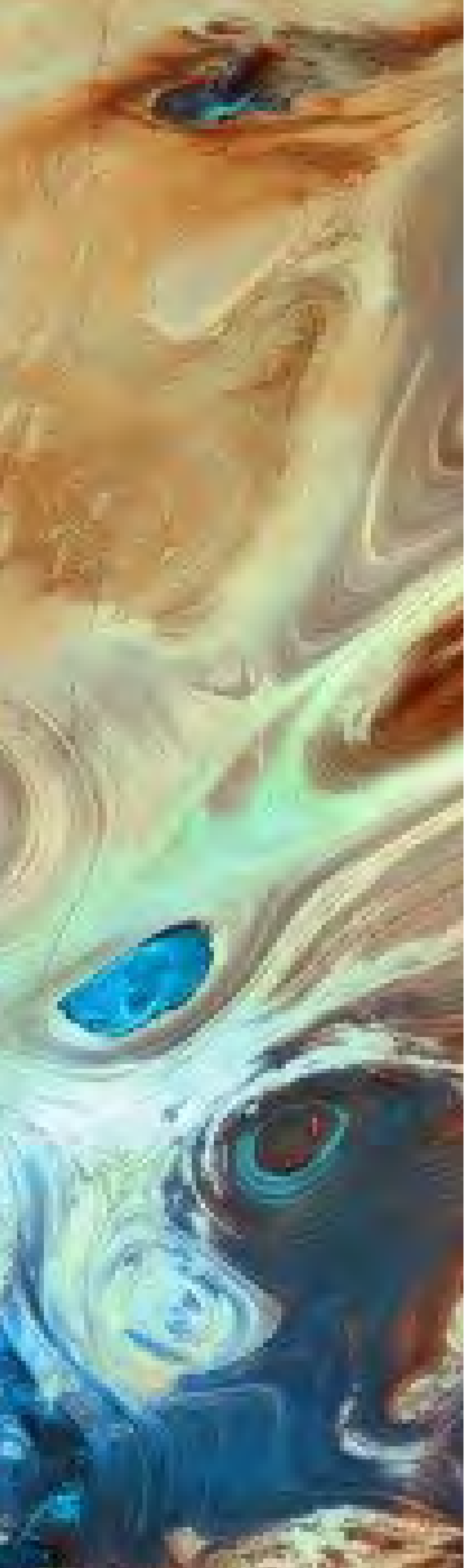
THE GRSG NEWSLETTER THERMAL EDITION JULY 2021

GRSG
GEOLOGICAL REMOTE SENSING GROUP

Welcome to the Thermal Special Edtion of our Geological Remote Sensing Group. Newsletter



Dear Members

Welcome to our first special newsletter special issue, a chance for us to show case on a specific topic. We intend to have a couple of special editions a year and would love to hear your feedback of what you think.

This year continues to be challenging for many of us and we are still hopeful of a hybrid event in December providing flexibility to all to be able to attend the conference in person, when it is possible to and as long as restrictions allow, as well as to ensure a virtual presence to ensure that despite restrictions it is still possible to join us.

Our call for papers will open very soon so please do consider submitting something as we go back to our home at the Geological Society in London. We can't wait to see you all, or as many as possible, again in person.

Our US Energy event planning is also well underway and the call for papers for this is now open. Join us online for the Remote Sensing for the Energy Sector from 31st August – 2nd September. More details, including the program and how to register will be released in August.

We will also shortly be announcing some online training for 2021 starting with a Python webinar led by Andrew Cutts. It has been a pleasure to work with Andrew over recent years and these short focused workshop webinars, driven by your feedback, will provide additional tools and guidance to help us all learn more about Python and other open access tools.

In addition we have a series of other events coming up later this year including the virtual William Smith meeting which GRSG is co-badging, and call for papers is still open for as well as the upcoming RSPSoc conference in September.

The GRSG will have a hosted session at the event we look forward to hearing from you if you are interested to submit an abstract for our session.

We were delighted to support the RISIG Rock Imaging Special Interest Group recently by co-badging their Hyperspectral webinar held on June 18th and look forward to working with them again in the future.

For our members we have also added a Member's Resources tab (accessible once you are logged in). This curated list includes a range of training, information, data sources etc that might be of interest, many of which are public access. We will continue adding to this list but if you see something missing from this list then please let us know and we would be happy to include it.

Finally as updates go it is with great pleasure we were able to award three student awards this year, you will hear more about the recipients later in this newsletter and in upcoming newsletters as they share more about how they will use their awards and present at our AGM later this year.

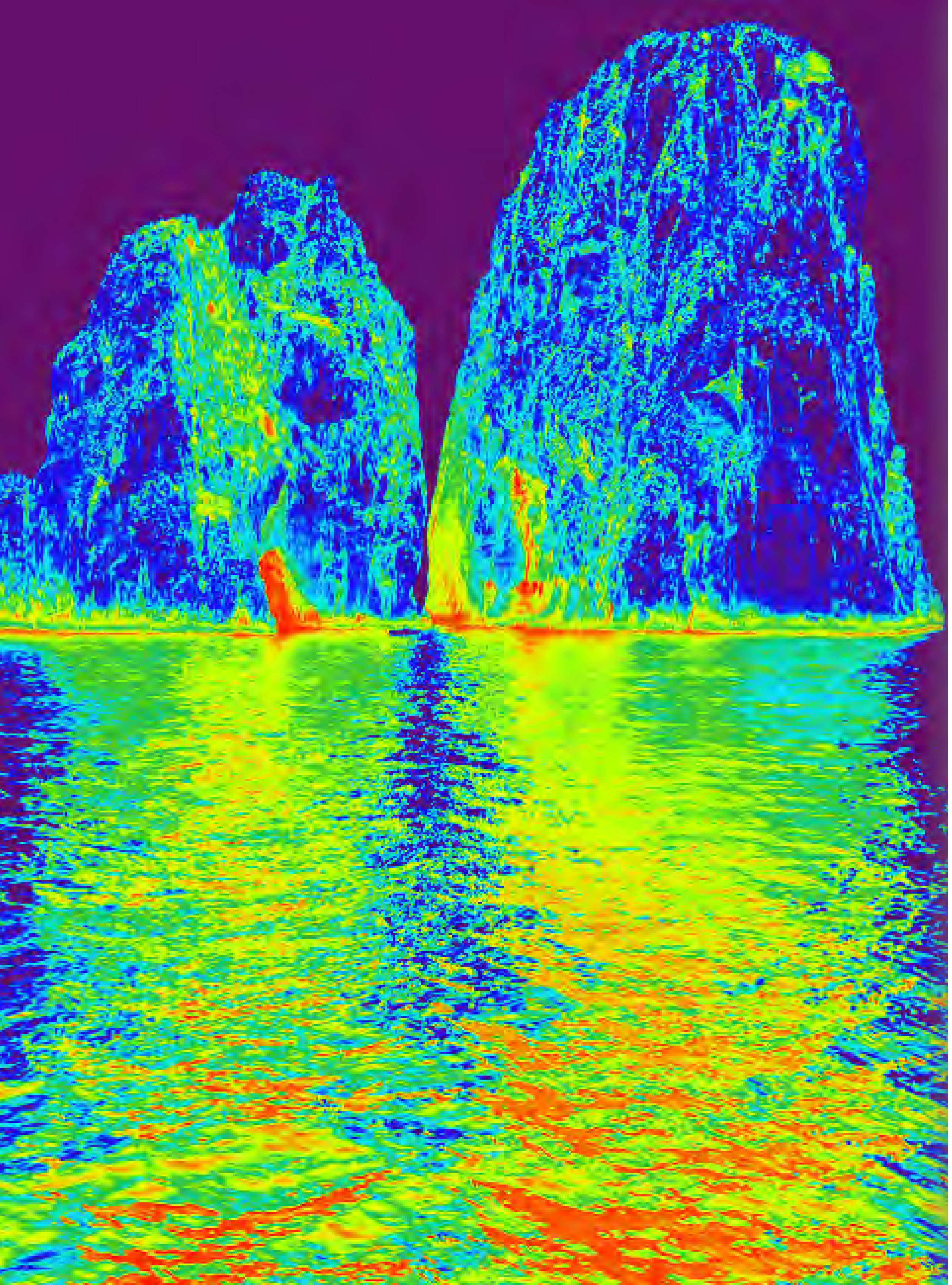
As always with the newsletter we try to capture the news and updates from across the community and have some excellent articles and news items this time around. Our newsletters are collated by a dedicated team but we actively encourage, and need, your inputs so read more about their plans and how you can help later in this newsletter.

For now we hope you all continue to take care and stay safe wherever you are in the world and we hope to see you later this year!

Best wishes

Charlotte Bishop

Chair, GRSG



THE THERMAL SPECIAL EDITION

From the Editorial Team

This Thermal InfraRed (TIR) special edition of the newsletter is focused on a highly useful but under-utilized method in Earth Sciences in general. The applicability of mid-wave and long-wave TIR (3-5 m and 8-14 m, respectively) to geologic applications is well-known within the laboratory environment but to a much lesser extent in real-world applications.

Historically, access to meaningful TIR measurements and imaging has been in the realm of government (specifically military) laboratories. The reason for this is simply that these instruments were orders of magnitude more expensive than their counterparts in the visible spectrum.

However, over the past decade, there has been a surge in not only new technology but, more importantly, in affordable technology that can accurately measure within the TIR region. There are now many manufacturers of broadband, multispectral and hyperspectral TIR instruments, such that, the ability to push the method into new commercial realms is at hand.

