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Geological remote sensing

1. Introduction

Geology is defined as the 'study of the planet Earth – the materials of which it is made, the processes that act on these materials, the products formed, and the history of the planet and its life forms since its origin' (Bates and Jackson, 1976). Remote sensing has seen a number of variable definitions such as those by Sabins and Lillesand and Kiefer in their respective textbooks (Sabins, 1996; Lillesand and Kiefer, 2000). Floyd Sabins (Sabins, 1996) defined it as 'the science of acquiring, processing and interpreting images that record the interaction between electromagnetic energy and matter' while Lillesand and Kiefer (Lillesand and Kiefer, 2000) defined it as 'the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation'. Thus Geological Remote Sensing can be considered the study of, not just Earth given the breadth of work undertaken in planetary science, geological features and surfaces and their interaction with the electromagnetic spectrum using technology that is not in direct contact with the features of interest.

Remote Sensing has typically perhaps been more associated with satellite imagery yet there were a number of aerial systems in use during the 1940s and whilst their main mission was intelligence It also allowed us to capture wide areas of geological importance remotely. As such it is perhaps difficult to pinpoint the onset of 'geologic remote sensing science'. A keyword (topic) search on WebofScience© using 'geology' and 'remote sensing' returns 917 publications and a publication from 1966 as the first entry (Beckman and Whitten, 1966) while the first paper on geology using ERTS (Earth Resources Technology Satellite, now known as Landsat) data dates back to 1975 (Lawrence and Herzog, 1975). Some other of the early works include Baker (1975), Siegal and Abrams (1976) and breakthrough research produced by Alexander Goetz and Larry Rowan (e.g., Goetz and Rowan, 1981). Moreover early missions like SEASAT, specifically designed for oceanography, were also gaining traction in the field of geology for offshore imagery of oil slicks as early as 1978 (Evans et al., 2005).

However, the field greatly benefitted, in particular those working on optical remote sensing data, from the laboratory work that Graham Hunt (Hunt, 1977, Fig. 1) and John Salisbury (Salisbury et al., 1989) did on systematically analyzing diagnostic absorption features of all main mineral groups and rock types published in a journal called 'Modern Geology'. It is said that the band 7 of Landsat Thematic Mapper was added at a late stage of the sensor design to the Landsat Program in recognition of its use and benefit to the geological community and was lobbied for heavily. However, in doing so at this late stage, the numbering could no longer be changed hence the Thermal Infrared (TIR) band 6 features before the Short Wave Infrared (SWIR) band 7 in numbering despite its longer wavelength (Pers. Comm. Mike Abrams NASA −JPL).

Geologic remote sensing got another boost with the advent of ASTER (the Advanced Spaceborne Thermal Emission and Reflection Radiometer) in 1999. With 3 NIR (Near Infrared), 6 SWIR bands and an additional 5 TIR bands, ASTER provided the opportunity to undertake semi-quantitative mineral mapping and its forward and backward looking telescope also provided the possibility to create digital surface models. In 2005, a special issue was published in *Remote Sensing of Environment* on the use of ASTER data with the launch of this sensor considered a real milestone in space capability for the geological community (Gillespie et al., 2005).

Another milestone was the launch of the first hyperspectral instrument to image the Earth (there is also one for Mars) with Hyperion being launched on EO-1 (Earth Observing-1) in 2000. Hyperion was part of NASA's New Millennium Program and a test-bed to demonstrate spectroscopic measurements could be made from space. The sensor was really a proof of concept that relatively cheap technology could work. This had its downside in terms of complexity in preprocessing (Khurshid et al., 2006), limited signal to noise (SNR), inconsistent data quality and coverage. Yet it offered scientists the possibility to acquire imaging spectrometry data worldwide at limited cost with the data becoming publicly available in ~2008.

