

Hyperspectral remote sensing study of the structurally-controlled Zn mineralization in the Flinders Ranges, South Australia

Anna Sorrentino^{1*}, Saeid Asadzadeh², Giovanni Camanni^{1,3}, Francesco Carotenuto¹, Sabine Chabrilat^{2,4}, Sarah A. Gleeson^{2,5}, Giuseppina Balassone¹, Nicola Mondillo^{1,6}

¹ *Department of Earth, Environment and Resources Science, University of Naples “Federico II”, Naples, Italy*

² *GFZ Helmholtz Center for Geosciences, Telegrafenberg, 14473 Potsdam, Germany*

³ *Department of Chemical and Geological Sciences, University of Modena and Reggio Emilia, Modena, Italy*

⁴ *Institute of Earth System Science, Department of Soil Science, Leibniz University Hannover, Hannover, Germany*

⁵ *Research Ireland Centre in Applied Geosciences (iCRAG), School of Earth Sciences, University College Dublin, Dublin 4, Ireland*

⁶ *Natural History Museum, London, United Kingdom*

[*anna.sorrentino2@unina.it](mailto:anna.sorrentino2@unina.it)

Electronic Supplementary Materials

Data and Methods

Spectral mineral mapping and absorption features

Fe-bearing oxy-hydroxides (i.e., hematite and goethite) exhibit diagnostic absorption features in the range 450 – 1200 nm, with the major CFA absorptions varying from ~ 870 nm for hematite to ~ 940 nm for goethite, and minor absorptions at ~ 540 nm and ~ 640 nm shifting towards ~ 480 nm and ~ 670 nm with the transition from hematite to goethite (Hunt 1977; Clark et al. 1990; Burns 1993). In addition, goethite shows water-related absorptions at ~ 1450 nm and ~ 1940 nm. Similarly, Zn^{2+} -bearing minerals can produce deep and broad crystal field absorption features between 800 – 1200 nm, centered at 960 nm (McConachy et al. 2007). In this study, the broad Fe^{3+} absorption, mainly associated with hematite and goethite mineral assemblages, was mapped through the band ratio $(R_{770}+R_{1080})/(R_{870}+R_{940})$ (modified from Sorrentino et al. 2024), combined with $(R_{620}+R_{690})/(R_{480}+R_{550})$ where $R\lambda$ is the reflectance value considered at the given wavelength λ (Tab. 1). The scatter plot between these two band ratios was employed to isolate pixels with ferric-bearing pixels and the outcomes were masked out for the topographic shadow. Hematite was distinguished from goethite by applying the compositional band ratio (R_{940}/R_{870}) ; Tab. 1).

Carbonate minerals in the SWIR range display several absorption features with the strongest feature ($3\nu_3\text{CO}_3$) located between 2300 – 2340 nm characterized by an asymmetric absorption feature, and other minor features located at ~ 1990, 2150, and 2480 nm. The changes in the feature position depend on the amount of Mg, Fe, and Mn substituting Ca in the octahedral site, causing a shift to shorter wavelengths (Gaffey 1986; Lampinen et al. 2019; Laukamp et al. 2021). In particular, this property can be used to spectrally discriminate between dolomite (with absorption at ~ 2320 nm) and calcite (at ~ 2330 nm; see Tab. 1) (Gaffey 1986; Clark et al. 1990; Van Der Meer 1995). When Zn is incorporated into the carbonate structure, the absorption shifts to longer wavelength positions, at ~ 2360 nm (e.g., smithsonite) and ~ 2390 nm (e.g., hydrozincite; McConachy et al. 2007). The main absorption feature, and its asymmetry, was fitted using a 4th-order polynomial between 2300 and 2370 nm (Tab. 1).

The di-octahedral sheet silicates, such as white mica, Al-smectites, and kaolinite, exhibit major absorption features at ~ 1400, ~ 1900, and ~ 2200 nm; the latter is related to the Al-OH bond. In white mica and smectite, the position of 2200 nm absorption depends on the coupled octahedral–tetrahedral Tschermak substitution, resulting in shifts towards shorter wavelengths due to the replacement of Al_{VI} by divalent cations (Fe and/or Mg) (Velde 1965; Laukamp et al. 2021). In the case of kaolinite, this major absorption is accompanied by a double, moderate to weak absorption at ~ 2165 nm (Laukamp et al. 2021). A 2nd-order polynomial fitted between 2182– 2224 nm was used to investigate the 2200 nm feature, and another 2nd-order polynomial between 2155 – 2170 nm was used for the 2165 nm feature (Tab. 1). The scatterplot of 2200D against 2165D was used to separate kaolinite from white mica and/or smectites. The plot of 2200D versus 2330D

52 was used to discriminate between white mica and Al-smectite based on the presence or absence of a feature at ~2350 nm
53 (Asadzadeh et al. 2024).