This special edition is meant as a way of introducing the GRSG community at large to the recent possibilities of using TIR data and how it can be an enormous asset to the working geologist / Earth scientist.

NEWS ARTICLE
Pléiades Neo 3 Imagery

May 2021 marked the first glimpse of the newly released Pléiades Neo 3 imagery by Airbus. Pléiades Neo 3 imagery has a stunning native resolution of 30cm with high-precision geolocalisation .

Over the next several months the imagery will continue to undergo radiometric and other systems corrections providing a commercial product expected within the third quarter of 2021.

When fully operational, the Pléiades Neo 3 is expected to acquire and produce 500,000 km2 of 30 cm imagery per day. It is expected that this system will provide superior very-high resolution imagery with equally precise geospatial accuracy.

The Pléiades Neo 3 system is the latest in the Pléiades contellation with Pléiades Neo 4, 5 and 6 expected to be launched by 2022.

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NEWS ARTICLE

Drone Footage of Mt. Fagradalsfjall

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NEWS ARTICLE
Mining for Climate Change

With the increasing emphasis on a Green Economy, the future of base and exotic metal mining looks very promising.

A detailed, and well-constructed 2020 study from the World Bank recently considered the roll of mining in the newly burgeoning Green Economy, with results being very positive for mining activities.

In fact, although mining has not traditionally been associated with Green initiatives, it is nevertheless, a critical component of getting to the net-zero carbon objectives that most countries have purported to be working towards.

The necessity of mining operations (including primary exploration), are key to providing the necessary raw material for the construction of the infrastructure of the Green Economy.

Be it, wind powered electric generators or the new revolution in solar technology, mining of base metals (copper, zinc, lead, etc) and exotic metals (lithium, neodymium, graphite, etc) appears to be a sector that will only be increasing in overall demand (as much as 500%) as we go forward towards the new Green Economy.

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NEWS ARTICLE

Thermal Mapping of Glacial Surfaces

While the activity of mapping and modelling glacial retreat is not new, there are some high-impact parameters in the modelling that requires considerably more precise estimates.

Specifically, thickness of surface debris - since a thin debris field will increase melting while a thick debris field will slow it.

In this work, the surface debris field thickness is determined via thermal imaging, where imagery collected overtop of glaciers has been examined and from that a determination can be made of the depth distribution.

As glacial retreat is a major large-scale effect and driver of climate change, the thermal imaging has a high impact value on the entire climate change prediction discussions that are on-going.

Further, this method is expected to be of considerable use when considering exploration for indicator mineralisations, such as garnets, near or at the base of the glacial melt.

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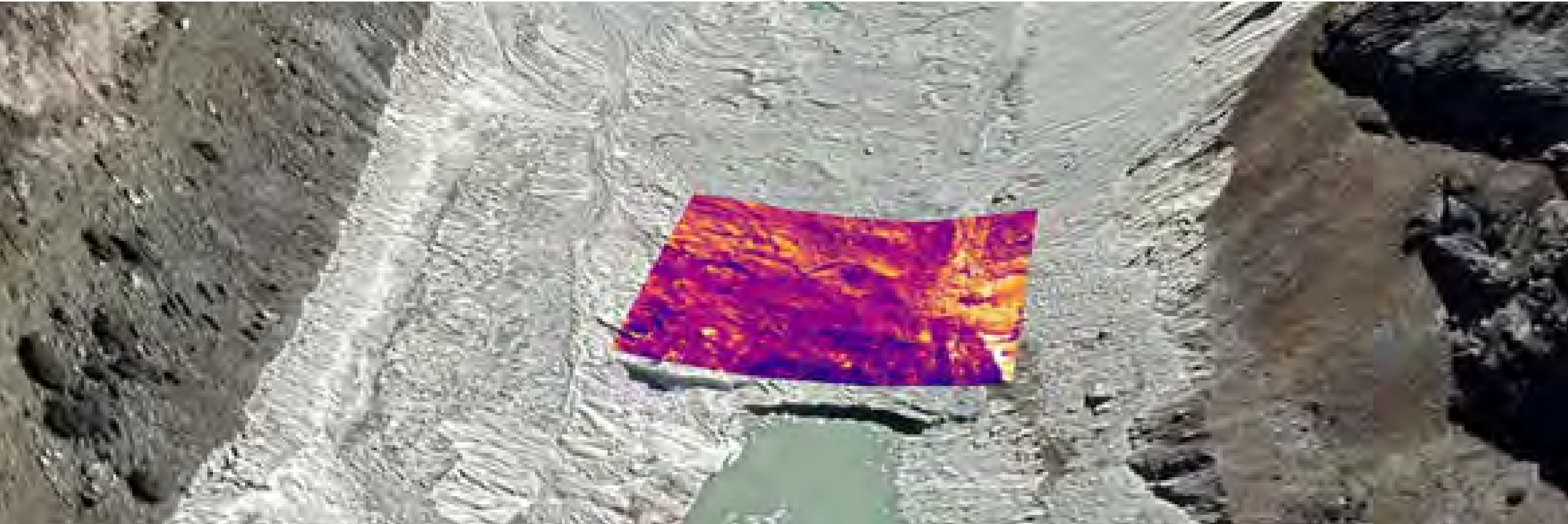

GRSG 2021 HYBRID CONFERENCE

PROGRESSION TOWARDS QUANTITATIVE GEOLOGICAL REMOTE SENSING

13TH - 16TH DECEMBER 2021

FEATURED ARTICLE

Thermal infrared work at ITC – a personal, historic perspective of transitions

UNIVERSITY OF TWENTE, THE NETHERLANDS
Christoph Hecker

Figure 1: Ground truthing radiant temperatures of coal fire -related thermal anomalies detected from space over an area in Inner Mongolia, China in 2003.

Over the past 20 years, my work in thermal infrared remote sensing (TIR-RS) has gone through a number of changes and transitions that have fundamentally impacted my daily work.

This is my personal perspective of these changes, but I am confident that many of you will have followed similar paths and will recognize part of my journey.

The early days

When I started working at ITC in 2001 thermal infrared remote sensing was exactly how it was described in the (geologic) remote sensing books of Sabins, Drury and Lillesand and Kiefer [1-3]: it was heavily based on a single, broadband channel 6 of the Landsat-series satellite suit, striping and "salt and pepper" in the images were common and relative radiant temperature comparisons were often used, as emissivity information of the targets were not known or had to be guessed from a land cover classification.

In that context, ITC executed a number of large coal fire detection and intervention projects in northern provinces of China and in India. TIR-RS with Landsat and later MODIS [e.g., 4] data was used to detect areas with unusual radiant temperatures, so called "thermal anomalies" as early warning indicators and for monitoring extinction efforts for coal fires in the shallow subsurface.

The regional monitoring was followed up by field visits with thermal hand-held cameras and radiant thermometers (Figure 1), and occasionally with an airborne thermal campaign of questionable quality.

Enter ASTER

Shortly after I had made my first baby-steps in TIR-RS, ASTER showed up on the scene. It was a game-changing sensor with multi-spectral capabilities in the TIR in addition to the typical SWIR bands that we had already become familiar with from the landsat suit sensors.

The multi-spectral TIR bands enabled the spaceborne thermal community for the first time to extract emissivity directly from the data, providing not only better kinetic temperature estimates, but also spectral LWIR information for regional geologic mapping.

ITC already had a strong research group on SWIR spectroscopy, so we decided that expanding into the TIR/LWIR domain would help to capture those minerals that are elusive in the SWIR, such as non-hydroxylated silicates (feldspars, quartz, garnets etc).

I reached out to those already working in the thermal domain and found a small, but very welcoming community. I visited Simon Hook at JPL and Lake Tahoe (Figure 2), Wendy Calvin at UNR, Lyle Mars and x`Jim Crowley at USGS, and Mike Ramsey at UPittsburgh for advice, and I received overwhelming support.

This fact finding mission resulted in two custom-made LWIR spectrometers, one for our ITC lab facilities [5] and one for the field.

Since then, we have fine-tuned the design and I have hosted and shared my knowledge with a number of visitors from England, Luxembourg, Germany, Sweden and Australia to pay it forward to the thermal community.

Apart from the typical spectral geology applications, I had the opportunity to measure plastics, solar panels and arctic avian eggshells [e.g., 6] with visiting colleagues, to name a few.

Organizing the community

As TIR-RS became a bit more mainstream, we realized that many of us were working on similar issues. To bundle efforts and increase efficiency,

I founded and chaired a new Special Interest Group on Thermal Remote Sensing (SIG-TRS) of the European Association of Remote Sensing Laboratories (EARSeL), together with Claudia Kuenzer from DLR in 2008.

Figure 2: Maintenance visit to JPL's Lake Tahoe validation buoy for spaceborne TIR sensors with Simon Hook (not in the picture) and research staff from UC Davis in 2006.

Claudia and I chairing the group together was an expression of the special duality of TIR-RS, where some of the applications are focused on land surface temperatures while other researchers are interested in the emissivity and material properties.

None of these groups could ignore the other field entirely, as the measured radiance data were an expression of both. Keeping the two communities under one organizations also created a bit more clout in what was still a niche application in remote sensing.

Under this SIG-TRS umbrella we organized various activities, particularly dedicated TIR sessions and side events at conferences to bring the thermal community (particularly of Europe) together and avoid thermal infrared topics being dispersed over less suitable conference sessions.

Figure 3: demonstration of our then new the prototype field LWIR spectrometer at the GRSG AGM of 2009 in London

Most memorable for myself was the 2009 GRSG AGM in London, where we added an entire TIR day to the programme, illustrating the thermal infrared interest within the GRSG community, as well as the support from the GRSG Committee for TIR topics.

