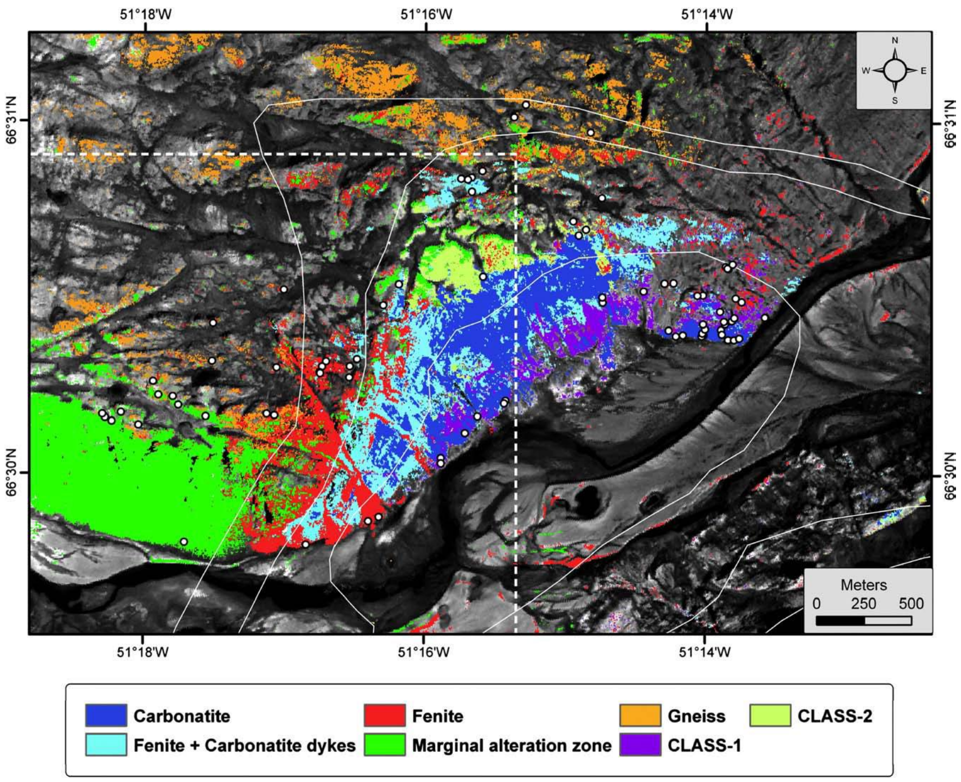

Figure 34. *Mapping of main lithologic units of the Sarfartoq carbonatite complex by SOM-based unsupervised classification of the hyperspectral data (HyMAP) for the main units of the Sarfartoq carbonatite complex. White circles show the locations of the field stations used to assess the accuracy of the mapping results. From Bedini (2009).*

5.13 Pituffik 2007: follow-up on Landsat and Aster studies

In 2003, a Landsat study of the Pituffik region immediately south of the Qaanaaq region in North-West Greenland was carried out (Krebs *et al.* 2003). The BMP-supported study aimed at the delineation of mineral exploration targets. The region´s *c*. 4,300 km^2 ice-free land exposes a high-grade Archaean crystalline shield overlain by the unmetamorphosed mainly Mesoproterozoic Thule Supergroup. This is a continental to shallow marine sequence with one interval of basaltic volcanic rocks, and basic sills at several levels. No economic mineral occurrences are known.

Four images of Landsat 7 ETM data were processed to pin-point localities with mineralisation potential by means of mapping minerals that carry iron oxides (rust zones) and hydroxyl ions (clay alteration) using the same techniques as in the Qaanaaq 2001 study, see Section 5.9. Twenty-four anomalies were outlined, six in shield lithologies and 18 in the Thule Supergroup, mainly Dundas Group (Figure 35).

Follow-up field work on the 2003 anomalies was carried out in 2007 by two persons with limited helicopter support (Thomassen & Tukiainen 2009). As an additional preparation for the field work, several Aster scenes were purchased and interpreted. Aster (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is an imaging instrument on the Terra satellite launched in December 1999 as part of NASA's Earth Observing System and used to obtain detailed maps of land surface temperature, reflectance and elevation. The Aster satellite data were processed to pin-point localities with mineralisation potential seen through minerals carrying iron oxides (rust zones) and hydroxyl ions (clay alteration). Most of the resulting anomalies are, like the Landsat anomalies, within the Dundas Group associated with dykes and sills. The satellite data were used in the field and processed on a laptop in an iterative process of comparing with the field observations. An example of an Aster image from Washington Land north-east of the project area is presented in Figure 36.

The field work showed that the distinct anomalies in the Dundas Group are caused by rusty contact zones between the Dundas Group sediments and Neoproterozoic mafic intrusions (sills and dykes), characterised by disseminated pyrite and low-temperature hydrothermal alteration of the sediments. Minor massive mineralisation slightly enhanced in gold and comprising pyrite, chalcopyrite, galena and sphalerite occurs in pockets and veinlets in both dolerite and adjacent sediments. An example of Aster anomalies representing hydrothermal alteration associated with dykes and sills is shown in Figure 37. The figure also illustrates how the remote-sensing data may facilitate follow-up on a gold-bearing float.

A Landsat anomaly indicating hydrothermal alteration at the contact between sediments of the Thule Supergroup and Neoarchaean basement could be caused by unconformity-type uranium mineralisation, and Krebs *et al.* (2003) recommended that this locality be checked for uranium and gold. Lack of time prevented this, but a geochemical uranium anomaly from a nearby area seems to confirm the uranium potential of this geological setting. A number of other Landsat and Aster anomalies were caused by surficial deposits, typically abundant fine-grained (clay-fraction) material on south-facing slopes, without any connection to mineralisation.

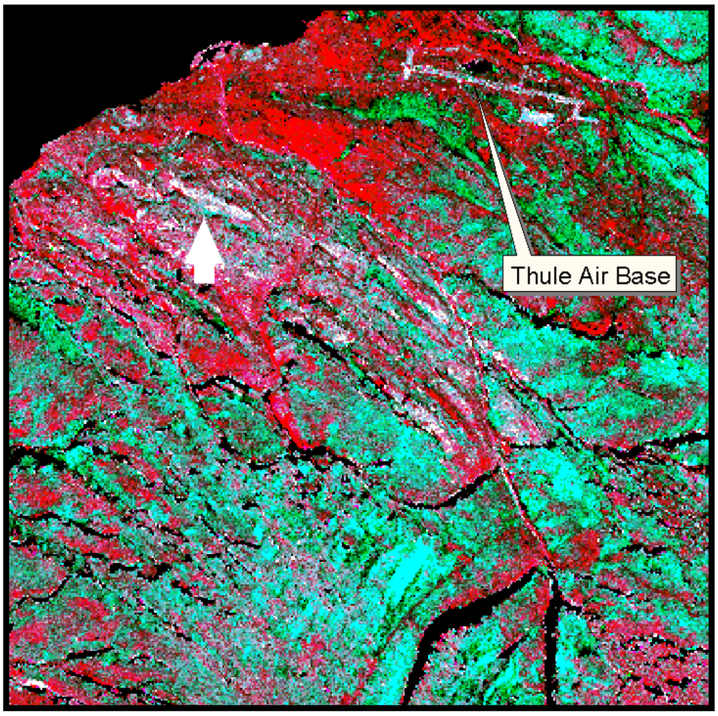

Figure 35. *NNW-orientated, c. 12 x 12 km Crosta image of the Pituffik area with the Thule Air Base runway standing out. The arrow indicates Landsat anomaly no. 24, an almost E–W-oriented oblong structure (white) of unknown origin in the Narssârssuk Group carbonate rocks. A number of other, less distinct alteration zones in the carbonates are also visible. From Krebs et al. (2003).*

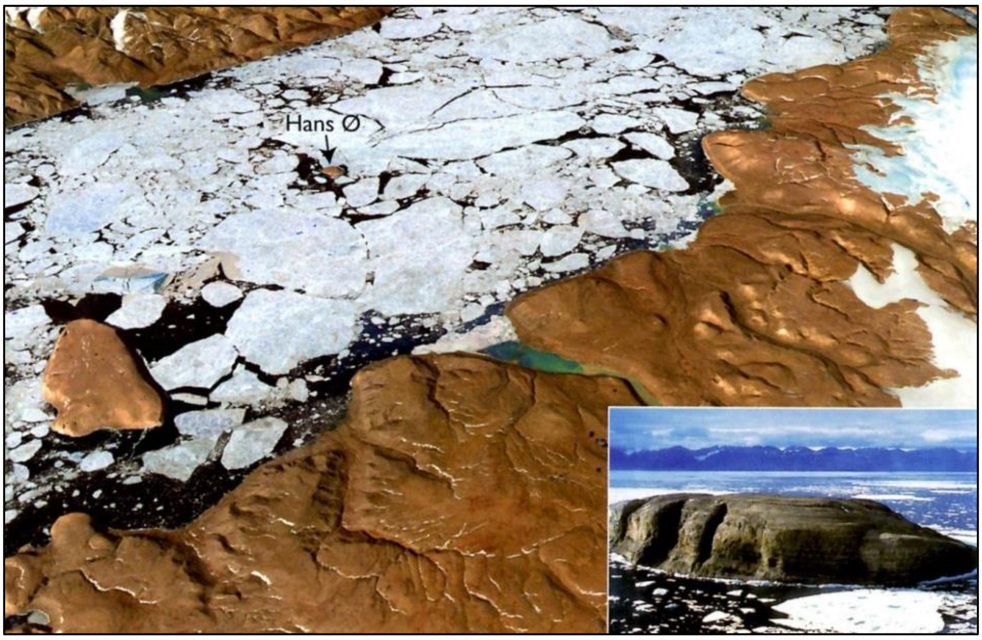

Figure 36. *Perspective view of Kennedy Channel showing Hans Ø and Franklin Ø viewed from the south over Washington Land towards Canada. The colour composite of the visible and near-infrared ASTER image data draped over the digital elevation model are extracted from four ASTER images taken between 26 June and 30 July 2003. Inset: Hans Ø viewed from the south-east. From Dawes & Tukiainen (2007).*

