Hyperspectral imaging of sedimentary iron ores – beyond borders

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SUMMARY

Banded iron formations (BIFs) and granular iron formations (GIFs) are the two primary types of sediment hosted iron ore deposits and provide the primary source for iron, globally. Although both deposit types are comprised of bedded chemical sediments and chert layers, these deposits show notable differences in mineralogy and texture which can affect grade and processing behaviour.

Hyperspectral imaging technology is able to map key iron ore minerals as well as the textural relationships between these minerals. This paper presents a case study comparing the mineralogy and texture of two distinct iron ore regions across the globe from one another: the Biwabik Iron Formation in Minnesota, U.S.A. (GIF) and the Pilbara Region in Western Australia (BIF). Using hyperspectral imaging data, the mineralogy and texture of these two distinct regions are compared to one another and to traditional iron ore characterisation from core logging. The results show that hyperspectral imaging technology is a useful tool in mapping the mineralogical, textural, and grade characteristics of both BIFs and GIFs. The application of this technology in the iron ore industry would provide rapid, accurate, and cost-effective ore characterisation to meet the ever-increasing production demand.

Key words: hyperspectral imaging, iron ore, BIFs, GIFs, mineralogy

INTRODUCTION

Iron (Fe) is one of the most abundant elements on Earth, and one of the earliest mineral resources to have been mined. While the earliest civilizations exploited iron stones and bog iron ores, sediment hosted iron ore is today the main source of mined iron (90%), and iron formations (such as banded iron formations or BIFs and granular iron formation or GIFs) the main types of sediment hosted deposits.

These sequences can be found all over the world in Australia, Brazil, Canada, China, Greenland, India, Namibia, South Africa and the U.S.A. They were formed at different periods of time throughout the Precambrian Eon with limited occurrences around 3.8 Ga (Greenland) and 0.7 Ga (Canada) and a significant increase in occurrences between 3.5 and 2.0 Ga with a maximum number occurring at 2.5 Ga (Australia). In the North American classification, a distinction is made between the Algoma (3.5-3.0 Ga), Lake Superior (2.5-2.0 Ga) and Rapita (1.0-0.5 Ma) types. These divisions, which are both temporal and geographic, are hard to apply to other formations outside of North America. As a result, a relatively simple textural classification is more often used that divides the BIFs from the GIFs. Despite their different textures, BIFs and GIFs share the same DNA: a bedded chemical sediment made of iron-rich and chert layers (macro-, meso- and microbanding) (Ramanaidou and Wells, 2014). Post-depositional metamorphism is common, with diagenetic to low-grade reactions for the GIFs (with additional regional metamorphism) and diagenetic to low-grade to medium-grade reactions for the BIFs (with varying degrees of deformation). The resultant mineralogy comprises an exhaustive list such as (from diagenetic to medium-grade): chert, magnetite, quartz, hematite, greenalite, and stilpnomelane (Klein, 2005). Fe-chlorite, dolomite, calcite, ankerite, siderite, riebeckite, and cummingtonite-grunerite can also be seen in both types of formations.

Understanding iron ore mineralogy is important. In the last 16 years, Chinese iron ore imports have risen by a factor of 14.6 from 70 million tonnes in 2000 to 1.02 billion tonnes in 2016 (source www.afr.com). This increase, largely driven by demand for high-quality iron ore, has resulted in a more demanding production environment. In order to meet this demand, iron ore companies need to invest in innovative technologies that are more accurate, cost-effective, and fast. One pinch-point has always been the speed and consistency of manual core logging, which is still a laborious and time-consuming process. The number of BIF/GIF minerals combined with their fined-grained character make the mineralogy challenging to identify. Core logging is even more arduous in Australia, where iron deposits are typically far more weathered than those in North America.

In response to these demands, hyperspectral technology has been successfully implemented over the last decade, using either a line or imaging spectrometer in the VNIR-SWIR (Visible Near-InfraRed – Shortwave InfraRed) range (450 nm to 2500 nm).

This technology is also able to characterise the gangue mineralogy which can drastically impact the grade quality and behaviour of the ore material in the processing plant (Duuring and Laukamp, 2017; Ramanaidou et al., 2008). Hyperspectral imaging system such as the Corescan’s Hyperspectral Core Imager-3 (HCI-3) provides detailed mineralogical characterisation with a pixel resolution of 500 μm. Individual mineral images alongside texture map images allow better definition of these iron formations which are made of bands from the centimetre to micrometre scale with complex and variable gangue mineralogy.

This present study will showcase the application of the HCI-3 system to two different iron formations: North-American GIFs from the Biwabik Iron Formation in Minnesota, and Australian BIFs from the Hamersley Province in the Pilbara Region of Western Australia (with derived enriched ores from the Hamersley Province). The goal is to demonstrate...
Hyperspectral imaging is a useful tool in the mineralogical and grade characterisation of BIFs/GIFs. For the North American GIFs, the interpreted hyperspectral mineralogy (including iron oxides, carbonates, silicates, iron silicates, brittle micas, micas and amphiboles) strongly correspond with the mineralogy described in site core logging as well as in studies by Jirsa et al. (2008) and the “Rosetta Stone” stratigraphy reported by Severson et al. (2009). As an example, Severson et al. (2009) identified up to 25 “Rossetta” units to define the stratigraphy of the Biwabik Iron Formation in Minnesota, U.S.A.. They identified a shared set of “Rosetta” Mesabi Range based on stratigraphic features, rather than on mineralogy. Using this technology, distinct zones of minnesotaite and talc were identified within a same stratigraphic unit.