At the end of the day we demonstrated the use of our (then brand new) ITC LWIR field spectrometer to the audience in the respectable halls of the Linnean Society Of London (Figure 3). As of 2020, Claudia and I have stepped down as chairpeople of the SIG-TRS to pass the baton to the next generation TIR enthusiasts.

Transition to hyperspectral airborne data

My personal research interests in LWIR spectroscopy took a sudden turn in 2009 when I was offered the opportunity to work with airborne SEBASS data (Figure 4). Dean Riley (formerly Aerospace Corporation) and Conrad Wright (formerly SpecTIR) had acquired a combined VNIR-SWIR-LWIR dataset over a mineral exploration study area in Yerington,

Nevada that I was given the opportunity to work on. I completed my PhD on the dataset and we have had numerous masters students working with me in the area since.

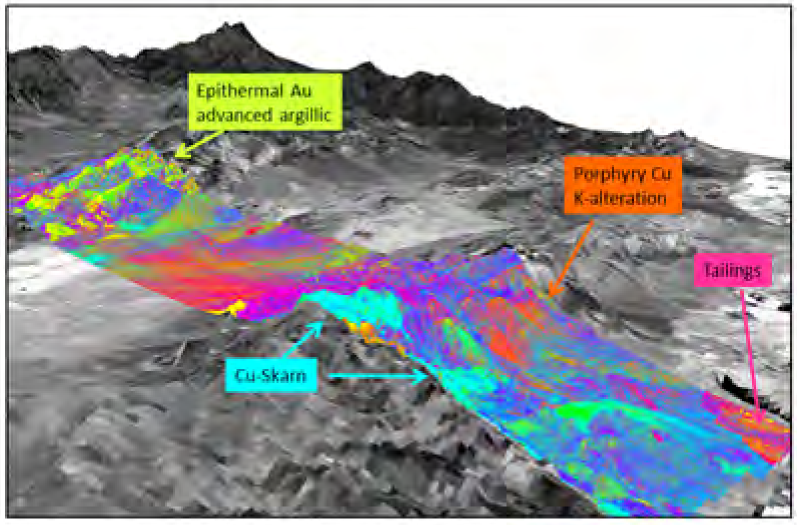

Figure 4: mosaiced and decorrelation-stretched LWIR color composite of airborne SEBASS data (4m pixels) over the Yerington Batholith in Nevada, USA highlighting different alteration styles in the areas.
Draped over a grayscale ASTER band & DEM.

SEBASS was (and is) a truly exceptional sensor. With 128 bands in the LWIR as well as MWIR, it was the first hyperspectral airborne LWIR sensor I had worked with. On the downside, its 128-pixel swath was extremely narrow and together with the liquid Helium cooling, it made deployability a challenge. Additionally, data sharing was restricted due to the "dual use" (military/civil) nature of the sensor, which is particularly difficult in an truly international classroom, as we have at ITC.

However, SEBASS was in my perspective a trail-blazer for the “explosion” of sensors that followed. Aerospace itself created follow-on instruments (e.g. MAKO and MAGI) that overcame some of the earlier SEBASS limitations.

But also commercial suppliers entered the market, like ITRES offered the spectral TASI sensor, Telops its airborne version of the Hypercam and SPECIM the OWL camera, to name a few.

With this technological development commercial operations of airborne spectral TIR sensors (outside of the defence and R&D realm) suddenly became a reality.

In the past few years, much effort has been put into atmospheric correction and emissivity separation algorithms by data providers to further lower the threshold for commercial users and deliver reliable Level2 (or higher) data products to the end users.
While there are still minor issues to be solved, we are now at the point where commercially available airborne hyperspectral TIR data is becoming a reality.

Transition to geothermal applications
Under the global need to transition away from our hydrocarbon-based economy, new applications of thermal remote sensing became increasingly opportune to add to the more traditional mineral exploration applications.

In 2013 ITC started working on geothermal exploration topics, and by 2014 lead an international multi-year geothermal capacity building programme (GEOCAP, [7]) which partially investigated remote sensing for geothermal exploration and monitoring in Indonesia.

Earlier work (particularly by teams from UNR and linked to Wendy Calvin and the late Jim Taranik) had shown that spaceborne TIR remote sensing could be used to map surface temperature anomalies related to fumarole activities [e.g., 8].

Our own results demonstrated that potential as well [9] but it worked best in desert-like environments and with night time data of high temperature contrast. In any non-ideal situation the delicate balance could easily shift towards inconclusive or no results.

The main reasons are a) vegetation cover, b) the pixel size of the spaceborne thermal data are often coarse compared to the actual surface expressions (often fumarole vents), and c) the overpass time of sun-synchronous satellites is not ideal for thermal anomaly detection (too early in the night to subdue effect of differential solar heating and different heat capacity of the materials) [10].

Because of the first reason (vegetation cover) we decided that, particularly for the Indonesian context, focusing on proximal sensing of drilling data would be the more promising avenue.

For the latter two reasons, we decided to launch an airborne campaign over a test area in Flores to see what unknown thermal anomalies could be detected from high-spatial resolution airborne thermal data instead.

We integrated our ITC-owned FLIR x6570sc cooled thermal camera into an existing airborne Leica mapping and LiDAR setup of a local commercial data supplier (Figure 5).

Figure 5: Part of the team from UT-ITC, U. Gadjah Mada, and airborne operator APG at the open hatch of the Pilatus Porter PC-6 at the Komodo International Airport, Indonesia (2018). The down-looking thermal broadband FLIR camera is visible between the Leica LiDAR head (big black box in center of image) and the water supply of the pilot (towards the right)

In an area where previously only a single ASTER pixel had been identified as thermally anomalous, we could now identify numerous new fumaroles and warm ground in the 50cm airborne early morning thermal data [11]. The alignment of the thermal anomalies also showed clear underlying surface structures which could be compared to deeper structures seen in previously acquired geophysical datasets.

From remote to proximal sensing

Another transition that I have gone through in the past 10 years, and with me many other spectral geologists, is from air- and spaceborne remote sensing to the proximal sensing domain in the laboratory.

At first sight it appears mainly an engineering challenge to get a hyperspectral imaging sensors equipped with the right fore-optics and lighting to use them on conveyor belts or drill tray scanners.

The processing chain is largely similar to the airborne imagery, but with the added benefit of less atmospheric disturbance and typically quite high signal-to-noise ratio. As usual, the devil is in the details and the closer you look, the more challenges you find.

One of these challenges is the co-registration of VNIR-SWIR-LWIR images from separate instruments that don't share a fore-optic.

Two specific ones for the thermal infrared are the effect of sample surface roughness on the results [12] and the compensation of the self-emission of the sample as they are being heated by the illumination sources.

And of course the geologic crux is how to combine information from different wavelength ranges into the most sensible (I leave it to each of you to judge what you think this should be) geologic/mineralogic information possible. As a community, we have made great strides but there are some major challenges still left to be tackled.

In the proximal sensing realm, we are currently progressing with SWIR and LWIR imaging for geothermal drill cutting characterization. These cuttings are coarse sand-sized particles that result from the drilling of the reservoir rocks in a geothermal prospect.

In geothermal exploration cuttings are much more common than drill cores, due to the much lower drilling costs, and the challenge is to identify important, yet elusive hydrothermal alteration minerals in the small cuttings that tell us about the current situation as well as the history of the reservoir in terms of environmental conditions.

The circle closes

In a recent development, I have somewhat returned to my thermal roots: the detection of surface temperature anomalies with spaceborne TIR data, in this case from the thermal infrared ECOSTRESS sensor on the International Space Station.

Due to its specific orbit, ECOSTRESS has an advantage over instruments on the more traditional sun-synchronous and geostationary orbits; it allows for different acquisition times but still at a near-global coverage and at a fairly high (70m) spatial resolution.

Opposite to my early days we are now detecting geothermal rather than coal fire-related temperature anomalies. With the precessing ECOSTRESS orbit, we also have the opportunity to choose ideal times of the day for the anomaly detection, and to quantify the influence of overpass time on the detection success rates.

A post-doc researcher has recently started working at ITC on the project with study areas in Kenya, Indonesia and New Zealand. For the

Figure 6: Installation of ground-based thermal cameras for the long-term monitoring of geothermal fumaroles.
Team picture of project staff from partners KenGen and UT-ITC (2019)

Kenya study area we have installed ground-based thermal cameras for long-term monitoring of fumarole activity in Olkaria geothermal field (Figure 6; [13]).

Through my own thermal infrared path over the past 20 years, I have observed a transition in the TIR platforms from spaceborne over airborne towards proximal sensing.

If miniaturization of hardware continues, LWIR spectrometers may move to larger UAV platforms in the coming years just like the SWIR sensors are currently doing.

In the instrument domain we have seen a change from relative instrument scarcity to a situation where now several commercial options for airborne hyperspectral LWIR acquisitions are available.

And in the application direction, we have seen moves towards alternative energy resources, such as geothermal energy.

But with critical raw materials being essential for the upcoming energy transition as well, a renewed interest in spectral geology and remote sensing for mineral exploration can certainly be expected.

And what wavelength range could we possible look at when we require additional information on REE-bearing silicates and Li-rich pegmatites ... ?

Exactly!

Acknowledgments
Chris Hecker is an Associate Professor in Thermal Infrared Sensing at ITC-University of Twente, The Netherlands.

Next to his research, he teaches classes in Spectral Geology and Thermal Infrared Remote Sensing in the Graduate Specialization Applied Remote Sensing.