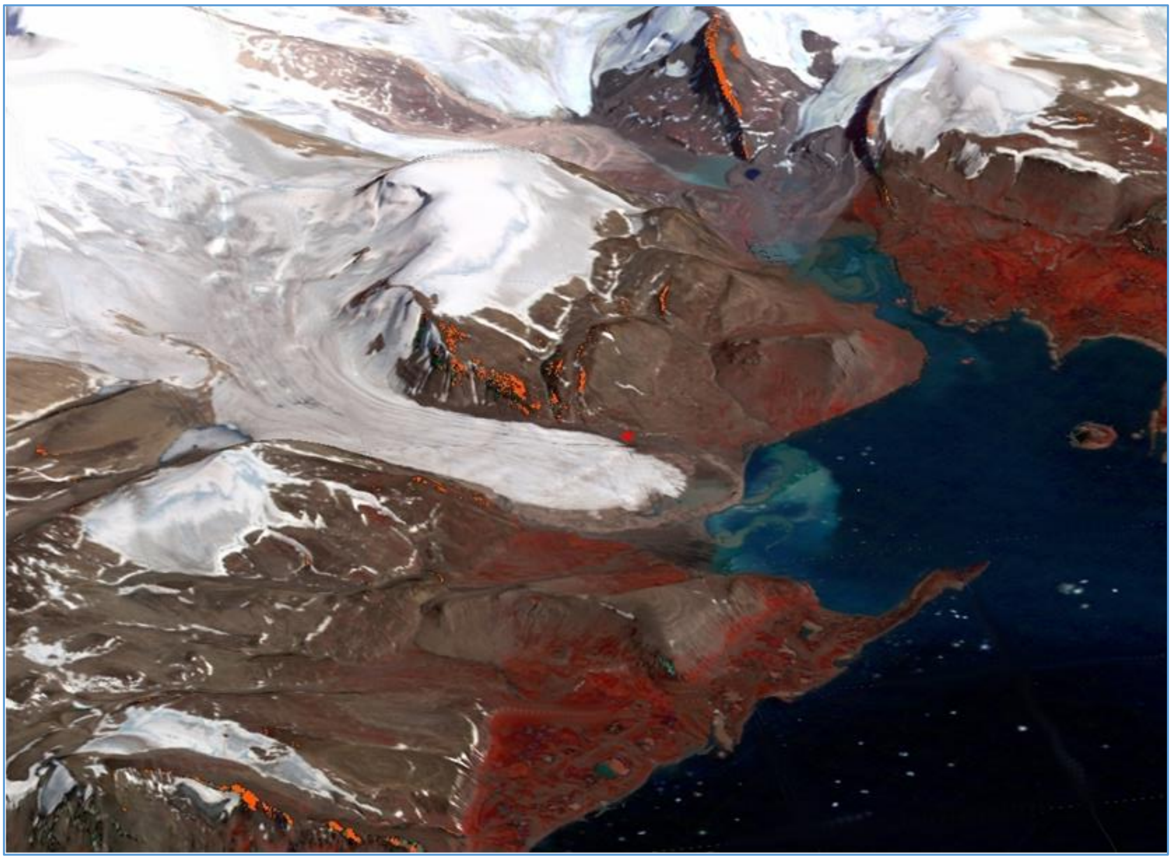

Figure 37. *Perspective view of the Booth Sund area from the south-west. Colour composite of the ASTER data R (band 3), G (band 2) and B (band 1) draped on a digital terrain model. Hues of red = vegetation, grey and brown = exposed rock and rock debris. Orange = gossan-like weathering and hydrothermal alteration occurring along contact zones between mafic intrusions (sills and dykes), and sediments of the Dundas Group. Vertical exaggeration x 1.5. The site of a gold-bearing float (5.6 ppm Au) is indicated by a red star. From Thomassen & Tukiainen (2009).*

5.14 Base maps southern West Greenland, 2005

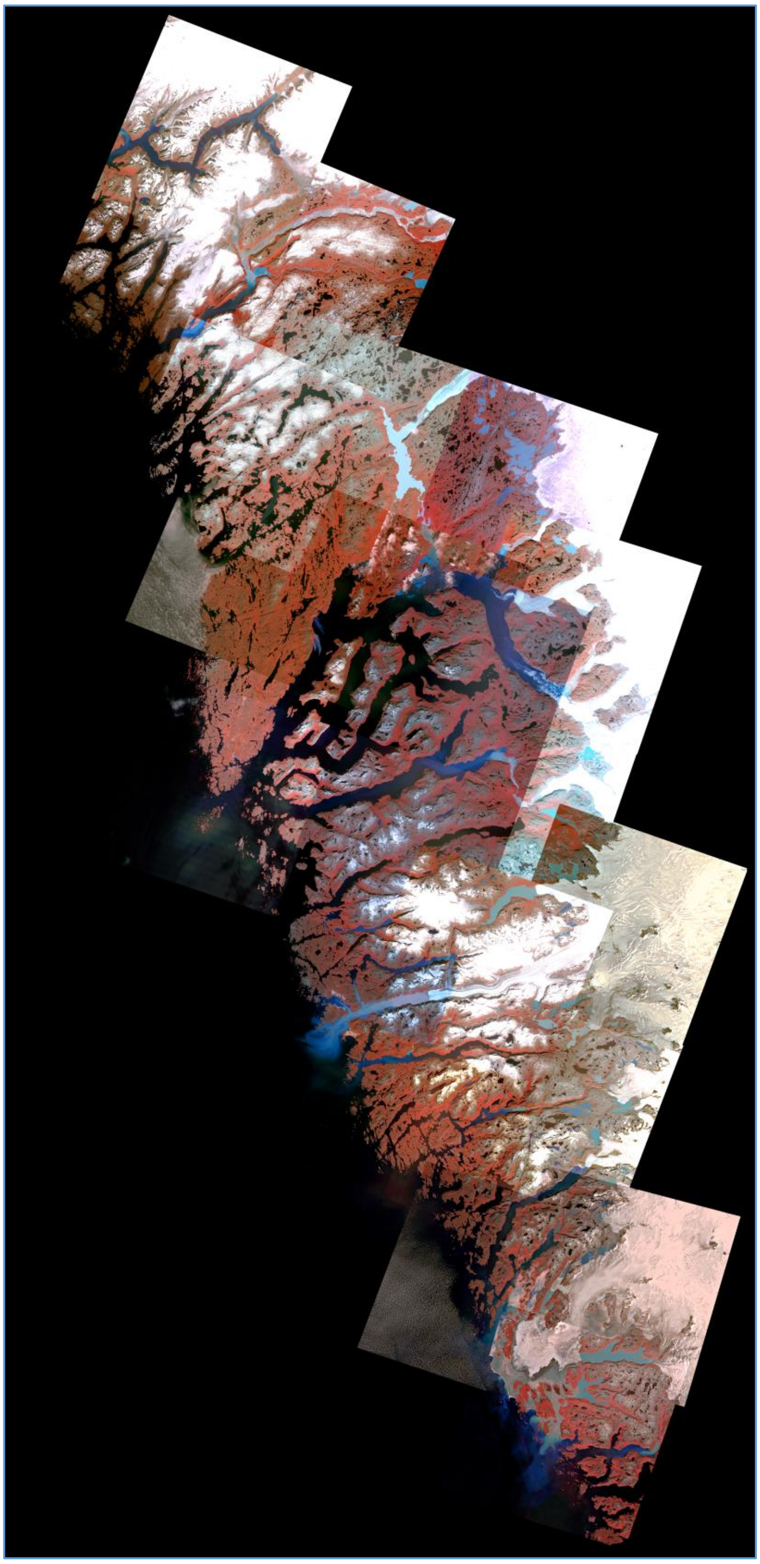

Figure 38. *Mosaic of West Greenland from c. 62° to 66° N from Aster data, resolution 15 m x 15 m pixels. Such overview maps are now standard for most GEUS operations in Greenland, used for many different purposes in different geological disciplines.*

5.15 Preparations for projects in South-East Greenland, 2009

In the early stages of the planning of the resource assessment of South-East Greenland, good modern maps of the area were not available. GEUS therefore exploited the fairly detailed data from ASTER to produce a satellite image map of the potential project area (Figure 39). This was used for the planning and for the first field visits, including the geochemical surveys and the aeromagnetic surveys. The quality of these maps based on Aster data (Figure 40) were not only sufficient for planning but could also be used in the field work for selecting sites for geochemical sampling and geological observations. In the actual mineral assessment projects, the Aster data were further processed to show geological features.