Since the 1980s geologists had been experimenting with field and airborne hyperspectral instruments such as NASA's AIS (Airborne Imaging Spectrometer) and AVIRIS (Airborne Visible and Infrared Imaging Spectrometer) systems, the Canadian CASI (Compact Airborne Spectrographic Imager) system and the commercial HyMAP series, but now hyperspectral data was available to all and not only to those that could afford commercial airborne campaigns or were part of science teams on airborne missions. A classic paper comparing Hyperion data to airborne data was written by Fred Kruse (Kruse et al., 2003, Fig. 2). As we prepare this special issue, EO-1 and as such Hyperion, intended only to last a year, came to the end of its service in March 2017–17 years after launch and having achieved so much more than it was ever intended. In particular this mission allowed the thorough testing of the 13 new instruments on board with collection autonomy not seen on other satellites, as well as milestones such as detecting the first methane leak from a facility from space. Whilst powered down it will remain in orbit until 2056.

For further reading there are a number of review articles that show the history and development of geologic remote sensing (Cloutis, 1996;

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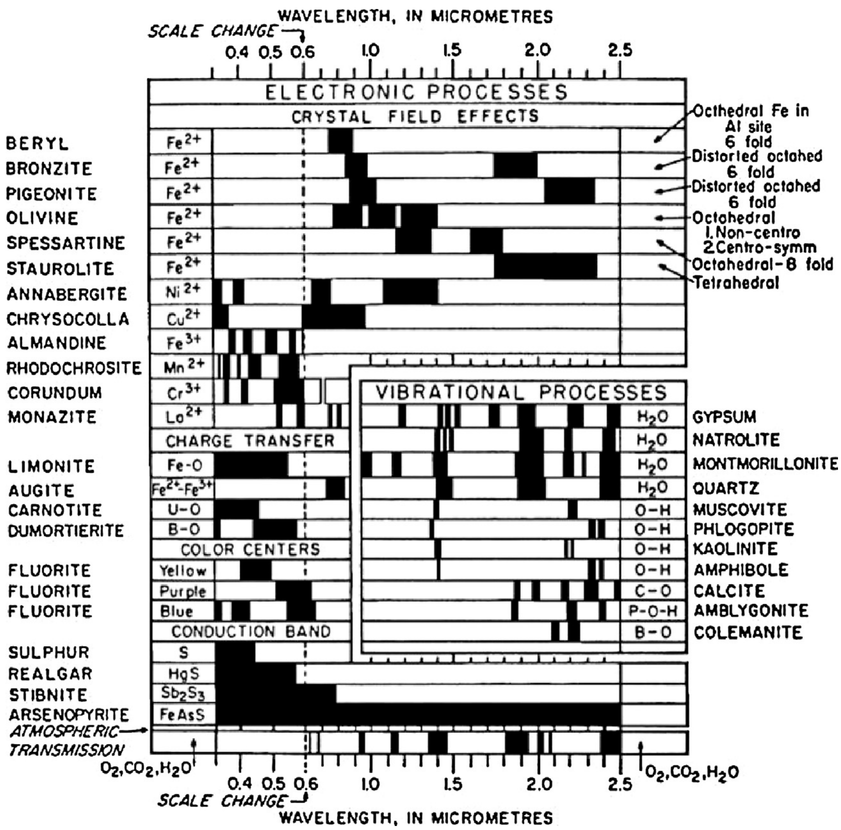

Fig. 1. Spectral signature diagram outlining the effects observed from electronic and vibrational processes in various minerals measured in the laboratory (after Hunt, 1977).

Buckingham and Staenz, 2008; Sabins, 1999; Goetz, 2009; Van Der Meer et al., 2012; Asadzadeh and Souza Filho, 2016).