Chris expresses his sincere gratitude to the thermal infrared community and all its members with which he has had a very constructive exchange of the collective thermal wisdom, or of ideas on how to gather that wisdom in the future.

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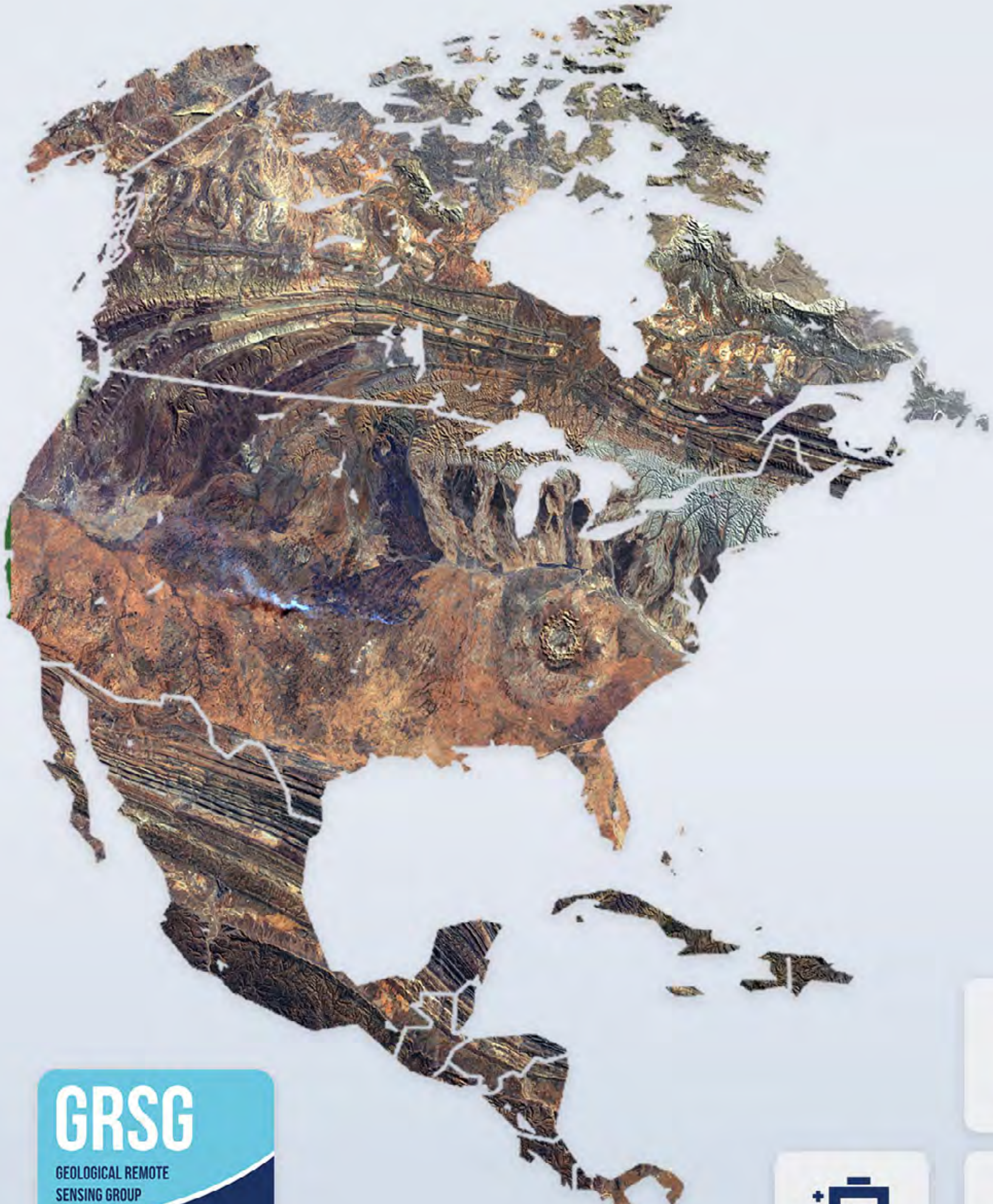

AUG 31 2021 - SEP 02 2021

GRSG NORTH AMERICA

Remote Sensing for the Energy Sector Workshop

GRSG
GEOLOGICAL REMOTE SENSING GROUP

FEATURED ARTICLE

Using Satellite Thermal Imagery to Map Sediment-Hosted Mineral Deposits Under Cover

NEIL PENDOCK
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Introduction

A year ago, Geoscience Australia (GA) released a lecture series after four years and A$100m worth of effort, under the banner "Exploring for the Future" [EFTF].

This work is groundbreaking in that it connects scientific data with the locations of large sediment-hosted base metal deposits in Australia and the rest of the world.

The lecture series, in very simple terms, discusses how to use continent-scale scientific data to map mantle-edge thermal gradients along modern-day cratonic margins.

One conclusion was a first order control for the localisation of large sedimentary-hosted base metal deposits.

This ground-breaking work has identified the most prospective horizon as the 170km deep lithospheric-asthenosphere boundary (LAB).

This contour between thick and thin lithosphere has been recognised as being associated with 85% of Australia's Tier One deposits. This association has been made independent of age of deposit and can be extrapolated worldwide [2].

The model applies outside Australia too: 85% of the world's sediment-hosted base metal deposits, including all those >10 Mt, occur within 200 km of the edge of thick lithosphere, irrespective of the age of mineralisation [1]. Recent work has shown that all giant sediment-hosted mineral deposits are located above steps in the LAB.

Around 80% of Australia is under cover, so homogenous datasets that have mineral system implications are required. For the past decade, seismic tomography has been used to map first-order lithospheric mantle controls on magmatic ore deposits. In particular, seismic tomography has been used to map the location of the LAB.

The most recent model used is called SL2013sv, available as a grid with resolution 0.5 of a degree latitude/longitude [5], which makes detailed exploration targeting tricky. It is shown overleaf in green.

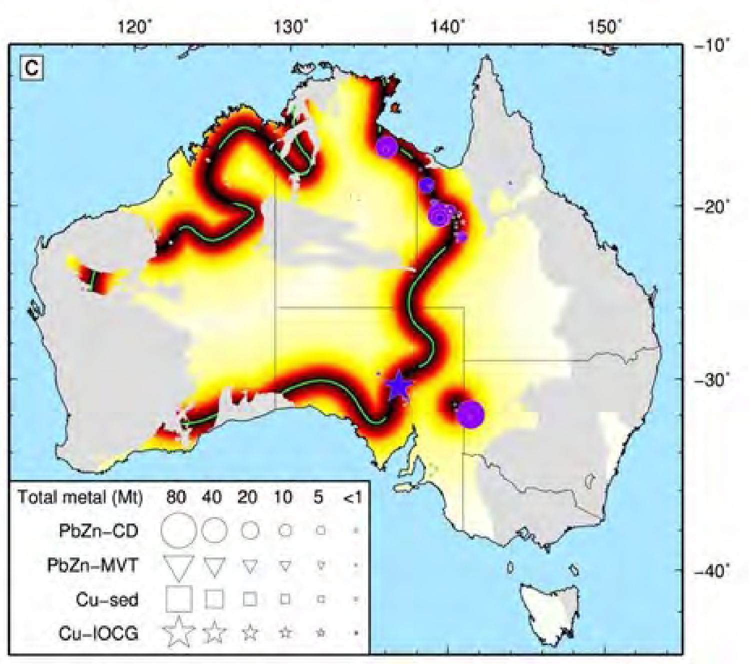

Figure 1: Mineral Potential heat map of Australia (after Czarnota et al, 2020).

Thick lithosphere results in increased basin subsidence rates during rifting; coupled with low geothermal gradients this ensures favourable metal solubility and precipitation. Sediments in such basins generally contain all the necessary lithofacies of a mineral system [4]. These considerations establish criteria for sediment-hosted base metal discoveries.

Conservative estimates place the undiscovered resource of sediment-hosted base metals in Australia at between 50 and 200 Mt. Distance to the thick lithosphere suggests that around 15% of Australia is prospective for giant sediment-hosted deposits. In particular, the Pilbara region of Western Australia is prospective, as the LAB carves a sinuous path through it.

Pilbara sedimentary copper example

The Pilbara is best known as one of the world's largest producers of iron ore; however, the region is currently in the midst of a gold exploration boom thanks to major discoveries in 2017 by Novo Resources and Artemis Resources.

Despite a well-established mining industry, the Pilbara remains underexplored, offering an opportunity to exploration companies in search of the next major discoveries.

But the location of the LAB is too poorly defined to be of much use for exploration targeting. Can it be improved?

The Sentinel-3 satellite of the European Space Agency measures daytime and nighttime temperatures of the surface of the earth at three orders of magnitude higher resolution (1 km which is approximately 0.008 degrees of latitude) than that available from the seismic network.

Geothermal gradients may be estimated by simply subtracting coregistered daytime and nighttime temperatures and after correcting for surface albedo, converted to thermal inertia.

Surface albedo may be approximated by the first principal component of a Sentinel-2 visible/near infrared [VNIR] mosaic of the region of interest at 10m spatial resolution.

In addition to constraining the location of the LAB, it is known that mineralized zones show very high thermal contrast (T) and low thermal inertia [3].
That these thermal contrast measurements are related to Cu deposit location is illustrated by a night time thermal mosaic of a central portion of the Pilbara, shown overleaf. Copper occurrences from Minedex, the Western Australia mineral occurrences database, are posted as white disks.