54 The tri-octahedral Zn-phylosilicate fraipontite, which was characterized spectroscopically for the first time in this
55 study (see Results section), had absorption features at ~1400 nm and ~2260 nm, due to the vibrational modes of OH-
56 and Zn-OH bonds, respectively. The 2260 nm feature depth was mapped by applying a 2nd-order polynomial fitted
57 between 2250 – 2280 nm (Tab. 1).

58 Zinc-phosphate minerals, like tarbuttite and scholzite, generally have well-developed absorption features between
59 2000 – 2500 nm, due to the overtones/combinations of PO_4^{2-} and/or Zn–OH vibrations. Tarbuttite shows two main
60 absorptions at ~2300 nm and ~2370 nm (Zn-OH bending), with minor features at ~1490, 1730 (OH), 1950, and 1980
61 nm (H_2O). In scholzite the Zn-OH occurs at ~2430 nm, with other minor features appearing at ~1480, 1590, 1780, 1960,
62 and 2000 nm (McConachy et al. 2007). Their presence in image data was mapped using a 2nd-order polynomial within
63 the range 2360 – 2380 nm and 2400 – 2450 nm for tarbuttite and scholzite, respectively (Tab. 1). The analysis was
64 restricted exclusively to hand samples, as it was unlikely to detect these features in the EnMAP data. Similarly, the
65 arsenate mineral group (e.g., hedyphane and mimetite) is likely to display absorption features at variable wavelength
66 positions (McConachy et al. 2007). Zinc phosphate minerals in hand samples were identified by their diagnostic OH- and
67 H_2O absorptions following quadratic polynomial fitting between 1400 -1900 nm (Tab. 1).

Table A1. Comparison between spectral sensors features

Sensor	Sampling interval	Band/channel number	Spectral bandwidth (FWHM)	Signal to Noise Ratio (SNR)	Spectral resolution	Spatial resolution	References
<i>Multispectral sensors</i>							
ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) - NASA	VNIR	4	-	-	-	15 m	(Yamaguchi et al. 2001)
	SWIR	6	-	-	-	30 m	
	TIR	5	-	-	-	90 m	
Landsat 8 - NASA	VNIR	6	-	-	-	30 m	(https://landsat.gsfc.nasa.gov)
	SWIR	2	-	-	-	30 m	
	TIR	2	-	-	-	100 m	
Sentinel 2A - Copernicus	VNIR	10	-	-	-	10/20/60 m	(Gascon et al. 2017)
	SWIR	2	-	-	-	20 m	
GeoEye-1	VNIR (450 - 920 nm)	4	-	-	-	1.64 m	(https://earth.esa.int)
<i>Hyperspectral sensors</i>							
DESI (DLR Earth Sensing Imaging Spectrometer)	VNIR (400-1000 nm)	253	2.55 nm	-	3.3 nm	30 m	(Alonso et al. 2019)
EMIT (Earth Surface Mineral Dust Source Investigation) - NASA	VNIR+SWIR (380-2500 nm)	286	< 8.5 nm	> 500 @ 700 nm	7.4 nm	60 m	(Green et al. 2020)
PRISMA (PRecursore IperSpettrale della Missione Applicativa) - ASI	VNIR (400-1000 nm)	66	≤ 15 nm	200–450 @ 450–1000 nm	≤ 12 nm	30 m	(Cogliati et al. 2021)
	SWIR (920 - 2500 nm)	173	≤ 15 nm	100 - 200 @ 1950–2350 nm	≤ 12 nm	30 m	