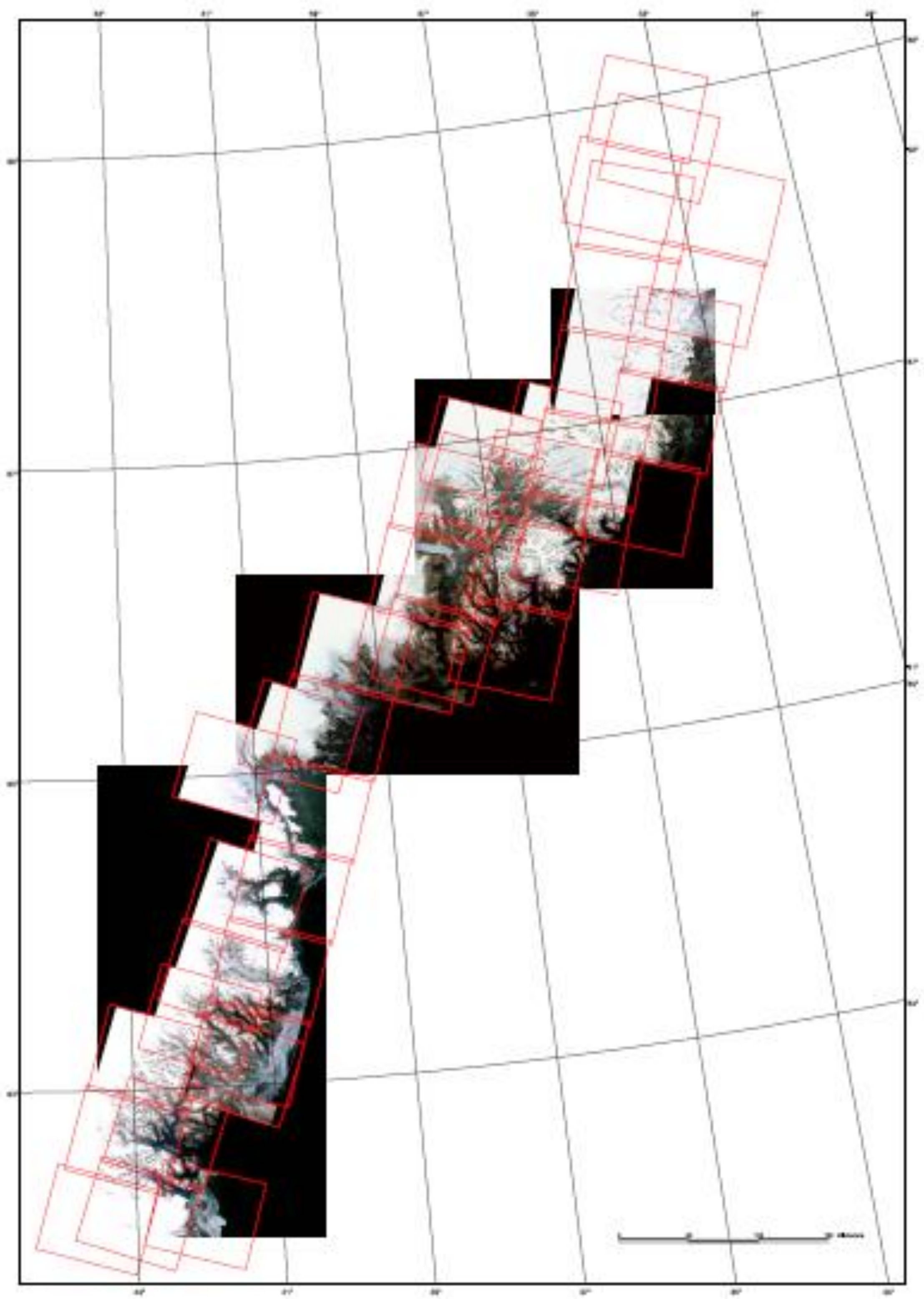

Figure 39. *Base map of South-East Greenland prepared from Aster data in preparation for the planning of mineral exploration, geochemical and geophysical surveys projects. From Thorning (2009).*

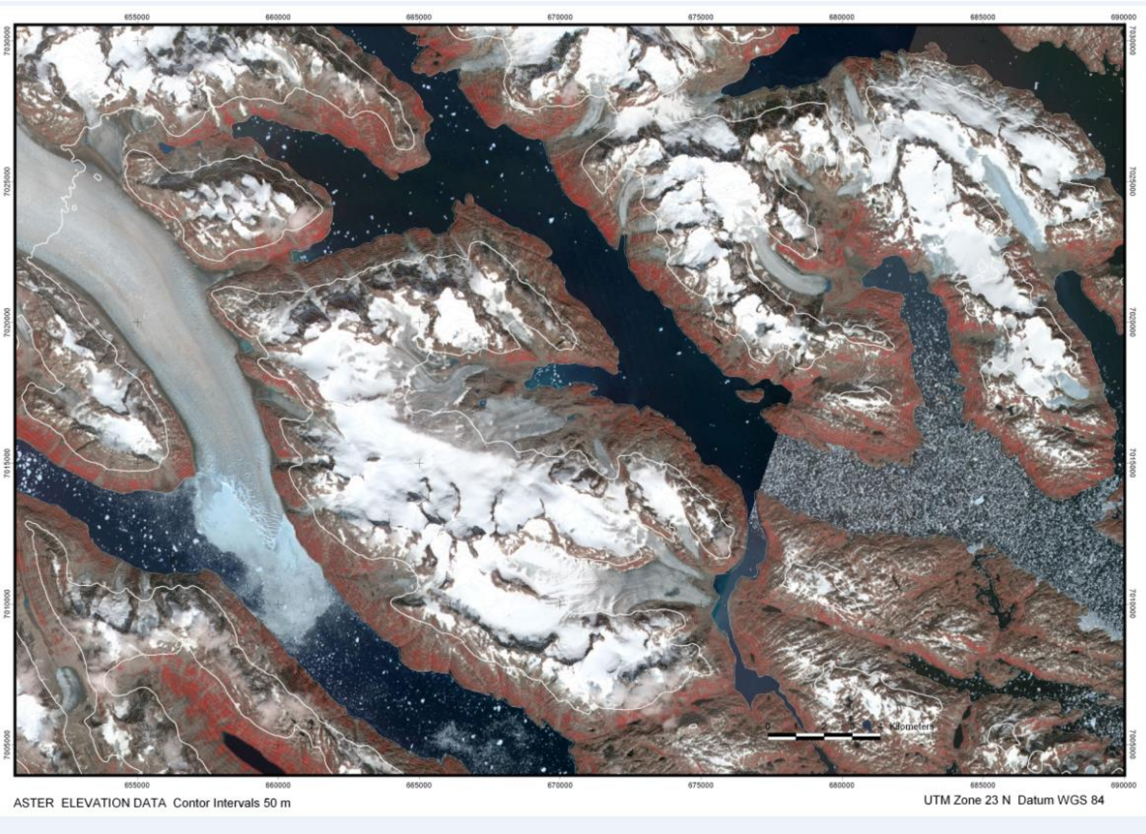

Figure 40. *Example of map in approximate 1:50,000 scale used for planning purposes in South-East Greenland. Made from Aster data. From Thorning (2009).*

5.16 ARSF hyperspectral survey, central East Greenland, 2012

In August 2012, an airborne hyperspectral survey was carried out by the British Natural Environmental Research Council, Airborne Research and Survey Facility (NERC ARSF) over an area in central East Greenland with widespread sediment-hosted copper mineralisation (Thomassen *et al.* 2014; Figure 41). This was a joint project involving and financed by GEUS, ARFS, BGS (British Geological Survey) and Avannaa Resources Ltd., who had mineral exploration licenses in the area.

Data acquisition was accomplished using Spectral Imaging Ltd. (Specim) Eagle and Hawk hyperspectral cameras. The Eagle camera covered the VNIR (450–970 nm), while the Hawk camera covered the SWIR (970–2500 nm) with spectral sampling of 2.3 and 6.3 nm, respectively. In addition to the hyperspectral data, LiDAR and digital aerial images were collected (Thorning *et al*. 2013). The survey covered approximately 2600 km^2 and was flown at a nominal elevation of 2500 m over Mean Sea Level resulting in 2–2.5 m spatial resolution.

The project was approached from the perspective of generating surface mineral maps and hybrid targeting metrics. The surface mineralogy mapping was limited to six dominant minerals: hematite, goethite, kaolinite, illite, calcite, and dolomite.

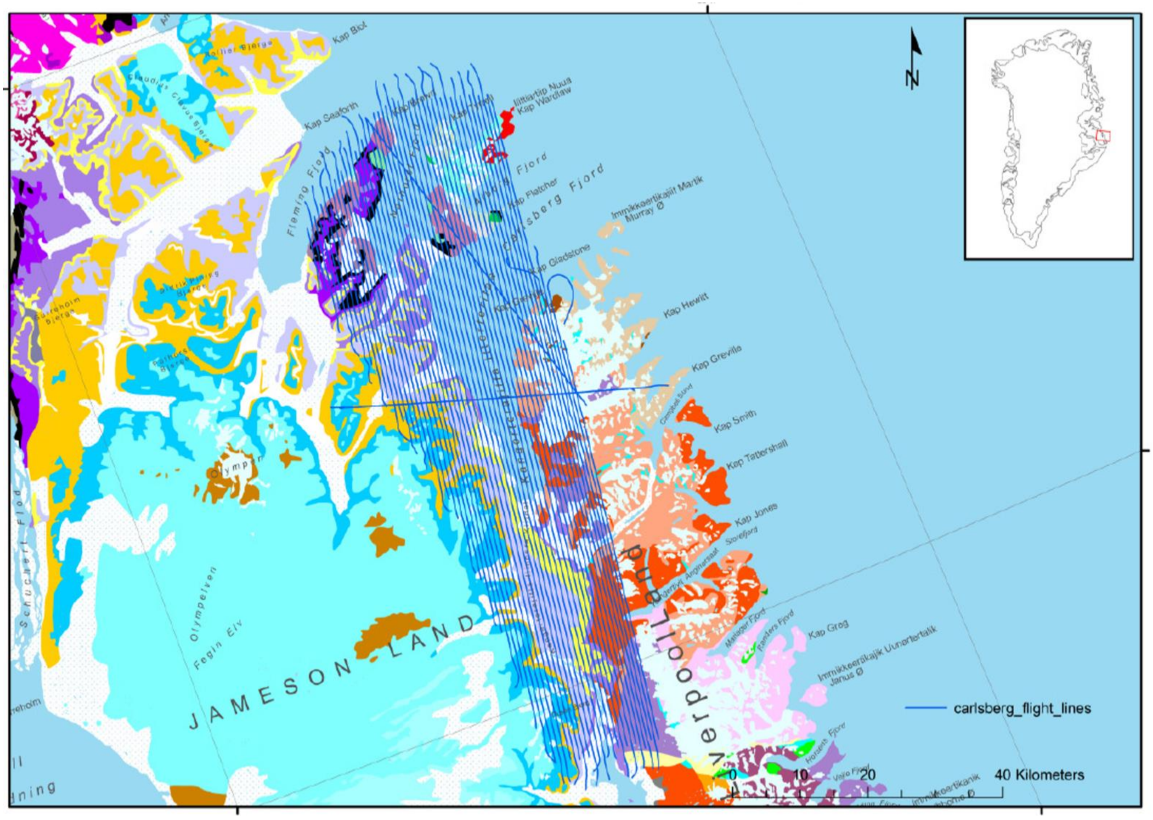

Figure 41. *Location of the ARSF hyperspectral survey (Thorning et al. 2013).*

Based on prior knowledge of the ore deposit model(s) present in the area, a set of reference spectra of likely alteration minerals were selected from USGS spectral library and resampled to the spectral response function of the hyperspectral data cubes. Spectral Correlation Mapper (Carvalho & Meneses 2000) was then used for a direct Pearson correlation calculation between the reference endmembers and image spectra. Using a predefined threshold, the results of the screening analysis were assessed to identify a small number of best matches and to generate an image-derived endmember library. The image-derived endmembers were then used to generate a preliminary mineral map. Next, a classification map was generated manually by thresholding and stacking best matches through the ENVI ROI tool (Coulter 2014).