So far this introduction has focused mainly on optical passive remote sensing, but there is also a vast community of geologists working with radar, also known as Synthetic Aperture Radar (SAR) data. This technology, prevalent since the early 1990s, has a number of advantages as an active

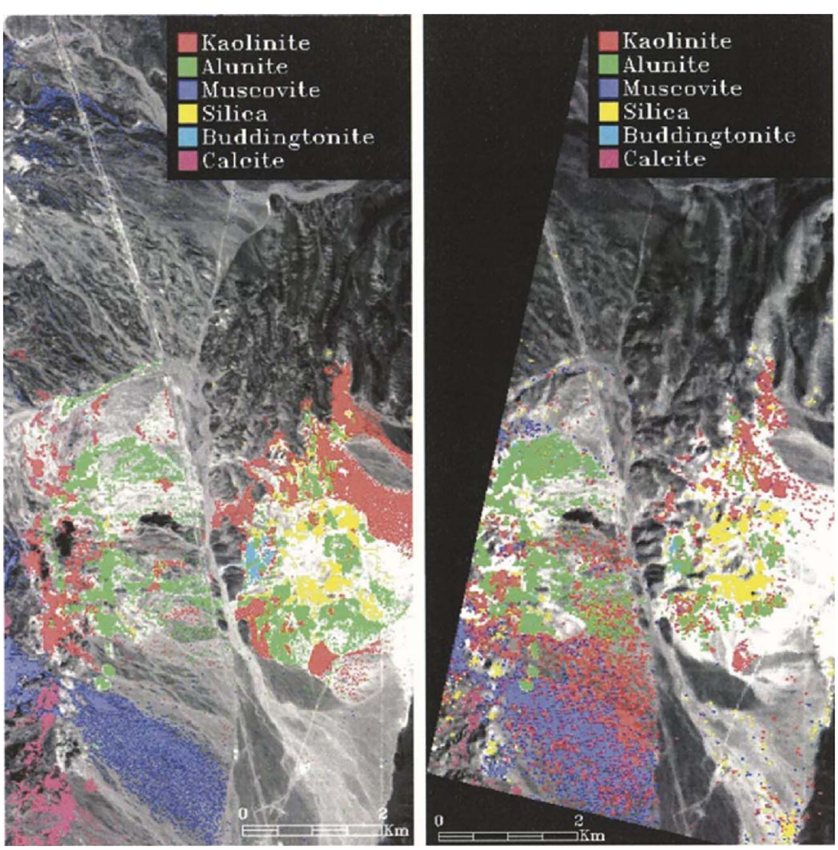

Fig. 2. Mineral maps for (left) AVIRIS and (right) Hyperion across Cuprite NV, USA. Coloured pixels show spectrally predominant mineral at concentrations greater than 10%. After (Kruse et al., 2003).