used in this study

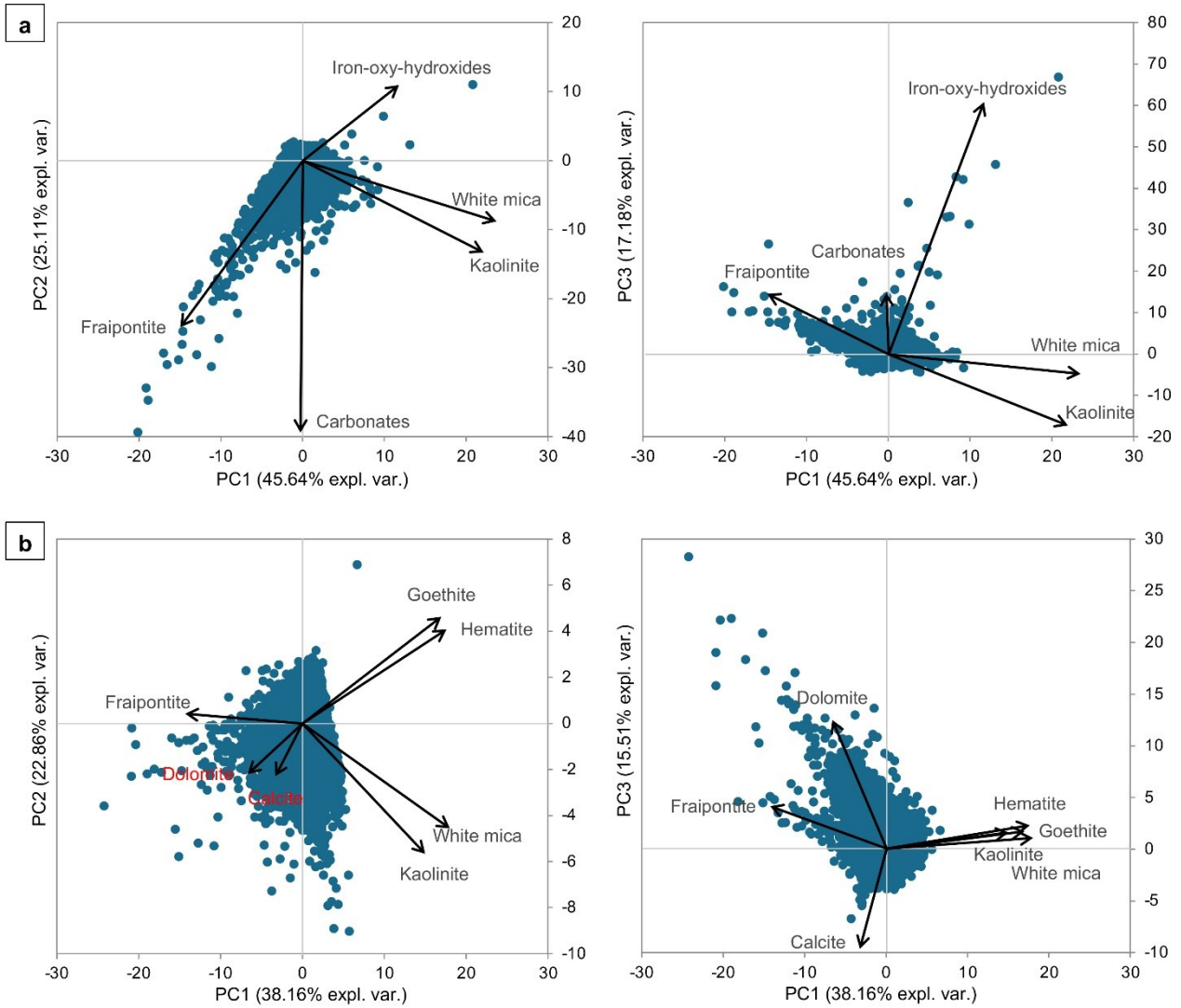
EnMAP satellite (Environmental Mapping and Analysis Program) - DLR	VNIR (420 - 1000 nm)	89	8.1 ± 1.0 nm	>400:1 @ 495 nm	6.5 nm	30 m	(Chabrillat et al. 2024)
	SWIR (900-2450 nm)	155	12.5 ± 1.5 nm	>250:1 @ 2200 nm	10 nm	30 m	
ASD FieldSpec-4 with contact probe	VNIR+SWIR (350-2500 nm)	2151	1.4 nm VNIR, 1.1 nm SWIR	-	3 nm VNIR, 10 nm SWIR	depending on the distance	(https://www.malvernpanalytical.com)
HySpex VNIR-1600 laboratory camera	VNIR (400-1000 nm)	186	-	>255	3.7 nm VNIR	1800 pixels	(https://www.hyspex.com/)
HySpex SWIR-320m-e laboratory camera	SWIR (950-2500 nm)	288	-	>1100	6 nm SWIR	384 pixels	