In the case of this survey the crystallinity of illite appeared to be the most important metric as high crystallinity illite was spatially associated with known mineralisation in some areas (Figures 42 & 43). In addition, illite characteristic absorption feature ~2200 nm was used for vectoring potential mineralisation. Shifts in the absorption minimum towards shorter wavelengths (~2189 nm) correlate with higher concentrations of Al within the crystal structure, whilst shifts towards longer wavelengths (~2214 nm) indicate Fe, Mn, or Mg are substituting for Al. Illites with high Al are associated with the paragonitic/sercitic higher temperature endmember of the illite series and are more likely to be associated with hydrothermal activity. Furthermore, the 'sharpness' and depth of the illite feature also indicate the illite is more crystalline and leaning toward sericite (recognizing that sericite is a textural classification and can only be identified visually). In summary, higher illite crystallinity and lower feature wavelength are good indicators of higher temperature hydrothermal activity. Given these observations, thirty-four prospecting targets were identified by Coulter (2014), in collaboration with the exploration staff of Avannaa Resources Ltd.

For estimating the sub-pixel mixing proportions of the iron minerals, an Optimized Cross Correlation Mixture analysis (OCCM) was used to run an optimization problem that finds the maximum correlation at each pixel between the image spectrum and a spectrum composed of mixed hematite, goethite, and jarosite spectra in the VNIR. Illite (± hematite and goethite) was found to be closely associated with known host rocks.

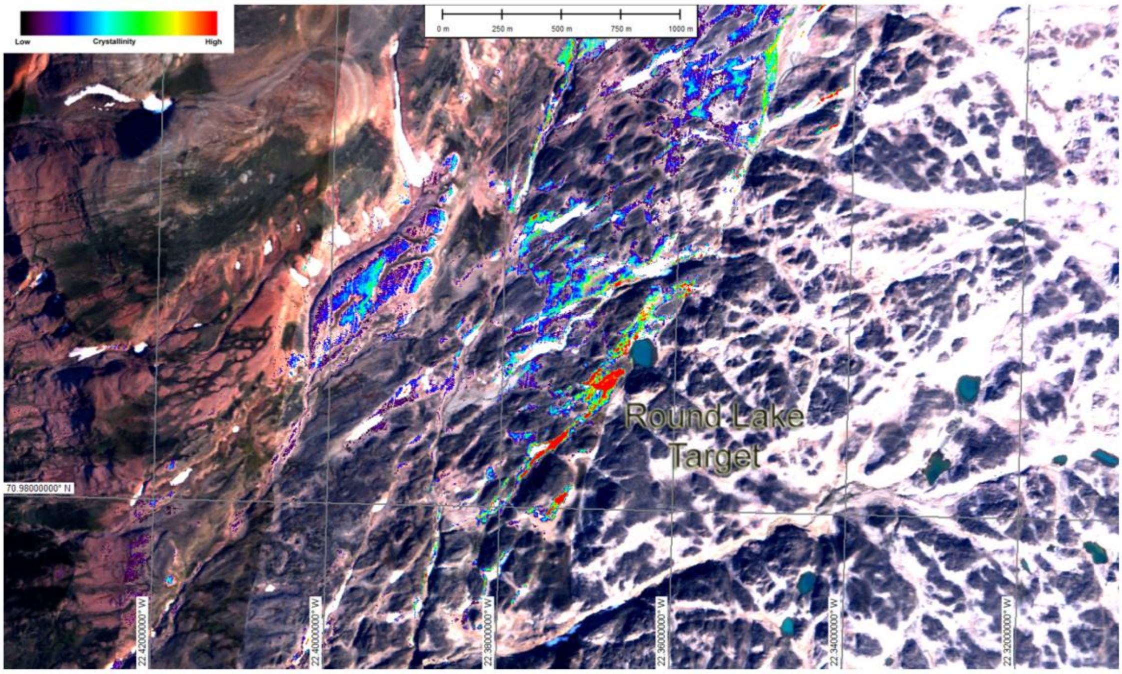

Figure 42. *The scene shows Proterozoic crystalline rocks overlain by Triassic clastic sediments to the left (West) in Klitdal. A number of high crystallinity zones were identified in the Proterozoic crystalline basement rocks. These targets need to be screened based on geology as muscovite also will give a high crystallinity illite response. There may, however, be some high permeability or structural plays in the basement near the overlying unconformity. An alteration zone is indicated at 'Round Lake' (Coulter 2014).*

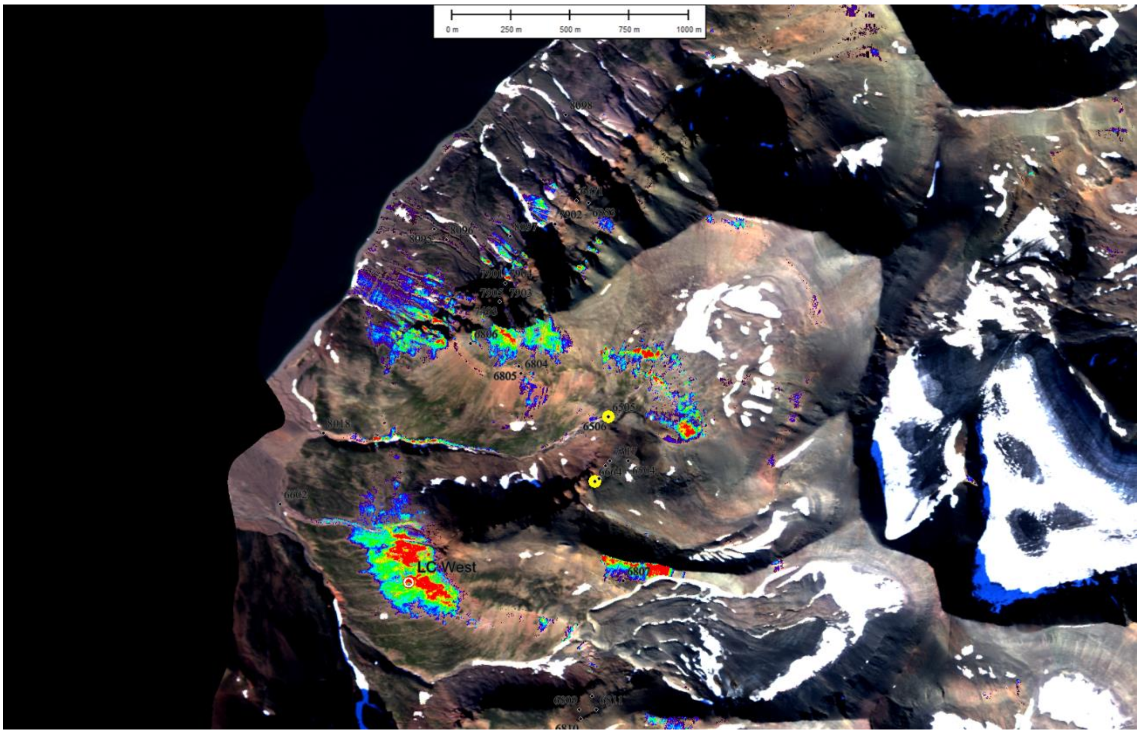

Figure 43. *Scene from south-western Wegener Halvø showing anomalous alteration zones in Devonian clastic sediments to the west (left) and in Upper Permian limestones to the east. From Coulter (2014).*

5.17 New developments: effects of lichens on the spectra of rock forming minerals

Generally, exposure of the geology is excellent in Greenland. However, although not apparent at a first glance, lichens and vegetation on the often weathered surfaced of rock outcrops can influence remote sensing data significantly and be a challenge for geological mapping and mineral exploration (Salehi 2018a). Salehi *et al.* (2017a) show how spectral mixing of lichens and bare rock can shift the wavelength position of characteristic absorption features, thereby complicating the spectral mapping of minerals and lithologies. This was studied in three different parts of Greenland, namely Liverpool Land (central East), Karrat area (central West) and Sisimiut–Kangerlussuaq (South West), see Figure 44. Salehi *et al.* (2017a) demonstrate through laboratory measurements of selected samples and synthetically generated mixed spectra how surficial lichen cover affects the characteristics of shortwave infrared (SWIR) mineral absorption features, influencing the effectiveness of automatic SWIR absorption feature extraction. The results of this study suggest that if the lichen cover is significant, the central wavelength position of some of the spectral features may be shifted or be completely masked (Figure 45). Salehi *et al.* (2017a) show the effect analysed as a function of percentage lichen cover for some typical rock forming mineral groups. For instance, the strong spectral features of mica group minerals around 2200 and 2340–2350 nm maintain their integrity for up to 30% lichen cover, despite a shift toward shorter wavelengths for higher percentage lichen cover.