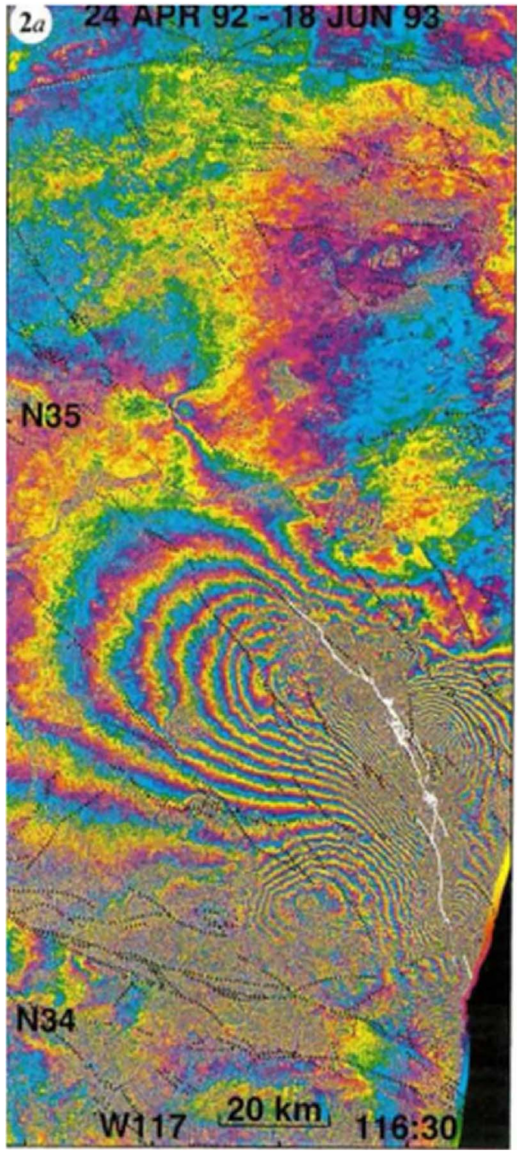

Fig. 3. Interferograms from ERS-1 (European Remote Sensing satellite) of the area around the 1993 Landers Earthquake. (After Massonet et al., 1994).

sensor. It allows images to be taken both day and night and even through clouds. This opens up the applications whilst also providing significant challenge and difficulty in processing and understanding such data for the non-specialists. Its side looking view of the world causes effects that could trigger confusion when mapping. That being said, one of its main uses, as seen with SEASAT in the late 1970s, was to look at the oceans. The clear differentiation between the sea surface and features such as oil spills, coupled with its all-weather viewing capability, enhanced its use for mapping and monitoring such phenomena and provided the Oil & Gas industry the opportunity to screen and assess their license blocks in a cost-efficient way.

However, perhaps an even more important capability of SAR was its ability to monitor ground motion through a technique called interferometry. The classic paper by Didier Massonnet and co-authors on deformation related to the Landers earthquake in 1993 started a wave of research on deformation monitoring using radar interferometry (Massonnet et al., 1994; Massonnet and Feigl, 1998, Fig. 3). Many studies appeared on earthquake dynamics (Delouis et al., 2002; Jonsson et al., 2002; Walters et al., 2009), subsidence related to groundwater extraction (Galloway and Burbey, 2011) and mining (Gourmelen et al., 2007), deformation of volcanoes (Fernandez et al., 2003; Pritchard and Simons, 2004; Yun et al., 2006), landslides (Colesanti and Wasowski, 2006; Hilley et al., 2004), carbon sequestration (Worth et al., 2014) and the surface deformation associated with enhanced oil recovery (Liu et al., 2015) and studies on geothermal systems (Lubitz et al., 2013).

More recently it has been demonstrated that such measurements are also possible from optical data to some degree with software like COSI-CORR, which was developed from research out of Caltech, USA correlating data to sub pixel precision enabling small deformations to be monitored between images (Leprince et al., 2007a, 2007b).

Geologic remote sensing has not been confined to studies of the Earth as alluded to above. There is a large community studying the geology of various planets such as the Moon (Pieters et al., 2009), Mars (Bandfield, 2002), and Venus (Saunders et al., 1991). For example, studies of Mars have focused on early life forms, water on Mars, surface mineralogy in relation to weathering and (or) hydrothermal processes using data from HiRISE (Mcewen et al., 2010), Crism (Ehlmann et al., 2009; Flahaut et al., 2010; Murchie et al., 2007; Mustard et al., 2008; Pelkey et al., 2007), OMEGA (Bibring et al., 2005; Mustard et al., 2007) and TES (Christensen et al., 2001).

Geological remote sensing science has found its way more into daily commercial practice yet it isn't as fully embedded across the different markets as some research may suggest. Kruse in 2012 (Kruse, 2012) and Sabins in 1999 (Sabins, 1999) suggest that this is firmly embedded into