Note: - = not vailable

Table A2. X-ray diffraction analysis of the investigated samples

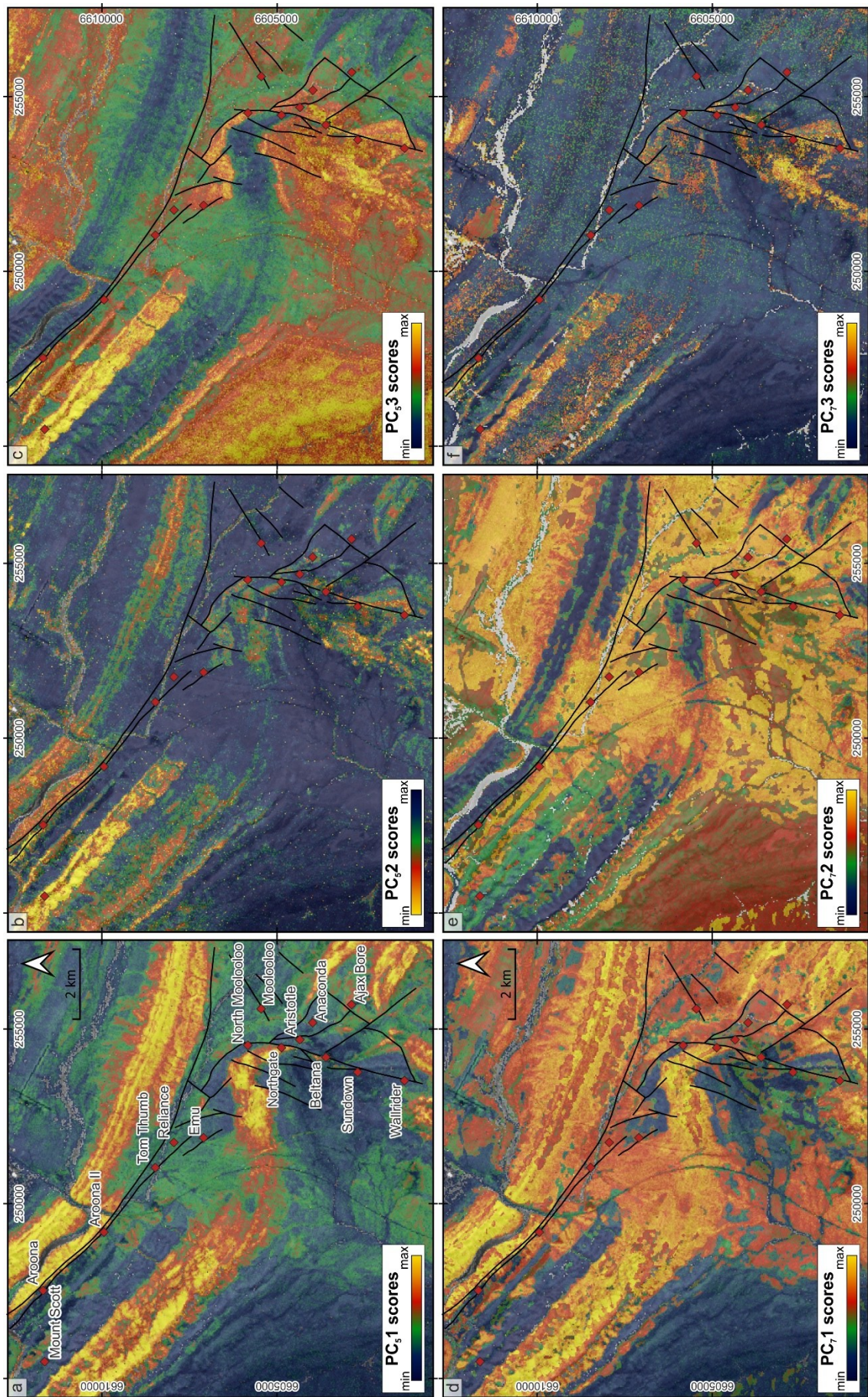
Sample	Wlm	Fr	Cor	Cal	Dol	Qz	K-Fsp	Ms	Fe-Hyx	Mn-Pb-Hyx	Ars	Brt	Slz	Tbt	Ap
BE 1.04	X	X		X							X				
BE 1.04 PIT	X	X		X							X				
BE 2.04				X	X	X	X			X		X			X
BE 2.04 PIT				X	X	X	X			X		X			X
BE 3.04					X				X						
BE 4.04			X	X	X	X				X	X				
BE 5.04	X	X	X		X										
BE 6.04					X	X	X	X	X						
BE 7.04	X	X	X			X					X				
BE 7.04 A	X	X	X												
BE 7.04 B	X	X	X	X	X						X				
BE 8.04				X	X										
RE 1.04													X		X
RE 2.04		X							X				X	X	X