Nighttime temperatures are coloured on a temperature scale so the warmer the colour, the hotter the temperature. The mosaic in Figure 2 is a composite of several thousand Aster land surface temperature estimates made since the satellite was launched in December 1999 and corrected for seasonal variation.

Two things are immediately obvious from the above image: all copper occurrences lie to the north of the LAB and in particular they fall in regions of high nighttime temperature.

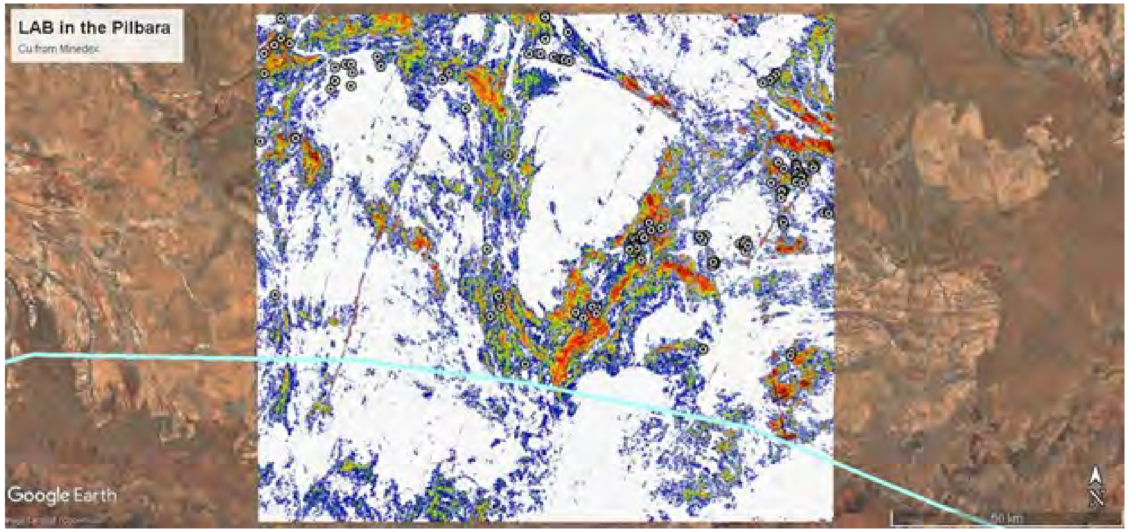

Figure 2: A several thousand image Aster mosaic, atop a Google Earth image, that shows nighttime temperatures in the Pilbara region.
Warmer colours represent hotter temperatures.

Whether these temperature anomalies are due to steps in the lithosphere or heat generated by oxidation of metal sulphides in the buried deposits, is moot. But at 90 m spatial resolution, the Aster temperature mosaic has a spatial resolution another order of magnitude higher than Sentinel-3.

Thus a thermal inertia map four orders of magnitude higher than the best seismic tomography model is eminently feasible.

The implications for mineral exploration are exciting.

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FEATURED ARTICLE

ECOSTRESS and the Future of Thermal Infrared Remote Sensing

KERRY CAWSE-NICHOLSON, SIMON HOOK, GLYNN HULLEY, CHRISTINE LEE, JOSHUA FISHER

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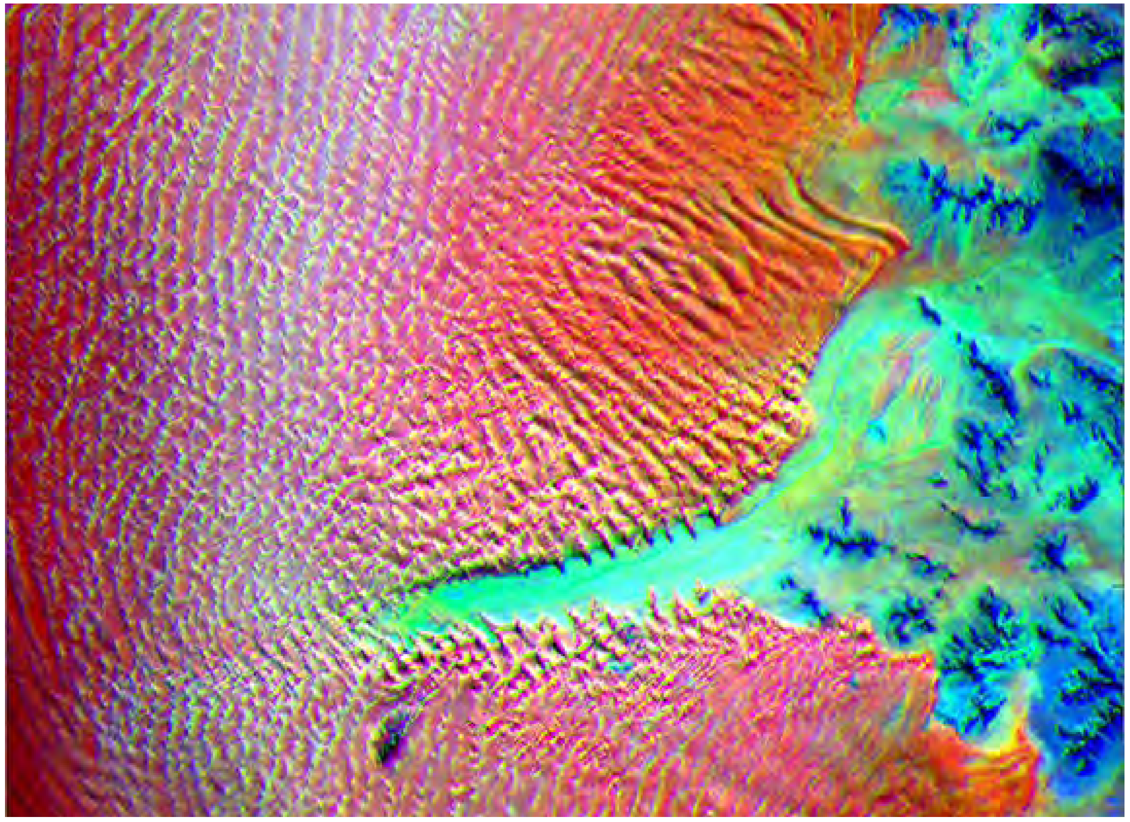

Figure 1: ECOSTRESS acquired data over Sossusvlei and the Namib dunes, Namibia on 1 August 2018. This image is a false color composite of a decorrelation stretch on surface radiance estimated from the Level 2 land surface temperature and emissivity products. Quartz-rich rocks appear red, carbonates appear green, maffic rocks appear blue-purple, and brightness changes represent temperature differences. (Source: https://ecostress.jpl.nasa.gov/gallery)

Remote sensing has been an important tool for geologists over the past half-century, beginning with black and white aerial photography and moving to early studies using 4-channel Landsat Multispectral Scanner (MSS) imagery (Landsat 1-5) and 6-channel Thematic Mapper imagery (Landsat 4-5) to detect hydrothermally altered areas (Rowan et al., 1974; Abrams et al., 1977).

Subsequently, technology evolved to enable acquisition at a number of additional wavelengths including thermal infrared (TIR) bands (8-12 um).

For example, the 14-channel Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) has been used to discriminate and identify rock and soil types based on their mineral composition and makeup since its launch in 1999 (Rowan and Mars, 2003; Ninomiya et al., 2005; Abrams and Yamaguchi, 2019).

Newer technological advances have facilitated measurements in hundreds of contiguous channels throughout the electromagnetic spectrum, enabling the identification of minerals using finer spectral features, such as the upcoming Earth surface Mineral dust source Investigation (EMIT) mission (https://earth.jpl.nasa.gov/emit/), which will measure the composition of mineral dust using the visible to shortwave infrared part of the spectrum (VSWIR; 0.4 – 2.5 um).

Part of ASTER's advantage was in combining measurements in different parts of the electromagnetic spectrum, from the visible to the thermal IR, and studies have shown that data acquired in the VSWIR is complimentary to data acquired in the TIR, particularly for mineral identification (Cawse-Nicholson et al., 2019).

In 2012, Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO) released 17 Geoscience mineral maps for the continent of Australia (Cudahy, 2012; CSIRO Data Access Portal, 2021) using ASTER data acquired between 2000 and 2008 – the first continental-scale mineral maps from an imaging satellite designed to measure clays, quartz and other minerals.

Using similar methods, global mineral maps could be generated using gridded TIR-derived emissivity datasets such as the ASTER Global Emissivity Dataset (GED), and combining these with VSWIR data.

Thermal imagery, although less widely available, has intrinsic benefits in the detection of minerals without distinctive features in the VSWIR, such as carbonates, sulfates, clays and silicates (see Figure 1).

In addition, measurements in the TIR enable the monitoring of volcanic gas and ash emissions and lava flows, as well as land surface temperature and its impact on natural landscapes and cities (Cawse-Nicholson et al., 2021).

In the 2017 Decadal Survey, the National Academy of Sciences, Engineering and Medicine (NASEM) made recommendations to NASA and other United States federal agencies on high-priority focus areas of primary importance for the coming decade, including those applicable to the Earth Surface and Interior (NASEM, 2018).

NASA has since incorporated these recommendations into a cohesive Earth System Observatory, which will measure Earth's climate and the impact of a changing climate on society (NASA, 2021).

Some of the science and applications areas designated most important are the forecasting and monitoring of volcanoes, seismic events and landslides; and capturing the impact of geological disasters on the earth system and society.

One of the recommended measurement approaches is to regularly acquire high-resolution measurements in the visible to thermal IR for the understanding of volcanic activity as well as supporting disaster response and mitigation.
Of primary importance is tracking of pre-, syn-, and post-eruption volcanic gases, ash and lava, quantifying disaster extent, and documenting ecological and mineralogical changes due to geologic hazards.