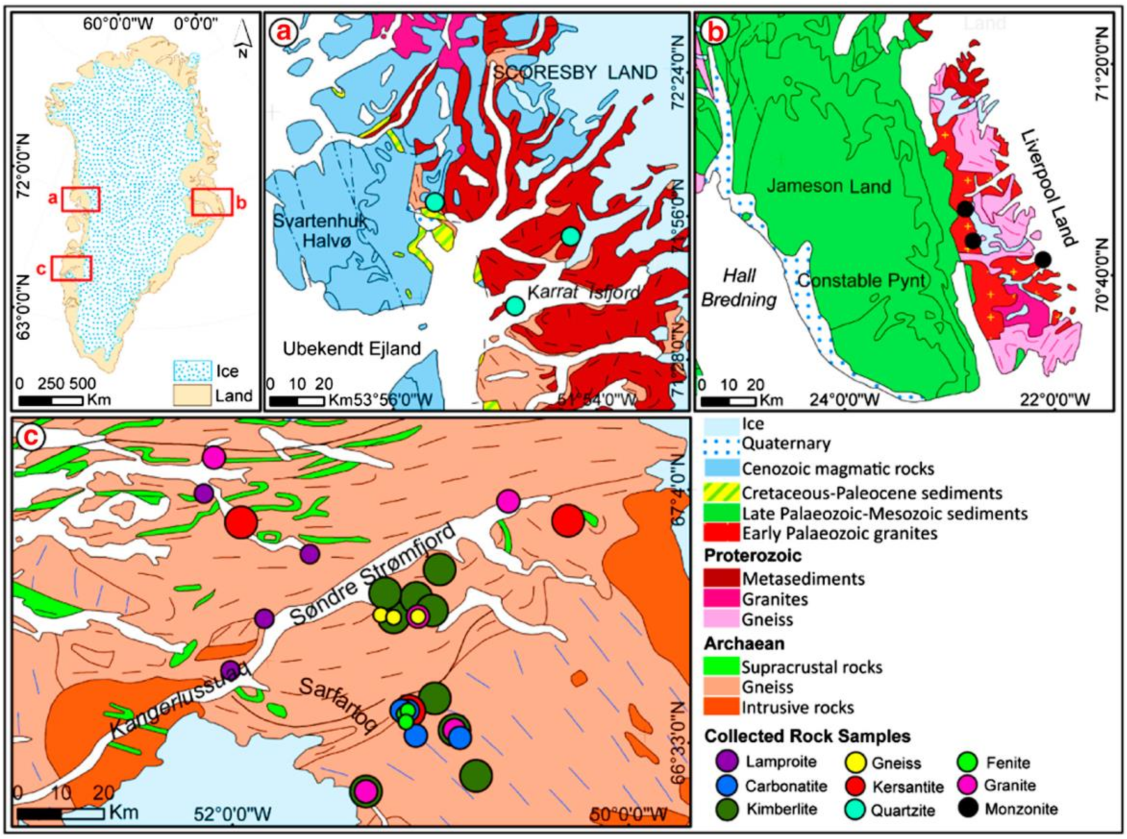

Figure 44. *Localities for the study of the effects of lichens on remote sensing data in different geological environments in Greenland. From Salehi et al. (2017a).*

In contrast, very weak absorption bands around 2440 nm in (white) micas spectra are completely obscured for lichen covers of ≥50%. The chlorite feature around 2250 nm is shifted toward longer wavelengths and the depth of this feature as well as the contrast between lichen and substrate spectra define the amount of lichen needed to mask it. Furthermore, lichens induce a spectral shift towards shorter wavelengths for the features around 2320 nm for the rocks containing amphibole, chlorite, carbonate and serpentine group minerals. No wavelength displacement is observed for chlorite, biotite and phlogopite features around 2380 nm in mixtures with lichens. In Figure 46, an example is shown for fenite and lichen combinations. This quantification of lichen cover effects on mineral absorption features highlights the importance of being precautious in any interpretation in areas characterized by abundant lichen-covered outcrops. This can be of significant importance for mineral and deposit vectoring as the presence of abundant lichen coverage can result in erroneous identification of vectors to a deposit.

Ongoing research at GEUS aims at finding means of ‘correcting’ for lichen cover in order to better discern the underlying mineralogy and lithology, when mapping by advanced remote sensing methods. Salehi *et al*. (2016) proposed a series of robust lichen spectral indices that can be used to directly reflect the mixture ratio of the rock and lichen in hyperspectral data, regardless of the mineral composition of the underlying rocks. The proposed indices are remarkable in the fact that their performance is independent of a prior knowledge about the exact effects of lichens—or any other substance—on the reflectance of the mixtures. Instead, this information is implicitly extracted, via an automated trial and error process.

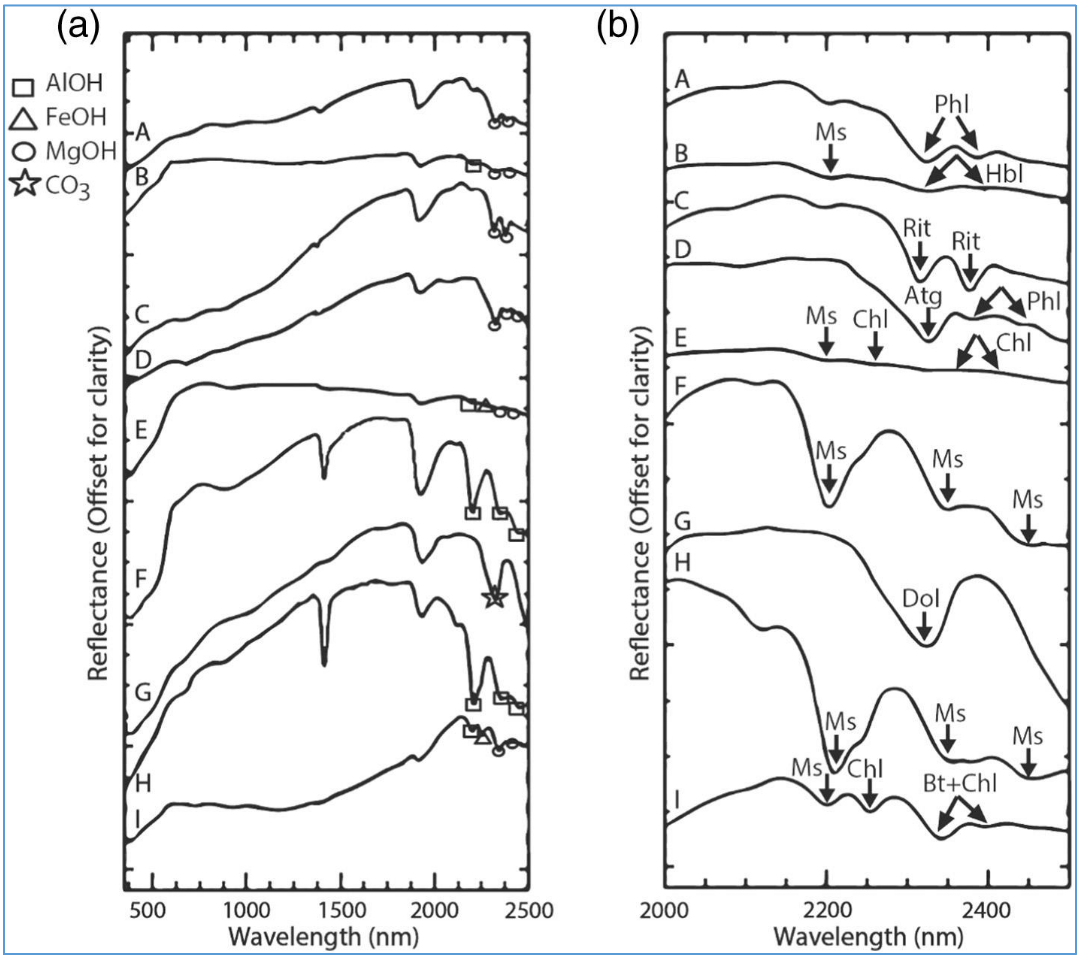

Figure 45. *Averaged spectral reflectance curves for the collected rock types. In a) the full spectra range are shown for kersantite (A), monzonite (B), lamproite (C), kimberlite (D), granite (E), fenite (F), carbonatite (G), quartzite (H) and gneiss (I). In b) only the SWIR range are shown and characteristic features are indicated that are related to the mica group minerals(muscovite: Ms., phlogopite: Phl, biotite: Bt), amphibole group minerals (hornblende: Hbl, richterite: Rit), serpentine group minerals (antigorite: Atg), chlorite group minerals (chlorite: Chl) and carbonate group minerals (dolomite: Dol). From Salehi et al. (2017a).*

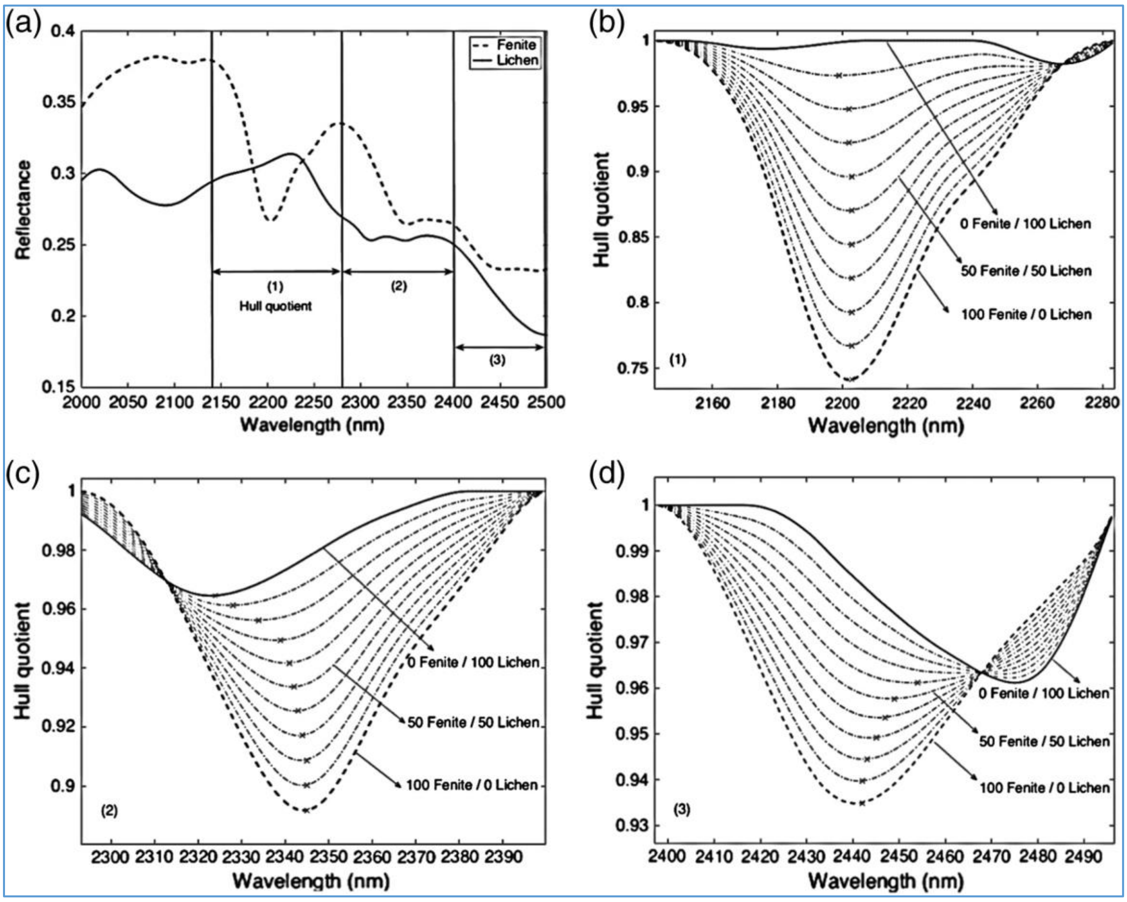

Figure 46. *(a) The averaged spectra of pure rock and lichen for fenite substrate in SWIR and (b, c, d) the corresponding hull quotient and band centres of mixed spectra associated with muscovite features. The spectral intervals (10%) that are used to investigate the three main absorption features are highlighted. An x denotes the wavelength positions of the local minima. From Salehi et al. (2017a).*

5.18 New developments: remote sensing field activities in 2015–2019

Aside from the complications with processing mixture signatures and extracting reliable information for performing mineral mapping, a second major challenge in the Arctic is the accessibility of the outcrops and the lack of feasible approaches to capture the data as part of a large-scale operation in a time- and cost-effective manner. Satellite images allow for the discrimination of rock units in the broader region and help in effectively defining the best initial targets for regional exploration. For areas and targets identified as potentially prospective, more detailed investigations are usually performed including focused field campaigns.