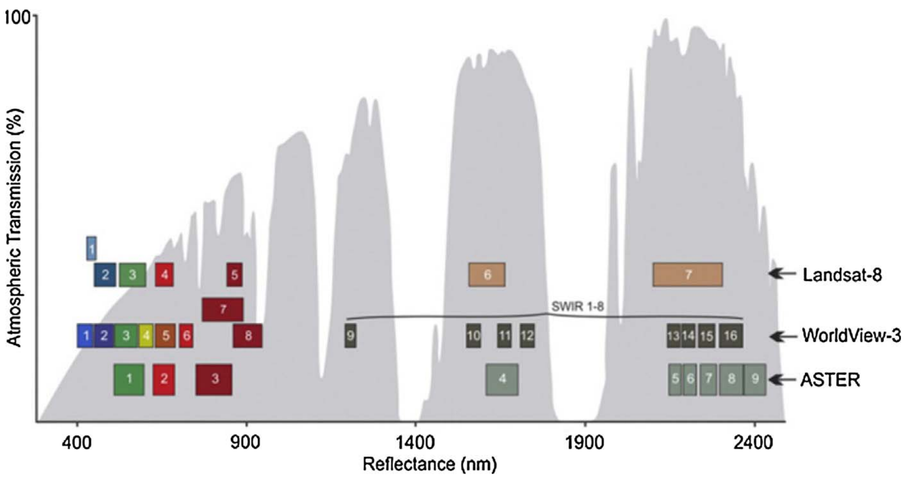

Fig. 4. Comparison of Worldview-3 spectral bands with ASTER and Landsat 8. Bars represent the full width half maximum (FWHM) coverage of each numbered band. After Asadzadeh and de Souza Filho 201.

exploration practices of major mining corporations, yet in reality this is rarely the case. It is now well used across mining, Oil&Gas and beyond; however, it is not yet part of the overall workflow for all organisations, largely due to a limited understanding of capability, value and fear of complexity of using such data.

That being said though there are numerous instances that we can refer to highlight the value for oil and gas exploration through studies of onshore and offshore oil slicks and seeps as proxies to the presence of petroleum reservoirs (Lammoglia and Souza Filho, 2011; Hodgetts, 2013; Scafutto and Souza Filho, 2016; Asadzadeh and Souza Filho, 2017) and more recently we see studies of geothermal systems (e.g., Van Der Meer et al., 2014a) linking geologic remote sensing to sustainable energy production, energy transition and climate change studies.

There are also a number of recent trends and developments in geological remote sensing to be mentioned. In particular, outcrop scanning (Kurz and Buckley, 2016; Hodgetts, 2013) is an interesting way of bridging the resolution gap in remote sensing from point based measurements to airborne and spaceborne acquisitions, which also brings the remote sensing community closer to the traditional geology community who rely on field studies of outcrops for regional geologic interpretations. Another development is hyperspectral core logging which adds a wealth of instant observations to traditional studies of mineral prospectivity (Tappert et al., 2011, 2015; Turner et al., 2017), sedimentology (Speta et al., 2016; Shchepetkina et al., 2017), ore grading (Speta et al., 2015). Finally, it is important to mention efforts to produce continent-wide (and potentially global) maps of seamless geology such as those undertaken by CSIRO (Cudahy et al., 2016) and USGS (Rockwell et al., 2015).

Recent years have seen the launch of a number of new satellite missions that the remote sensing community is or has deployed for studying the Earth where there is specific functionality of importance to the geologic community. For example, DigitalGlobe's Worldview 3 (Kruse and Perry, 2013) which has some similar spectral capabilities to ASTER but at four times enhanced spatial resolution (Fig. 4). In addition it is also important to note the European Space Agency (ESA) Sentinel Missions (both SAR and Optical), Sentinel-1 (Torres et al., 2012) and the Sentinel-2 mission (Van Der Meer et al., 2014b) and we are preparing ourselves for the data from the German EnMAP (Environmental Mapping and Analysis Program) mission (Stuffler et al., 2007) and possibly NASA's HyspIRI (Hyperspectral Infrared Imager) (Lee et al., 2015). This of course does not preclude the use of other missions to support geological applications with vast amounts of data now being collected from constellations such as those of Planet, other high-resolution datasets including (but not limited to) those of Airbus, KARI, 21AT as well as SAR constellations like Cosmo-Skymed, ALOS and the soon to be launched Radarsat Continuity Mission constellation of 3 high resolution SAR sensors.