These fall under the designated observable referred to as Surface Biology and Geology (SBG).
The surface of the Earth is the meeting of the Earth's interior processes with the land and the atmosphere, where volcanic emissions fertilize soil, transform the land surface, and release gases into the atmosphere.

With ASTER nearing its end of mission, newer multichannel (> 3 band) thermal missions are continuing this legacy, with ECOSTRESS (https://ecostress.jpl.nasa.gov/) launched in 2018, making observations in 5 TIR bands from the International Space Station.

Other upcoming missions include the Thermal InfraRed Imaging Satellite for High-resolution Natural resource Assessment (TRISHNA; Lagouarde et al., 2018) (joint mission between the French and Indian space agencies; anticipated launch at the end of 2024), SBG-TIR (NASA; to launch no earlier than 2027) and the Land Surface Temperature Monitoring mission (LSTM; Koetz et al., 2018) (European Space Agency; to launch 2028).

Between the decommissioning of ASTER and the launch of LSTM, ECOSTRESS will be the only instrument to provide multichannel thermal measurements from space.

ECOSTRESS has revolutionized thermal imagery, with images acquired as often as multiple times per day, with an average of 1-5 days repeat (depending on ISS orbit) at 38 x 69 m resolution at nadir.

Although its primary mission was to detect drought and plant water and heat stress (Fisher et al., 2020), it also produces near-global high resolution Land Surface Temperature (LST) as a primary product that is freely available.

These data have been used extensively in the mapping and monitoring of urban heat. Vo and Hu (2021) showed the importance of vegetation in cooling urban centers by evaluating diurnal changes in temperature over New York City, and Chang et al. (2021) used similar measurements to observe temperature trends in different building zones in Xi'an, China. Hulley et al. (2019) used ECOSTRESS to produce a heat vulnerability index (HVI) in Los Angeles by combining socio-demographic data with green vegetation abundance and land surface temperature during heatwaves.

The high spatial resolution enabled mapping of vulnerable communities at a sub-city block scale. ECOSTRESS provides temperature information to the city of Los Angeles, who are exploring means to mitigate and adapt to rising heat in cities (Spotts, 2021).

ECOSTRESS also provides the highest spatial and temporal resolution sea surface temperature product for coastal and inland aquatic systems available to date, with the ability to resolve thermal release from power plants, eddies, and freshwater discharge into the coastal ocean.

Thermal imagery is also important in the monitoring of volcanic eruptions, as seen in Figure 2. Silvestri et al. (2020) evaluated ECOSTRESS over a number of active volcanoes in Italy and found that the instrument was well suited for the mapping of lava flow. This same technology can be used to find small temperature variations associated with geothermal fields, which will be essential for the development of renewable energy sources.

Petroleum hydrocarbons have also been shown to change the temperature and emissivity of minerals, pointing to the feasibility of detection through instruments such as ECOSTRESS and future thermal missions (Scafutto et al., 2021).

A new era of thermal imagery will begin in the coming decade, with complementary radiometers due to launch from various international space agencies (including LSTM, TRISHNA and SBG-TIR).

With careful collaboration, the combination of these instruments could yield near-daily high-resolution (~60 m) imagery and data products that will enable high priority science and applications to be pursued.

In a survey of over 500 respondents, these data were identified as fundamental to a variety of science and application priorities across the mining industry, fire detection, monitoring and response, drought and agriculture, and coastal ecosystems (Culver et al., 2020).

Further, ECOSTRESS and this continued thermal record will enable substantial advancements in our understanding of Earth as a system, climate change and feedbacks.

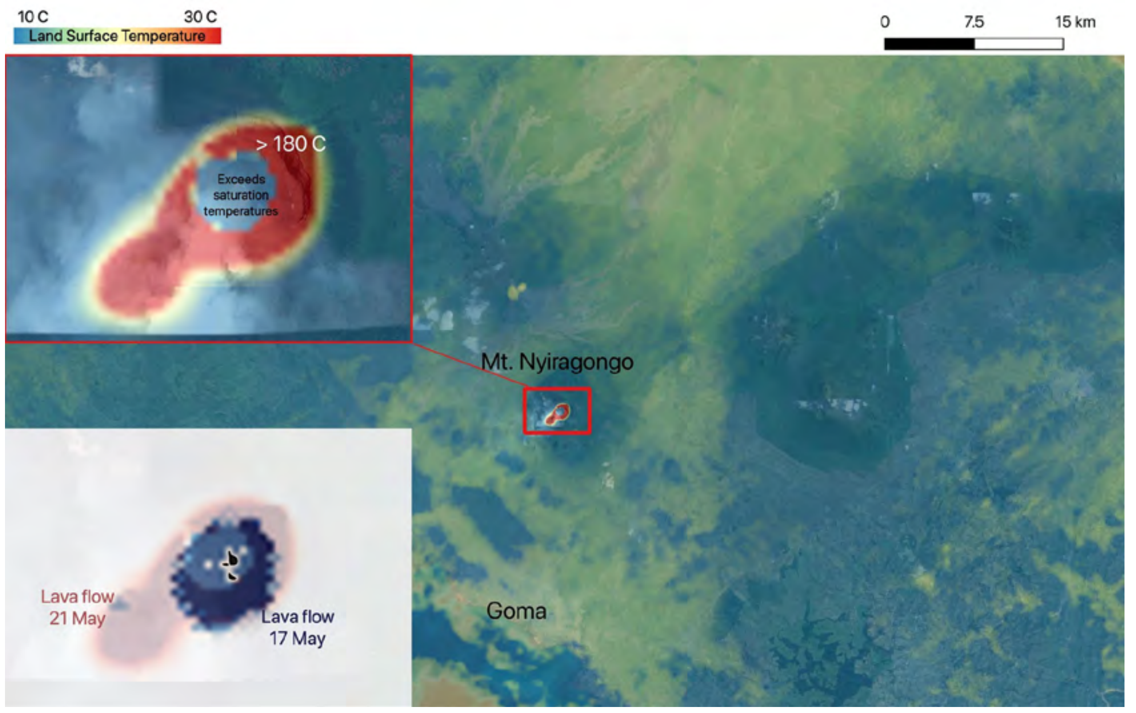

Figure 2: ECOSTRESS acquired data over Mount Nyiragongo, Democratic Republic of Congo, on 21 May 2021 hours before an eruption. In this image of land surface temperature the active lava pool is shown in red, and is substantially larger than the lava detected the week prior to eruption (inset).

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Airborne Thermal Infrared Hyperspectral Imaging for Mineral Mapping

GAGNON JEAN-PHILIPPE, BOUBANGA STEPHANE AND SAUTE BENJAMIN

Telops, Quebec City, Canada

Figure 1. Hyper-Cam Airborne Mini.

Summary

Minerals such as quartz, silicates, aluminosilicates (feldspar), magnesium silicates (serpentine) and olivines are among the most commonly encountered in the environment.

Airborne mineral mapping of these minerals using conventional visible-near infrared (VNIR, 0.4-1.4 μm) and shortwave infrared (SWIR, 1.4-3 μm) sensors can be very challenging since the Si-O bounds are featureless or exhibit very weak spectral features in these spectral ranges.

The fundamental vibrations associated with most functional groups composing the different ores mostly occurs in the thermal infrared (TIR, 8-12 μm) spectral range.

In order to illustrate the benefits of thermal infrared hyperspectral imaging (HSI) with an instrument like the new Hyper-Cam Airborne Mini (figure 1), we will focus on an airborne survey carried out over an open-pit mine in the Thetford Mines (Qc, Canada) area.

The results show how the high spectral resolution data provided by the Telops airborne system facilitates temperature emissivity separation (TES) and atmospheric correction in order to retrieve a thermodynamic temperature map of the area and its associated spectral emissivity datacube.

Mineral mapping of various minerals such as lizardite, serpentinite and quartz was achieved through linear unmixing of the emissivity data using reference emissivity curves found in spectral libraries.

Introduction - Mineral Mapping
The use of airborne remote sensing techniques to characterize mining environments offers many benefits as it allows coverage of large areas in a very efficient way.

Both visible-near infrared (VNIR, 0.4-1.4 µm) and shortwave infrared (SWIR, 1.4-3.0 µm) are well established techniques in this field.

In general, the reflectance spectral features measured in the VNIR and SWIR spectral ranges are overtones and/or combination bands from fundamental absorption bands of the longwave infrared (LWIR, 8-12 µm).

For this reason, the reflectance features measured by VNIR and SWIR sensors are typically broad and/or suffer from strong overlapping which raises selectivity issues for mineral identification in some cases. Since the spectral features associated with fundamental vibrations are stronger and sharper than their overtones, LWIR may also improve selectivity in certain situations.

In addition, the overtone signals of many minerals such as silicate (Si-O), feldspar (Al-O-Si) and olivine ($(Mg,Fe)_2[SiO_4]$) are too weak to give appreciable spectral features in the VNIR and SWIR.

As illustrated in Figure 2, these minerals are likely to be encountered in many environments and regions of the world as they result from the geological processes involving the first most abundant elements encountered on Earth.
Most silicates, aluminosilicates and magnesium silicate minerals such as quartz (SiO_2), feldspar (Na-feldspar, K-feldspar and Ca-feldspar), serpentine (Mg-O-Si, antigorite, chrysotile and lizardite), olivine (e.g. fayalite and forsterite) have strong absorption and emission bands in the LWIR spectral range.