Near-vertical cliff sections particularly offer excellent rock exposures for investigating and characterizing mineral deposits. The spatial extent of these outcrops can range over kilometres, resulting in costly and time-consuming data acquisition, mapping, and interpretation. Due to the inaccessible nature of alpine, near-vertical topography, detailed mapping of lithologies and the spatial variation of mineral–chemical content is extremely challenging. In addition, air/spaceborne nadir remote sensing sensors offer inadequate viewing direction for mapping of minerals in steep mountain cliffs. Oblique photogrammetry has been used extensively in areas of difficult access in Greenland for regional scale spatial information data acquisition and mapping of steep cliffs.

Photogrammetry is a classical remote sensing discipline dating back to the middle of the 19^{th} century when Aimé Laussadat first used terrestrial photographs for topographic map compilation (Blachut & Burkhardt 1989). Since then, the technology of the method has developed significantly from plane table photogrammetry, to analogue and analytical photogrammetry and is now in the evolving stage of digital photogrammetry. Studies in the 90´ties pioneered the use of photogrammetry in the geological workflow (Dueholm 1990, 1992). In, what at the time was called multi-model photogrammetry, conventional aerial photographs (nadir looking) was combined with oblique stereo-photographs of steep mountain walls using calibrated analogue handheld cameras while flying, sailing or walking. By doing so, the geologist was able to investigate regional structures that are typical well resolved in conventional aerial photographs, while more detailed observations, not well resolved in conventional aerial photographs, could be made in the oblique stereo-photographs which are much better at resolving the geology because of resolution and optimized viewing angle. Technically, the stereo-images were viewed in computer-controlled analytical stereo-plotters. Nowadays, the workflow is all digital. Images are collected using digital cameras and 3D visualization of the data is undertaken using digital photogrammetry software packages, which has greatly improved the feasibility and user-friendliness of this technology. Digital stereo-images are now routinely collected from helicopter, plane or boat while conducting field work in remote regions of Greenland.

Being limited to three optical bands, oblique photogrammetry offers inadequate spectral resolution to allow for detection of subtle lithological differences. To complement photorealistic geological outcrop models with quantitative information about mineral variations, oblique photogrammetry can be combined with hyperspectral dataset (Salehi *et al.* 2018), (Figure 47). This add-on information allows for improved separation between rock formations, and distinguishing barren ground from potential economic ore deposits that are exposed in inaccessible, high vertical sea cliffs.

The application of close range (up to couple of hundred metres distance between sensor and the target) sub-horizontal hyperspectral imaging using terrestrial platforms and integration of spectral data with accurate terrain models extracted from photogrammetry has recently gained attention for mapping of steep outcrops. Long range terrestrial outcrop sensing (several kilometer distance between the target and sensor for full coverage of the outcrop) was tested for the first time during a field campaign in the summer of 2016 in South-West Greenland in the region between the fjords Ikertoq and Kangerlussuaq (Søndre Strømfjord). Karrat region in West Greenland was selected as the second test site for demonstrating the applicability of this new data acquisition approach (Rosa *et al.* 2017; Salehi & Thaarup 2018; Lorenz *et al.* 2018).

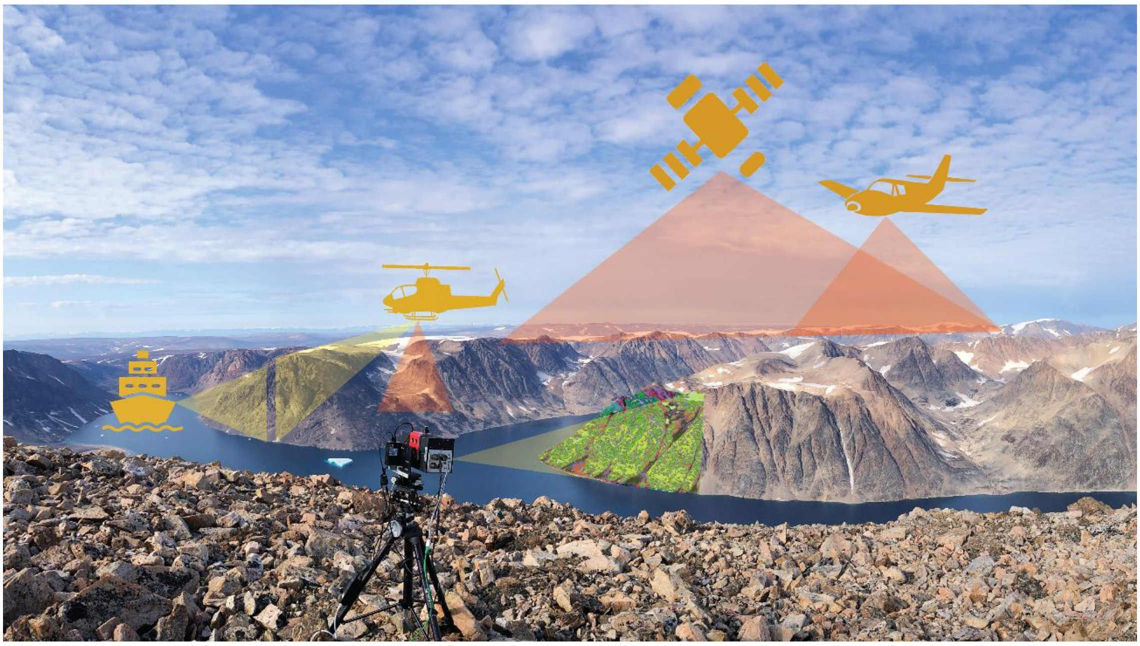

Figure 47. *The use of multi-scale and multi-source remote sensing dataset for geological mapping in the Arctic terrain (Salehi 2018b). The image is from the survey in 2019 in North-East Greenland.*

In continuation of this, a novel approach was introduced for mapping near-vertical cliff sections along fjords, involving integration of digital photogrammetry with vessel-based hyperspectral imaging. The two-dimensional maps generated from hyperspectral imaging are transformed to three-dimensional hyperclouds and integrated with terrain models generated from oblique photogrammetry. The high spatial resolution of terrain models allows investigating e.g. faults and the general morphology of lithologies whereas spectral data provides information regarding the mineralogy and chemical composition of the rocks. The method was tested in the same summer (2016) using experimental data acquired from near-vertical walls in the Uummannaq region in West Greenland (Rosa *et al.* 2017) and Kangerlussuaq fjord in South-West Greenland (Figure 48).

Figure 48. *Kangerlussuaq fjord in South-West Greenland, summer 2016 (Salehi & Thaarup 2018). The Specim AisaFenix hyperspectral scanner is used to acquire near-horizontal hyperspectral scenes. Oblique stereo-imagery was collected using a handheld camera (Nikon D800E).*