Within this context we prepared the Special Issue on Geologic Remote Sensing for the International Journal of Applied Earth Observation and Geoinformation. This Special Issue stems from various meetings of the Geological Remote Sensing Group (GRSG; see below). The idea was launched at the 26th Annual Conference of GRSG on 'Challenges in Geological Remote Sensing' held in December 2015 at the ESA ESRIN facility in Frascati (Italy). In this Special Issue we aim to cover a wide range of Geological Remote Sensing including terrestrial Earth analogues studies as well as planetary studies.

2. The Geological Remote Sensing Group

The Geological Remote Sensing Group (GRSG) is a special interest group of the Geological Society of London and the Remote Sensing and Photogrammetry Society (RSPSoc) and was established in 1989. Whilst formed in the UK, it is a truly international organization with corporate, academic and student members from across the world working within the breadth of remote sensing using satellite, aerial and hand held spectral systems for geological applications. The broad field of geology is well catered for with representation from within mining, national geological surveys, national space agencies, Oil&Gas, image processing/analytics specialists, data/software suppliers to academic institutions. The group is headed up by a voluntary committee lead by Charlotte Bishop as incumbent Chairman since December 2016. Each year the GRSG holds its annual conference in either London or another location focusing on a specific yet relatively broad theme. The focus of which is a technical programme coupled with networking/social events with the group being considered one of a kind and many see the GRSG as one of the few places to share not just scientific research but also commercial applications in such a way that is largely unrivalled in the industry. It is with great pleasure that the GRSG has been able to support this Special Issue.

3. The special issue

The following topics are addressed in this special issue on Geological Remote Sensing.

SWIR geological remote sensing:

- Mapping alteration using imagery from the Tiangong-1 hyperspectral spaceborne system: example for the Jintanzi gold province, China by Lei Liu, Jilu Feng, Benoit Rivard, Xinliang Xu, Jun Zhou, Ling Han, Junlu Yang and Guangli Ren.
- Hyperspectral remote sensing applied to mineral exploration in southern Peru: a multiple data integration approach in the Chapi Chiara gold prospect by Thais Andressa Carrino, Alvaro Penteado Crósta, Catarina Labouré Bemfica Toledo and Adalene Moreira Silva.
- Application of visible and infrared spectroscopy for the evaluation of evolved glauconite by Shovan L. Chattoraj, Santanu Banerjee, Freek van der Meer, P.K. Champati Ray.

LWIR-TIR geologic remote sensing:

- Evaluation of Thermal Infrared Hyperspectral Imagery for the Detection of Onshore Methane Plumes: Significance for Hydrocarbon Exploration and Monitoring by Rebecca Del Papa Moreira Scafutto, Carlos Roberto de Souza Filho, Dean N Riley and Wilson José de Oliveira.
- Mapping Rock-forming Minerals at Boundary Canyon, Death Valley National Park, California, using Aerial SEBASS Thermal-infrared Hyperspectral Image Data by Dean Riley, Zan Aslett and James V Taranik.

Synergy of TIR and SWIR geologic remote sensing:

• Comparison of lithological mapping results from airborne hyperspectral VNIR-SWIR, LWIR and combined data by Jilu Feng, Derek Rogge, and Benoit Rivard.

Lunar geologic remote sensing:

- Comparing experts and novices in Martian surface feature change detection and identification by Jessica Wardlaw, James Sprinks, Robert Houghton, Jan-Peter Muller, Panagiotis Sidiropoulos, Steven Bamford and Stuart Marsh.
- VenSAR on EnVision: taking Earth Observation radar to Venus by Richard C. Ghail, David Hall, Philippa J. Mason, Robert R. Herrick, Lynn M. Carter and Ed Williams.

Weathering and geological remote sensing:

• Regolith-geology mapping with support vector machine: a case study over weathered Ni-bearing peridotites, New Caledonia by Florian De Boissieu, Brice Sevin, Thomas Cudahy, Morgan Mangeas, Stéphane Chevrel, Cindy Ong, Andrew Rodger, Pierre Maurizot, Carsten Laukamp, Ian Lau, Touraivane, Dominique Cluzel and Marc Despinoy.