Mineral abbreviations: Ap: Apatite; Ars: Arsenates; Brt: Barite; Cal: Calcite; Cor: Coronadite; Dol: Dolomite; Fr: Fraipontite; Hyx: Hydroxides; Ms: Muscovite; K-Fsp: K-Feldspar; Qz: Quartz; Slz: Scholzite; Tbt: Tarbuttite; Wlm: Willemite



72

73 **Fig. A1** Graphical representation of the principal component analysis (PCA) conducted on five and seven variables shown
 74 in A and B, respectively (see text for details). The graphs show the covariance between PC1 vs PC2 and PC1 vs PC3
 75 together with the relative amount of variance explained by the models



76

77 **Fig. A2** Spatial distribution of the PCn scores of the five variables PCA (a to c) and of the seven variables PCA (d to f)

References

- Alonso K, Bachmann M, Burch K, et al (2019) Data products, quality and validation of the DLR earth sensing imaging spectrometer (DESI). *Sensors* 19:4471
- Chabrillat S, Foerster S, Segl K, et al (2024) The EnMAP spaceborne imaging spectroscopy mission: Initial scientific results two years after launch. *Remote Sensing of Environment* 114379
- Clark RN, King TVV, Klejwa M, et al (1990) High spectral resolution reflectance spectroscopy of minerals. *Journal of Geophysical Research: Solid Earth* 95:12653–12680. <https://doi.org/10.1029/JB095iB08p12653>
- Cogliati S, Sarti F, Chiarantini L, et al (2021) The PRISMA imaging spectroscopy mission: Overview and first performance analysis. *Remote Sensing of Environment* 262:112499
- Gaffey SJ (1986) Spectral reflectance of carbonate minerals in the visible and near infrared (0.35–2.55 microns); calcite, aragonite, and dolomite. *American Mineralogist* 71:151–162
- Gascon F, Bouzinac C, Thépaut O, et al (2017) Copernicus Sentinel-2A calibration and products validation status. *Remote Sensing* 9:584
- Green RO, Mahowald N, Ung C, et al (2020) The Earth surface mineral dust source investigation: An Earth science imaging spectroscopy mission. In: 2020 IEEE aerospace conference. IEEE, pp 1–15
- Hunt GR (1977) Spectral Signatures Of Particulate Minerals In The Visible And Near Infrared. *Geophysics* 42:501–513. <https://doi.org/10.1190/1.1440721>
- Lampinen HM, Laukamp C, Occhipinti SA, Hardy L (2019) Mineral footprints of the paleoproterozoic sediment-hosted Abra Pb-Zn-Cu-Au deposit capricorn orogen, Western Australia. *Ore Geology Reviews* 104:436–461
- Laukamp C, Rodger A, LeGras M, et al (2021) Mineral physicochemistry underlying feature-based extraction of mineral abundance and composition from shortwave, mid and thermal infrared reflectance spectra. *Minerals* 11:347
- McConachy TF, Yang K, Boni M, Evans NJ (2007) Spectral reflectance: preliminary data on a new technique with potential for non-sulphide base metal exploration. *Geochemistry: Exploration, Environment, Analysis* 7:139–151
- Sorrentino A, Chirico R, Corrado F, et al (2024) The application of PRISMA hyperspectral satellite imagery in the delineation of distinct hydrothermal alteration zones in the Chilean Andes: The Marimaca IOCG and the Río Blanco-Los Bronces Cu-Mo porphyry districts. *Ore Geology Reviews* 105998
- Van Der Meer F (1995) Spectral reflectance of carbonate mineral mixtures and bidirectional reflectance theory: Quantitative analysis techniques for application in remote sensing. *Remote Sensing Reviews* 13:67–94. <https://doi.org/10.1080/02757259509532297>
- Velde B (1965) Phengite micas; synthesis, stability, and natural occurrence. *American Journal of Science* 263:886–913