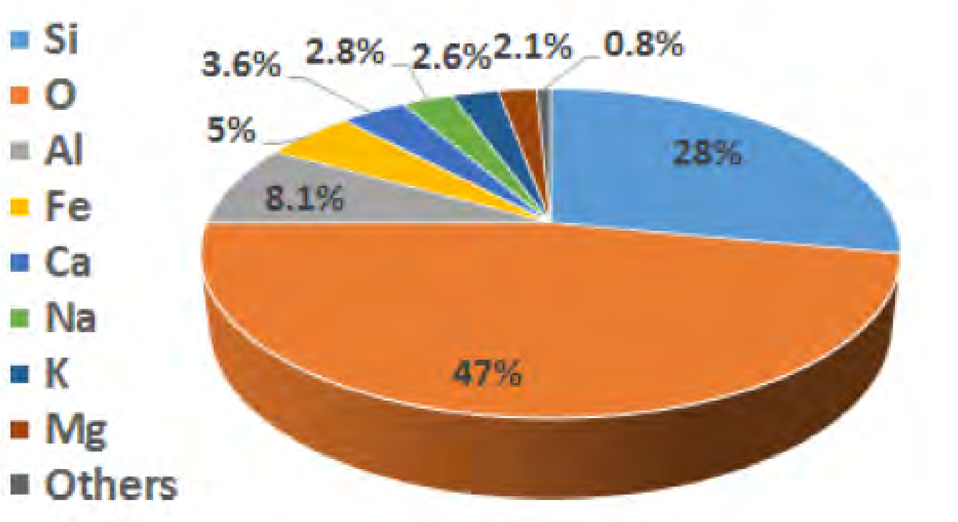

Figure 2. Natural abundance of elements in the Earth crust

In addition, other commonly encountered minerals such as carbonates (e.g. calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), phosphates (e.g. apatite) and sulfates (e.g. gypsum ($CaSO_4$) and alunite) also have important spectral features in the LWIR.

Therefore, LWIR presents itself as a method of choice for the characterization of minerals.

The inherent self-emission associated with LWIR under ambient conditions allows airborne surveys in various weather (cloudy, partly cloudy or clear sky) and illumination (day or night) conditions. For this reason, LWIR often refers to the thermal infrared (TIR) spectral range.

Therefore, in order to achieve efficient TES and atmospheric compensation, airborne hyperspectral data should preferably be collected at high spectral resolution in order to discriminate the sharp spectral features associated with gases from the broad infrared signal typically associated with minerals.

In order to illustrate the potential of airborne TIR hyperspectral imaging for mineral mapping, an airborne survey was carried out above an open-pit chrysotile mine (not in operation anymore) using the Telops Hyper-Cam airborne system, a passive thermal infrared hyperspectral sensor based on Fourier transform spectroscopy, which provides high spectral resolution data.

TES was carried out on the hyperspectral data in order to retrieve a thermodynamic temperature map and spectral emissivity data.

Spectral «unmixing» of the emissivity data was then carried out using the spectral signatures of selected minerals which were obtained from commercial spectral libraries.

Chemical maps of serpentine minerals (lizardite, serpentinite) and silicates (quartz) were obtained.

Experimental Information - The Telops Hyper-Cam Airborne Platform

All measurements were carried out using the Telops airborne platform. The newer version of the platform is the Hyper-Cam Airborne Mini (Figure 1 and Figure 3); a revolutionary infrared hyperspectral imaging system that couples high spatial, spectral and temporal resolution with advanced miniaturization engineering.

Designed to fit small aircrafts and other compact vehicles, this lightweight imaging sensor is a versatile tool for hyperspectral IR surveys,

Figure 3. Hyper-Cam Airborne Mini installed in a Piper Navajo aircraft collecting data.

The Telops Hyper-Cam features a focal plane array (FPA) detector containing 320 × 256 pixels over a pixel field of view of 750μrad.

In its airborne configuration, the spectral resolution is user-selectable up to 1 cm-1 over the 7.4 μm (1350 cm-1) to 11.8 μm (855 cm-1) spectral range. The Hyper-Cam Airborne Mini is equipped with a global positioning system (GPS) and an inertial motion unit (IMU) for geo-referencing and tracking of the aircraft movements in flight.

An image-motion compensation (IMC) mirror uses the GPS/IMU data to compensate efficiently for the aircraft movements during data acquisition since acquiring a full datacube typically lasts about one second.

The data includes all the relevant information for orthorectification and stitching. Visible images are simultaneously recorded along with the infrared data using a boresight CCD high resolution camera on the airborne platform.

Experimental Information - Flight Conditions During Mineral Mapping Data Collection Campaign

The flight was carried out above an open-pit mine in Thetford Mines (Canada) around 5 PM at an altitude of 3000 feet and a speed of 110 knots. A visible image showing different regions of the surveyed area (GPS position: 46.077304, -71.312765) is shown in Figure 4.

The mean ground elevation was in the order of 300 meters. Therefore, the average above ground level (AGL) was 800 meters leading to a ground pixel size of 1.25 m2/pixel.

A spectral resolution of 6 cm-1 was used which gives a total of 82 spectral bands equally spaced over the whole range covered by the FPA detector.

A total of 6 parallel flight lines were required in order to survey the whole area. Ambient temperature and relative humidity at ground level were 11 ˚C and 26 % respectively.

Figure 4. Airborne overview of the Thetford Mines area.

Experimental Information - Data Processing

Radiometric temperature maps were obtained by computing the mean values of each pixel put on a brightness temperature scale.

Temperature emissivity separation (TES) was carried out by solving (1) where L is the radiance measured at the sensor level, εv the target spectral emissivity, Dw the effective downwelling radiance on the target, $Ltarget$ the target's self-emission which is function of its thermodynamic temperature as described by the Planck equation, τatm is the atmospheric transmittance, and $Latm$ the radiance associated with TIR self-emission of all atmospheric components.

$$L = [Ltarget\ \varepsilon\bar{v}\ \ + Dw\ (1 - \varepsilon\bar{v}\ )]\ \tau atm + Latm\ (1 - \tau atm)$$

A smoothing criterion, similar to the one described in the work of Borel [5] was used to minimize both atmospheric and downwelling radiance contributions.

Radiometric temperature maps were obtained by calculating, for each pixel, the mean brightness temperature value over whole detector spectral range.

Chemical imaging was carried out by estimating the relative contributions (coefficients ,...) of the different components ($\varepsilon\bar{v}n$) within the overall spectral emissivity ($\varepsilon\bar{v}tot$), as shown in (2).

$$\varepsilon\bar{v}tot = A\varepsilon\bar{v}1 + B\varepsilon\bar{v}2 + C\varepsilon\bar{v}3 + \mathrm{D}\varepsilon\bar{v}n$$

Results and Discussions - Mineral Mapping

In order to retrieve spectral emissivity information and gather knowledge about the mineral composition of the ground, Eq.1 must be solved efficiently.

The same procedure was applied to all pixels in order to retrieve the two outputs from a TES algorithm: a thermodynamic temperature map and a spectral emissivity datacube.

The thermodynamic temperature map obtained upon TES is shown in Figure 5. As expected, most temperature values are higher than their corresponding brightness temperature values since the reflection of a cold irradiance source, i.e. the sky, and the atmospheric contribution have been accounted for.

The atmospheric absorption creates some kind of a systematic temperature offset in the radiometric temperature values. Since the TES procedure accounts for such effect, it is expected that thermodynamic temperature values are higher than their corresponding radiometric temperature values.

As expected, vegetation and water areas are cooler then the roads, the city areas and bare rock surfaces found in the mining and tailing pounds areas.

It can also be seen that the preliminary «thermal» contrasts seen on Figure 5, which were in fact emissivity contrasts, are also mitigated.

The spectral emissivity datacubes associated with the whole survey area contain the information about the mineral composition of the ground surface.

However, as no pure substances are commonly encountered in the environment, spectral unmixing must be carried out on the data in order to obtain chemical maps for individual minerals.

In order to achieve mineral mapping, the spectral emissivity datacube must be unmixed, i.e. one must estimate the relative contributions (coefficients ,...) of the different components (), associated with the different minerals, within the overall emissivity signal ().

Various strategies based on statistical, end-members, continuous wavelet analysis [4], or algebraic approaches can be used for the analysis of the emissivity data. In this case, a linear mixing approach was selected as expressed in (2).

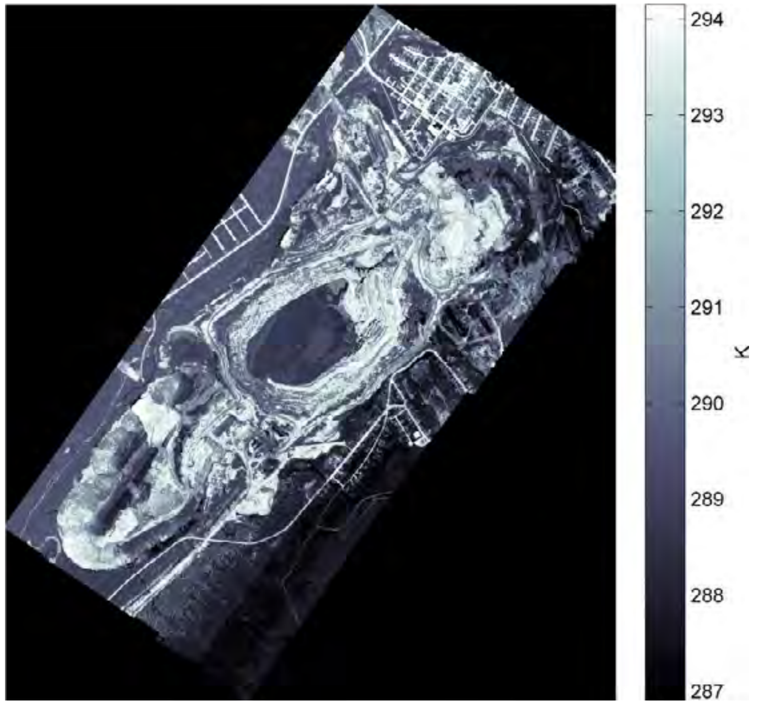

Figure 5. Thermodynamic temperature map as obtained after temperature-emissivity separation.