InSAR geological remote sensing:

• Using PS-InSAR to Detect Surface Deformation in Geothermal Areas of West Java in Indonesia by Yasser Maghsoudi, Freek van der Meer, Christoph Hecker, Daniele Perissin, and Asep Saepuloh.

Below we summarize the main highlights of these contributions.

In their paper 'Evaluation of Thermal Infrared Hyperspectral Imagery for the Detection of Onshore Methane Plumes: Significance for Hydrocarbon Exploration and Monitoring' Del Papa Moreira Scafutto et al. (Del Papa Moreira Scafutto et al., 2017) investigate the potential of detecting methane plumes using airborne thermal infrared remote sensing. These plumes may arise from leakages of pipelines carrying hydrocarbons but they could also potentially be related to natural leakage of subsurface oil and gas reservoirs. At the Rocky Mountain Oilfield Testing Center (RMOTC), Casper, WY (USA) the authors prepared various experiments to simulate leakage in the field. The leaks are overflown with the SEBASS (Spatially-Enhanced Broadband Array Spectrograph System) and data processing and analysis shows regions with higher gas density and interpretation allowed to locate the actual source of the leakage in the field accurately.

In their paper entitled 'Mapping Rock-forming Minerals at Boundary Canyon, Death Valley National Park, California, using Aerial SEBASS Thermal-infrared Hyperspectral Image Data' Riley and co-authors (Riley et al., 2017) also use SEBASS data for geologic mapping in a sedimentary terrain including quartz-rich sandstone, quartzite, conglomerate, and alluvium; muscovite-rich schist, siltstone, and slate and carbonate-rich units. The study shows the potential of longwave thermal infrared data for geologic mapping in sedimentary terrains where shortwave data usually fails to delineate units.

Another classic paper on the use of hyperspectral data for mineral exploration is presented by Liu et al. (Liu et al., 2017): 'Mapping alteration using imagery from the Tiangong-1 hyperspectral spaceborne system: example for the Jintanzi gold province, China'. These authors for the first-time show results from the Chinese Tiangong-1 Hyperspectral Imager, which is a new spaceborne hyperspectral remote sensing system launched on September 29th 2011. The system has 64 SWIR bands and a spatial resolution of 20m. Tiangong-1 data and the resulting mineral maps are compared to maps of the SASI system (Shortwave infrared Airborne Spectrographic Imager) for the Jintanzi area, Beishan, Gansu province, northwest China where gold bearing veins are known from field exploration.

In their paper 'Comparison of lithological mapping results from airborne hyperspectral VNIR-SWIR, LWIR and combined data' Feng and co-authors look at the synergy for geologic mapping of Airborne Hyperspectral Imaging Systems (AISA) VNIR-SWIR data and Spatially Enhanced Broadband Array Spectrograph System (SEBASS) longwave infrared (LWIR) data in the subarctic region area of Cape Smith Belt, Nunavik, Canada (Feng et al., 2017). The area is regionally metamorphosed to lower greenschist facies and mafic, ultramafic and sedimentary rocks are exposed, however, with severe lichen coatings which complicates the analysis and interpretation. Continuous wavelet analysis (CWA) is used to improve the radiometric quality of the imagery, minimizing noise and enhancing spectral features. Iterative spectral unmixing approaches are used to prepare mineral maps that compare favorably to published geologic maps.

Wardlaw and co-authors (Wardlaw et al., 2017) in their contribution to the special issue entitled 'Comparing experts and novices in Martian surface feature change detection and identification' look at change detection mapping using satellite data from Mars. The paper centers on the hypothesis that novices can map changes in different geomorphological features as well as experts do that. They develop an online tool that allows experts and novices to look at multiple images of the same site and do an interpretation. The analysis shows that the two groups, novices and experts, both were equally capable of identifying objects; however, there were significant differences in the way these two groups would classify these changed targets into changes as dust devil tracks, slope streaks, impact craters and other features.