The hyperspectral dataset also allowed for the detection of previously unreported ammonium-rich illite/white mica, as well as variations in the composition of carbonates (Ca-, Fe- and Mg-rich), chlorites and micasilicates. North American GIFs or “taconite” mines are currently mining low-grade deposits which result in the production of pellets. Using high spatial and spectral resolution hyperspectral technology, martite-rich bands were able to be differentiated from the more magnetitic bands which is very useful for the mines as the magnetite/martite content is critical for pellet production.

The 500 μm spatial resolution of the HCI-3 system facilitates the imaging of the deformed microbands characteristic of the Australian BIFs from the Pilbara craton. They exhibit similar low-grade metamorphic mineralogy compared to their younger North American “cousin” including calcite, chert, chlorite, jasper, hematite, magnetite, quartz, siderite and stilpnomelane. In contrast, Australian BIDs or Bedded Iron Deposits (enriched BIF ores) far outweigh the BIFs in terms of reserves and total production because of the intense weathering suffered by these formations in the Australian climate. This ore material necessitates a different ore processing scheme with the production of lumps and fines. By combining crystal field absorption features of the different iron oxide species with spectral ratios, resulting iron ore texture maps can assist in the characterisation and dating of the ore grade quality of the complex enriched BIFs (or BIDs, Bedded Iron Deposits) from the Hamersley Province. Differentiation between ochreous and vitreous type goethite was possible using an algorithm developed by Haest et al. (2012b) which has important implications for lump/fines ratio and lump quality. Combining the observations from these various hyperspectral products can assist iron ore companies in characterising and producing high quality iron ore.

**RESULTS**

Mineral class maps were created using the interpreted mineralogy form the hyperspectral imaging dataset. These maps display the mineralogy as well as the textures for both the Biwabik Iron Formation drillholes and the Hamersley Province drillcore. Figure 2 shows the mineral class maps for the North American GIF data set alongside a close up of the coarse and granular character of the banding textures well captured by the hyperspectral imaging system. The hyperspectral mineralogy correlates well with the mineralogy reported by Jirsa et al. (2008).

Thanks to the high resolution of the hyperspectral imaging system, the mineralogy and textures of Australian fined-banded iron formations are well highlighted by the resulting mineral class map (Figure 3). Hyperspectral imaging is also a powerful tool in the ore grade/quality characterisation. By using a combination of absorption feature extraction, spectral ratio and spectral match algorithms, martite-rich bands can be differentiated by more primary magnetitic bands in the American GIFs (Figure 4). This differentiation can then assist mining companies in pellet production as the magnetite/martite ratio is a critical parameter. The right side of figure 4 illustrates an example where the mineralogy within a stratigraphic Rosetta Unit can be quite variable as highlighted by the mapping of talc and minnesotaite. One of the primary objectives of the MDNR analysis the Biwabik Iron Formation drillholes was to track distinctive mineralogy in the Rosetta Stone Units. Figure 4 highlights the ability of this technique to successfully map key mineralogical changes in these rocks.
Additional observations, such as variations in the iron content of carbonate from dolomite/siderite to ankerite/calcite, were investigated using hyperspectral composition images. Undocumented occurrences of NH4-Illite/White Mica were also noted in drillholes LWD-9-2 and MGS-8.

Finally using algorithm from Haest et al. (2012b) and Ramanaidou and Wells (2008) respectively, a rapid and consistent tracking of the ochreous/vitreous goethite content as well as the hematite/goethite ratio has been achieved in Australian BID cores from various locations in the Hammersley province (Figure 5).

CONCLUSIONS

Hyperspectral imaging technology is a powerful tool to characterise the mineralogy of two distinct iron ore regions from the Biwabik Iron Formation in Minnesota, U.S.A. and from the Pilbara region in Australia. The numerous and complex mineralogical characteristics of these formations were successfully identified using hyperspectral match images and mineral class maps.

Using a combination of absorption feature extraction, spectral ratios, spectral match algorithms and specific algorithms from the literature, the HCl-3 system is able to assist in the characterisation of the ore grade/quality which is specific to each studied iron formation.

The application of this technology in the iron ore industry would provide rapid, accurate, and cost-effective ore characterisation to meet the increasing production demand. Future work on the mapping of maghemite (product of topotactic oxidation of magnetite) is currently being undertaken as it is a critical parameter in the production of pellets.

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Figure 2. Mineral class map created for the GIFs data set (left) – Close-up of the mineral class map image (0.04 m width) within a 1.2’ long section of whole core from LWD-99-2.

Figure 3. Mineral class map created for the BIFs data set (left) – Close-up of the mineral class map image (0.04 m width) within a 0.5 m long section of whole core located in the Pilbara craton.

Figure 4. Left: Hyperspectral match images (0.04 m width) of martite-rich bands and magnetite-rich bands – Right: Mineral class map image (0.04 m width) displaying mainly talc (light green) and minnesotaite (light pink) classes within a same stratigraphic Rosetta Units (Wavy Bedded in this case).
Figure 5. Hyperspectral composition images (0.04 m width) displaying the variation in ochreous/vitreous goethite and hematite/goethite contents.