Linear unmixing of the spectral emissivity data was carried out using reference spectra from commercial libraries such as John Hopkins University (JHU), Jet Propulsion Laboratory (JPL) and United State Geological Survey (USGS). The component list comprised quartz (sand), calcite, lizardite, serpentinite (mostly antigorite) and magnesite (MgCO3), granite, feldspar and dunite (mostly olivines).

The spectral signature selection was carried out according to local geological information as well as recent work in a nearby area [7]. The reference spectra of a few minerals are shown in Figure 6 as well as the spectral emissivity data of the two selected locations retrieved by the TES procedure described earlier.

Reasonably good matches were obtained between the estimated spectral emissivity data (blue curve) and the best fit from Equation 2 (green curve) as seen in Figure 6.

Many factors can explain the disparities between the measurements and the fits such as the uncertainties in emissivity data retrieved from the TES algorithm or a mismatch between the encountered mineral

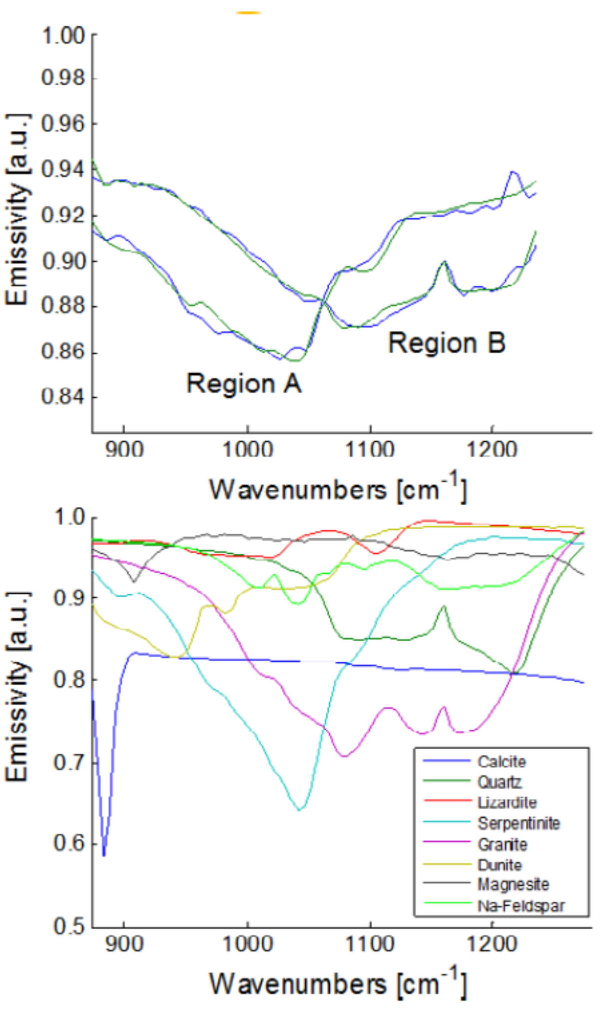

Figure 6. Spectral emissivity unmixing (top) of the signals associated with mining (Region A) and the road (Region B) areas. The blue curves correspond to the spectral emissivity curves obtained upon TES and the green curves correspond to the best fit of Eq.2. Reference spectra are shown (bottom) for comparison purposes.

polymorph and the one selected from the reference library.

Despite the uncertainties associated with the spectral unmixing approach used in this work, reasonable relative abundancies maps were obtained.

A thematic mineral map, derived from the main (highest relative abundancies coefficient) component obtained for each pixel is presented in Figure 7.

As expected, serpentinite and lizardite are highly located in the mining area and in the tailing pounds where the mining residues are stored. As expected, both minerals are also co-registered spatially since the chrysotile milling process does not include separation of these two components.

Dunite corresponds to bedrock, i.e. unaltered areas (incomplete or no serpentinization). Quartz spectral signature was exclusively detected outside of the mining area. Olivine and serpentine minerals are unlikely to be found associated with quartz minerals because of their different crystallisation processes.

Quartz is often encountered in soils, sand and used in the production of many materials such as concrete and asphalt.

Therefore, it is not surprising to obtain positive detection for quartz mineral in urban areas and roads [5]. The blank areas correspond to unstructured emissivity or undetermined components.

The water pond seen in the center portion of the mining area and the vegetation mostly behave like a grey body, i.e. have no spectral features and an emissivity lower than unity, making their detection based on spectral features very difficult in the TIR spectral range.

Conclusion

Airborne thermal infrared (TIR) hyperspectral data recorded at a high spectral resolution allows efficient compensation of atmospheric and sky reflection contributions in the measured radiance.

The spectral emissivity could be successfully unmixed using basic geological components expected to be found in the area. The chemical maps derived from the emissivity data are in good agreement with the expected results illustrating the benefits of airborne thermal infrared HSI for mineral mapping of silicate minerals.

In addition, the thermodynamic temperatures estimated from the TES algorithm emphasizes the temperature contrasts resulting from the higher concentration of high-emissivity materials found in urban areas.

The chemical map of quartz emphasizes the presence of man-made objects within the surveyed area. Combination of thermal and chemical information provides a better understanding of the relationship between man-made materials and UHI.

The results show that airborne TIR hyperspectral imaging (HSI) provides a valuable approach for the characterization of urban heat islands.

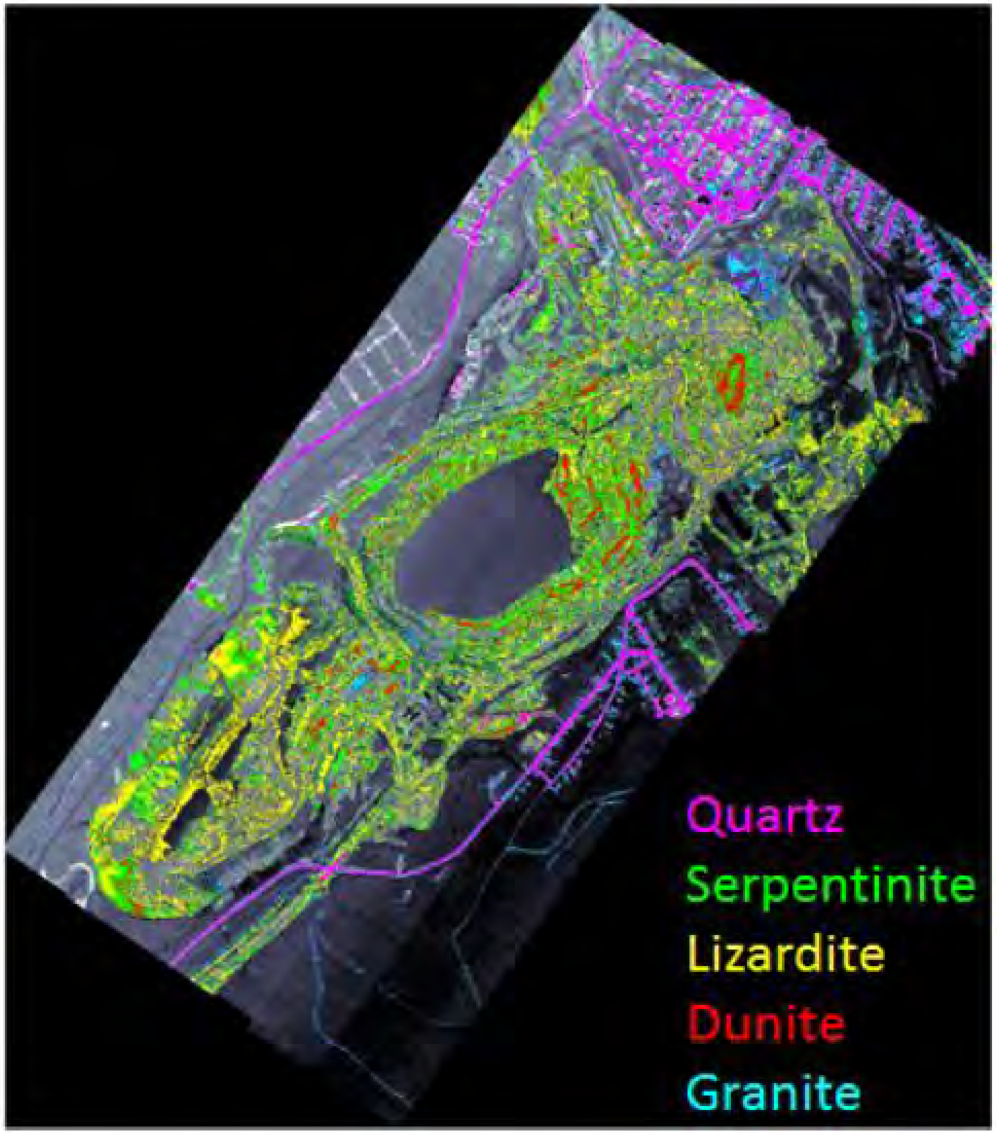

Figure 7. Thematic mineral map of the Thetford Mines area.

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