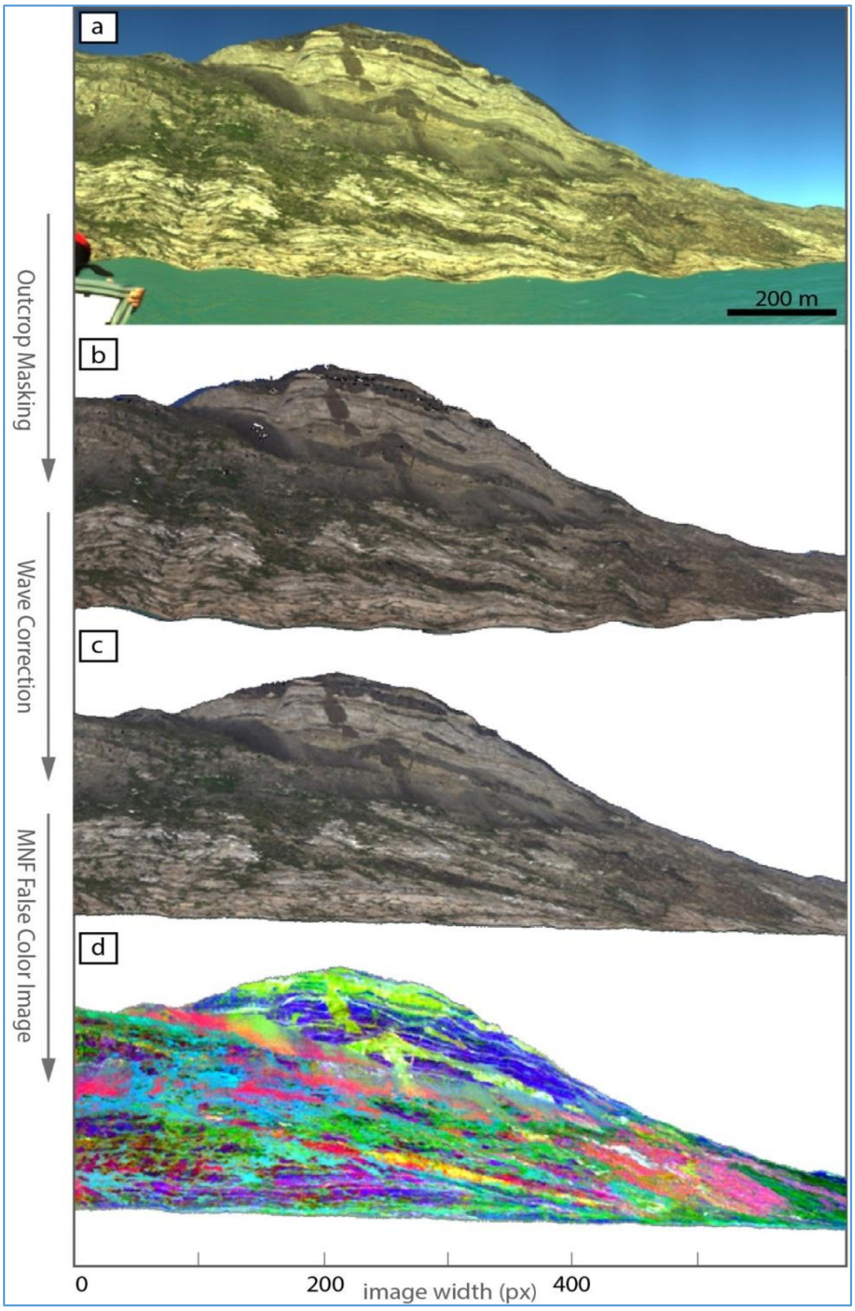

Figure 49. *Results from the different steps in the processing. a) original reflectance image featuring distortion effects originating from the periodic movements of the vessel, b) application of the calculated non-outcrop binary mask, c) resulting wave-corrected reflectance image, d) MNF False Colour Image. Red: Band6; Green: Band7; Blue: Band8. Kangerlussuaq fjord.*

First step is to correct the hyperspectral images for the periodic movements of the vessel (Figure 49a). Considering the distance from the coastline during acquisition of the data, the general coastline trend is assumed a flat line and is thus predicted with a line-regression model. This line is used as a reference. The coastline is extracted by finding the last non-zero pixel in each column of the non-outcrop binary mask (Figure 49b). The difference between the extracted coastline and the reference line defines the amount of shift to be applied for each column along the width of image to eliminate the effect of waves (Figure 49c).

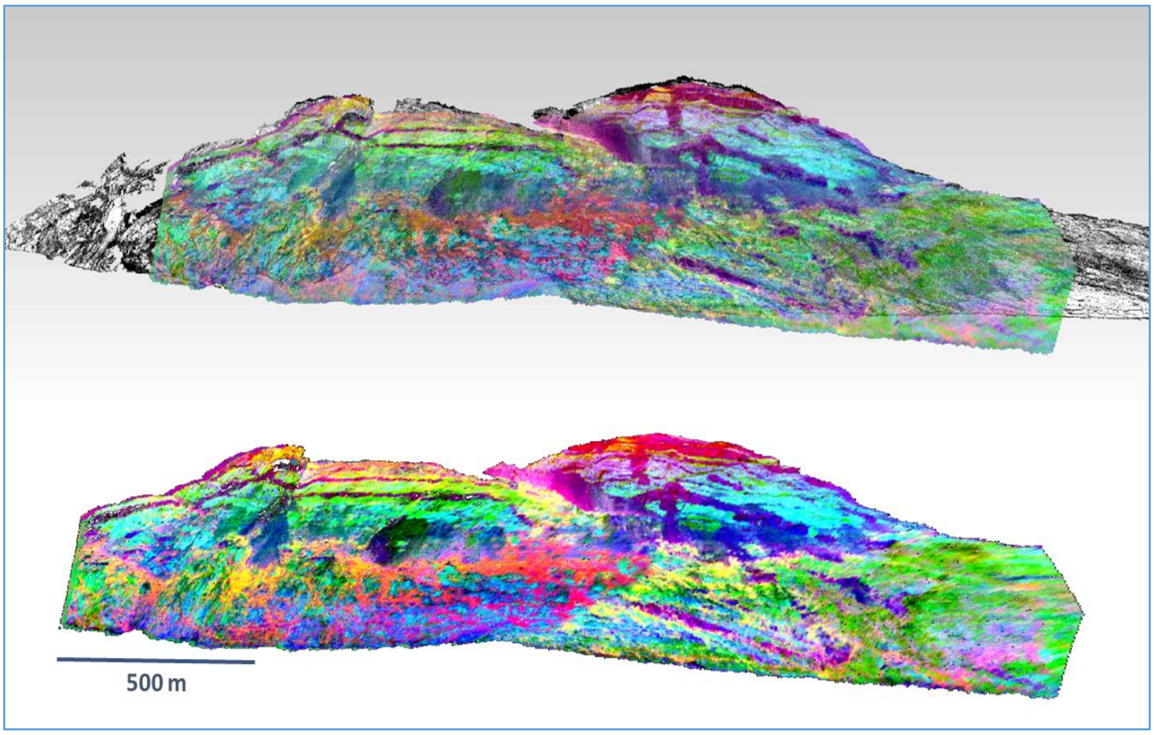

Figure 50. *Matching hyperspectral products to the 2D outcrop model. Kangerlussuaq fjord.*

After extraction of point cloud data from stereo-imagery, the 3D point cloud is projected onto a 2D plane (pseudo-orthophoto), mimicking the viewing angle of the hyperspectral scenes. The hyperspectral data is then registered to the pseudo-orthophoto, to derive the spatial information per pixel for the hyperspectral imagery. Once the correspondence between the hyperspectral scans and the pseudo-orthophoto is found, the transformation matrix is used to project the individual hyperspectral products on the 2D pseudo-orthophoto (Figure 50). Dimensionality reduction methods such as Minimum Noise Fraction (MNF) transformation (Figure 49d) or spectral unmixing methods for generating mineral abundance maps are among the possible approaches one might use depending on the purpose of the project. The 3D image-based surface reconstruction allows the visualization and interpretation of hyperspectral image products in conjunction with the photorealistic 3D models (Figure 51).

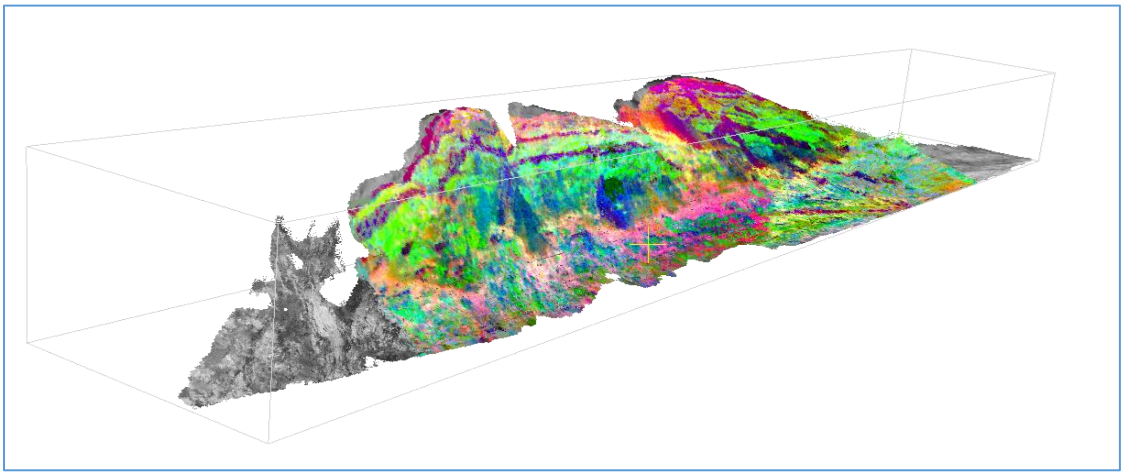

Figure 51. *3D hypercloud generated from projection of hyperspectral products on 3D point cloud. Kangerlussuaq fjord.*

Despite the promising results achieved by using long range terrestrial scanning, the rugged topography and difficult terrain accessibility in the Arctic often hinder the instrumentation setup and limit the employment of such a data acquisition strategy. Moreover, this approach is more suitable for local scale investigations. Vessel-based scanning enlarges the scale of mapping and provides more flexibility, however not all outcrops are reachable via fjords.

To address these issues a helicopter has been utilized by GEUS as a versatile means of acquiring remote sensing data emphasizing both spatial and spectral information (Salehi *et al.* 2019b). The focus lies hereby on the integration of digital photogrammetry with helicopter-borne hyperspectral imaging to gather high-resolution geometric data as well as quantitative information about mineral variations in the outcrop. In the alpine terrains of Greenland with many near-vertical cliffs neatly showing the geology, scanning vertical sections from a helicopter flying in the fiord, will give an improved presentation of layered geology or sections with alterations containing economic deposits. Adding the spectrum measured directly on the rocks or surface material, in nature or in the laboratory, we can create direct links from site data to satellite data. Use of appropriate sensor combinations to acquire geo-referenced images being corrected for orientation information, will make the system more flexible in terms of system integration. The method is tested in North-East Greenland (Clavering Ø, Figure 52), where stereo images and hyperspectral data cubes have been collected simultaneously and from both nadir and off-nadir viewing angles (red frames in Figure 52). The study demonstrates the potential of using helicopters to help understand the geology in poorly accessible areas and to provide information that may help in the future exploration activities.