Venus is known to bet the most 'Earth-like' planet and is the object of study in the paper 'VenSAR on EnVision: taking Earth Observation radar to Venus' by Ghail and colleagues (Ghail et al., 2017). EnVision is ESA system proposed for orbiting Venus carrying the Venus Emission Mapper (VEM), the Subsurface Radar Sounder (SRS), and the VenSAR, a phased array synthetic aperture radar. This paper explores the potential of synergistic use of these data sets to unravel the geology of Venus.

De Boissieu and colleagues (Boissieu et al., 2017) studied 'Regolith-geology mapping with support vector machine: a case study over weathered Ni-bearing peridotites, New Caledonia'. Surface regolith is in many areas of exploration very thick and blankets the underlying host rocks that are the actual exploration target. Most remote sensing studies simply avoid looking at these areas with thick regolith, but in this study the authors chose to use airborne hyperspectral data over a weathered and vegetated peridotite sequence to explore how much information could be extracted on the host rock by characterizing the regolith. Support vector machine techniques are used to map serpentine mineralogy, which is the typical weathering product of olivine-rich strata such as peridotites. Also, secondary iron oxides and hydroxides (hematite and goethite) are mapped as a proxy for laterite development. The final classified regolith map was assessed against interpreted regolith field sites showing good similarity.

The paper 'Hyperspectral remote sensing applied to mineral exploration in southern Peru: a multiple data integration approach in the Chapi Chiara gold prospect' by Andressa Carrino and co-authors (Carrino and Crósta, 2017) is a classic paper on geologic remote sensing in a hydrothermal system. The Chapi Chiara is a epithermal system and the authors characterize the system by looking at assemblies of high sulfidation minerals integrating airborne hyperspectral HyMAP data with petrography, XRD analysis and magnetic data. Their interpretation shows that the advanced argillic alteration zones are controlled by regional NW-SE trending structure.

In the paper 'Application of visible and infrared spectroscopy for the evaluation of evolved glauconite' Chattoraj and colleagues (Chattoraj et al., 2017) study spectra of glauconite minerals from the Oligocene Maniyara Fort Formation in western India. There are two distinct types of glauconite representing two distinct maturation stages of these sedimentary sequences, which are characterized by their spectral response in the visible to infrared spectrum of electromagnetic radiation. The study shows a correlation between the proportion of expandable layers in the glauconite structure and the absorption band wavelength position, which allows to link spectroscopy to maturation state of glauconite.

In the contribution 'Using PS-InSAR to Detect Surface Deformation in Geothermal Areas of West Java in Indonesia' Maghsoudi and co-workers (Maghsoudi et al., 2017) look at enhancement of surface deformation related to geothermal exploration in two exploration sites (Patuha and Wayang Windhu) in Java, Indonesia. Use of the Persistent Scatterer InSAR (PS-InSAR) technique allows to monitor ground deformation in and around the injection and production wells. Time-series of ALOS PALSAR and Sentinel-1A acquisitions are combined to cover the time frame of 2007, 2009, 2015 and 2016. The performance of the ALOS data is also compared to Sentinel-1A to look at data continuity issues of these SAR systems that deploy different wavelengths. It is shown that uplift was observed around the only available injection well in the area.

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Charlotte Bishop*, Benoit Rivard, Carlos de Souza Filho, Freek van der Meer
Terrabotics Ltd, Vintage House, 37 Albert Embankment, London, UK
Department of Earth and Atmospheric Sciences, 1-26 Earth Sciences Building, University of Alberta, Edmonton, AB, T6G 2E3, Canada

Institute of Geosciences, University of Campinas (UNICAMP), PO Box 6152, 13083-970, Campinas, SP, Brazil
University of Twente, Faculty Geo-information and Earth Observation (ITC), Department of Earth Systems Analysis, Enschede, The Netherlands
E-mail address: charlotte@tbotix.com

* Corresponding author.