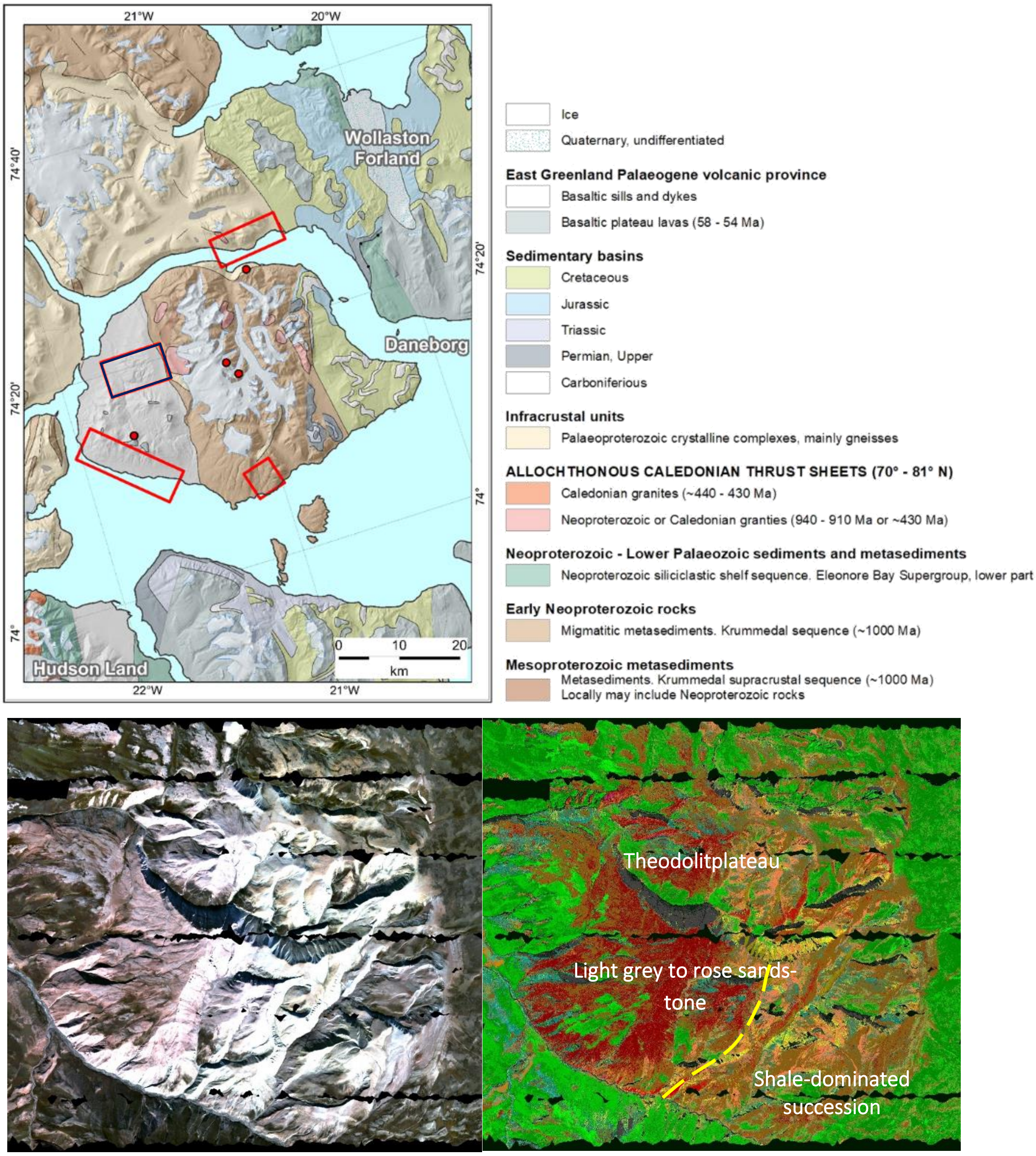

Figure 52. *Oblique and nadir helicopter-borne data acquisition in North-East Greenland. Upper panel: selected test sites in Clavering Ø for testing the approach. Red circles highlight terrestrial hyperspectral scanning while red and blue frames highlight helicopter borne scanning. Lower panel: True-colour hyperspectral mosaic and the classification results produced for one of the test sites (highlighted with blue frame). This test site is around 50 km^2 large and has been covered by 10 flight lines.*

6. Status and trends for the future (2020 status)

The activities and case stories described in section 5 represent a major investment in projects, hardware, field work, remote sensing methods and training. The work is continuing today with emphasis on time- and cost-efficient methods to acquire high quality data from large and inaccessible regions with the aim of mapping geology and geological processes. At the time of finishing of this report, GEUS is engaged in several mineral exploration projects utilising expected developments in the hyperspectral remote sensing sciences. Some developments of methods and strategies well suited for use in Greenland will be pursued.

The ongoing international technological development points to an explosive expansion of instruments and methods along many directions. Not only are there more satellites to be launched over the coming years, instrumentation for airborne and drone scanning and imaging detection of signals is steadily being improved. The driving force behind these developments are not so much the need for geological data, as for data reflecting man's specific environment, e.g. vegetation, soil use, urban developments, monitoring of many aspects of civilisation and the effects of climate changes. However, without doubt the methods and the instruments will also find a use in relation to the mapping of geology.

The fusion of data acquired with multiple sensors is challenging and therefore improvements in multi-sensor spectral imaging for a combined interpretation of geology is to be gained. GEUS is an active partner in new projects to be initialised in international cooperation, focused at combined use of VNIR, SWIR, TIR and Lidar data for geological interpretations.
In summary, the tentative aims for the following years, depending on funding and other resources, are:

- Continued development of practical standard processing and interpretation procedures, in pre-field mode and in more detailed interpretation after field work. This will involve development of both strategies and methods and assumes some additional funding.

- Continuation of the 'standard' processing of Aster data from all, ice-free areas in Greenland to produce a series of maps showing several different parameters of interest in geological exploration and mapping. Preparations for similar products from new satellite data becoming available within a few years.

- Continued development of data fusion techniques for better geological interpretations, such as integration of geophysical and optical data.

- Continuation of systematic work with spectra of rocks and minerals in Greenland, also including different degrees of weathering and lichen growths.

- Continued improvement of hardware and software of the GEUSRSIF workstation and server towards faster functionality and more generally available remote sensing functions.

In section 3.10 we touched briefly on the subject of timing of remote sensing work or surveying in a large regional exploration/mapping project and reducing processing time required. Looking ahead, it is necessary to return to this subject in general. Without much argumentation, most would be prepared to accept that the ideal order of investigations could be this:

1. Compilation of all existing data of any type; this should include relevant spaceborne remote sensing data. Recognising the fact that one undeniable benefit of using current and future satellite data is coverage of large areas, GEUS will continue to process and interpret free spaceborne data from all ice-free areas of Greenland. Some 50 % of this area has been treated so far in an ad hoc manner, when the opportunity offered itself but now a more systematic effort towards coverage of all of ice–free Greenland is within reach (Figure 53); in cooperation with Greenland authorities, funding is being sought to intensify the work aiming at different satellite maps series each covering all of ice-free Greenland. The maps and associated data and information will be presented on the internet in the portal on mineral resources in Greenland, or in a separate portal for remote sensing products.

2. New airborne surveys, geophysical and hyperspectral, systematic and designed to appropriate scale and detail. Production of appropriate geophysical and hyperspectral maps. Often it would make sense to include geochemical sampling and mapping.

3. Production of preliminary geological maps based on data available so far, with high-priority zones and locations for the geological field mapping teams. This would be the basis for a major part of the geological sampling and field work in general.

4. Final integrated interpretation of all layers of data and production of final products in GIS setting.

In principle, for the results of new remote sensing work to be ready when required in the following stages of such a project plan, processing time in general must be reduced as much as possible. We would recommend that airborne/helicopterborne hyperspectral surveys from commercial contractors be instructed to deliver ready-off-the-aircraft data, so that any additional data corrections can address issues of direct relevance for the interpretation.

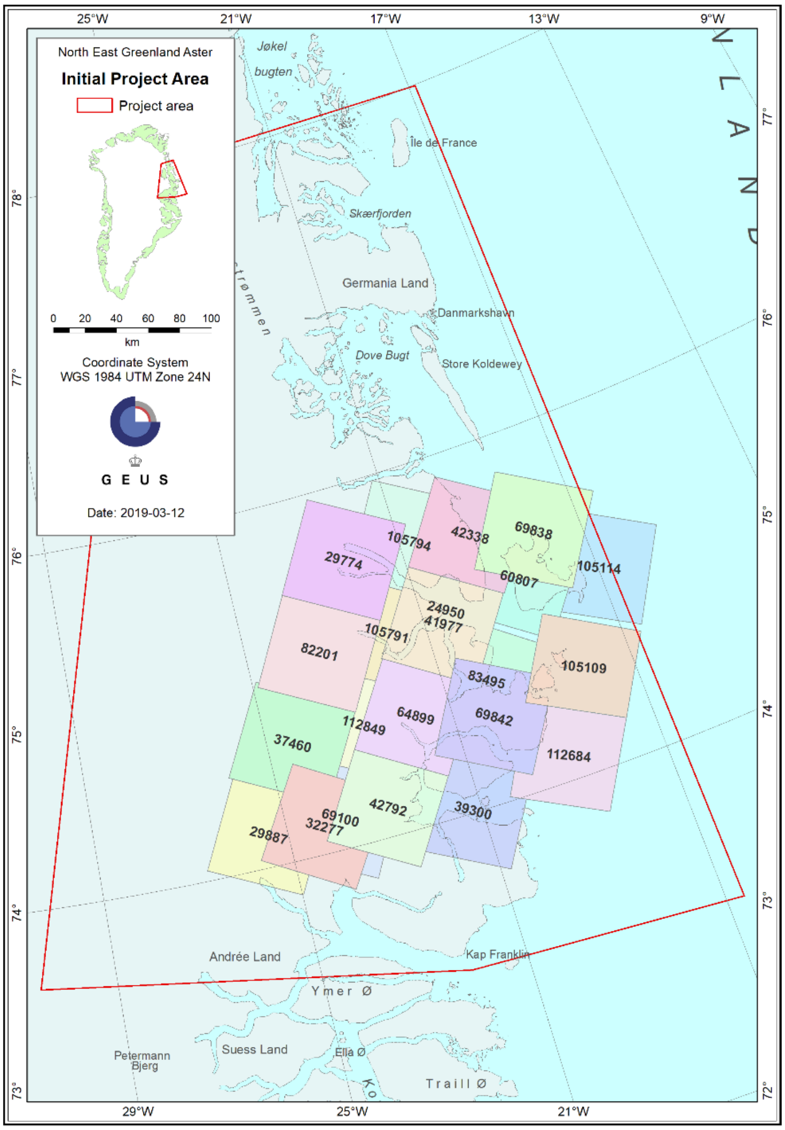

Figure 53. *ASTER data analysis applied to mineral and geological mapping in North-East Greenland (Salehi et al. 2019a).*

7. Acknowledgements

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