



AN INTEGRATED REMOTE SENSING APPROACH TO LITHOLOGICAL MAPPING AND CRITICAL RAW MATERIAL EXPLORATION IN THE SOUTH PORTUGUESE ZONE, SPAIN

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Abstract: *The need for effective, economical, and environmentally friendly methods of mineral exploration has grown as worldwide demand for critical raw materials (CRMs) has increased. In this regard, particularly in geologically complex areas, remote sensing provides a quick, non-invasive way to map lithology and assess mineral prospectivity. The potential of Sentinel-2 images for greenfield exploration in the South Portuguese Zone (SPZ) of the Iberian Pyrite Belt, Spain, is assessed in this study. Before analysis, vegetation and water bodies were masked to improve the accuracy of spectral interpretation. The efficacy of remote sensing methods, Band Ratio (BR) and Linear Spectral Unmixing (LSU), in identifying potential zones linked to CRMs and in discriminating lithological units was compared. The outcomes of these approaches were combined to create prospectivity maps for target identification and prioritization of fieldwork areas, and the results were verified using geochemical datasets. The practical contribution of the work is realizing a transferable BR-LSU Sentinel-2 workflow, able to use low-cost satellite observations to get ranked field-check targets. The results show that early-stage mineral exploration can be significantly enhanced by integrating complementary geological and geochemical data with multispectral Sentinel-2 analysis. In complex volcanogenic massive sulfide terrains, the suggested workflow can guide sampling, reduce unnecessary field traverses, lower early-stage exploration costs, and promote more sustainable exploration practices.*

Keywords: *critical raw materials; lithological mapping; greenfield exploration; Sentinel-2; band ratios; linear spectral unmixing.*

1. Introduction

Critical raw materials (CRMs) have become a pivotal concern for energy transition technologies, including solar systems, wind turbines, batteries, power grids, and electric transportation, all of which necessitate reliable supplies of metals and other vital elements. Copper is particularly significant because it facilitates electrification and power transmission, whereas other related elements may be by-products in complex mining systems. Consequently, Europe has prioritized local resources, responsible exploration, and safe supply chains [1, 2, 3]. These policies do not eliminate the need for environmental stewardship; rather, they require identifying potential regions for less intrusive activities and improving early-stage information.

Conventional greenfield exploration relies significantly on field mapping, geochemical sampling, and geological analysis. These operations are crucial; however, they are costly and inconsistent in regions where access, land use, climatic conditions, or geological complexities hinder direct observation.

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Satellite remote sensing can mitigate this uncertainty by providing continuous geospatial data before the commencement of extensive field activities. In mineral exploration, multispectral photography is especially advantageous when exposed rocks, mine wastes, gossans, and hydrothermal alteration products provide distinctive spectral responses in the visible, near-infrared, and shortwave-infrared spectrum [4, 5, 6].

The South Portuguese Zone (SPZ) of the Iberian Pyrite Belt (IPB) offers an appropriate environment for doing such research. The area has volcanic and sedimentary rocks, structurally regulated mineralization, weathered sulfide deposits, gossanous surfaces, and materials associated with mining activities. These characteristics generate a multifaceted yet enlightening spectral terrain. Iron oxides and hydroxides may indicate sulfide oxidation; clay and hydroxyl-bearing minerals may signify alteration envelopes; and comparatively unmodified host rocks serve as the backdrop for distinguishing these fingerprints [7, 8, 9].

Sentinel-2 is particularly advantageous for regional lithological and alteration mapping due to its systematic coverage, unrestricted access, and spectral bands that span the visible, red-edge, near-infrared, and shortwave-infrared regions. While it cannot directly identify every mineral, it can augment significant mineral proxies for exploratory purposes. Iron oxide and ferric iron can be highlighted using certain band ratios. These products emphasize regions where surface materials contrast with the adjacent background and where field verification should be addressed [10, 11, 12].

Band Ratio (BR) analysis is a direct and transparent approach for using Sentinel-2 in geological mapping. It compares reflectance between two bands, facilitating the interpretation of absorption and reflectance differences. This method can mitigate the impact of lighting and topographical variations on exposed geological formations while amplifying mineralogical distinctions. In CRM exploration, BR results primarily serve as indicators of processes and materials associated with mineralization, such as oxidation, gossanization, and acid-sulfate weathering, rather than as evidence of ore [13, 14, 15].

Linear Spectral Unmixing (LSU) provides a complementary perspective. Instead of categorizing each pixel into a singular class, LSU evaluates the fractional contributions of designated spectral endmembers. This is crucial in mineral prospecting, as Sentinel-2 pixels often contain mixtures of rock, soil, alteration minerals, iron oxides, mining waste, and residual vegetation. LSU can thus determine if a pixel is predominantly influenced by gossan-related elements, clay-rich alteration, chloritic alteration, or background host lithologies. When corroborated by field observations, geological maps, and geochemical data, these abundance patterns serve as valuable components for prospectivity mapping [16, 17].

This paper outlines a concise Sentinel-2 methodology for greenfield CRMs exploration in the SPZ of the IPB. It focuses exclusively on two methodologies: BR and LSU. The aim is to demonstrate how a functional Sentinel-2-based approach can differentiate lithologies, corroborate them with geochemical data, and incorporate them into prospectivity maps for effective target selection.

2. Study Area

The study area is situated in the Spanish segment of the Iberian Pyrite Belt, which is a component of the South Portuguese Zone. The IPB extends from southern Portugal into western Spain and is considered one of the world's most significant volcanogenic massive sulfide (VMS) provinces. It contains numerous sulfide deposits and prospects, predominantly associated with Late Devonian to Mississippian volcanic and sedimentary sequences [7, 9]. The belt has been mined for millennia for sulfur, copper, zinc, lead, gold, and silver, and is today considered significant for key raw materials [17].

The selected greenfield site (hereinafter referred to as the "study area") is situated within the South Portuguese Zone (SPZ) (Fig. 1). It is defined by volcanic-sedimentary sequences, felsic and mafic intrusive rocks, altered host units, gossanous surfaces, and structurally controlled mineralized zones. The geological conditions are conducive to further mineralization, as VMS systems typically generate extensive alteration halos surrounding sulfide deposits, and subsequent weathering can yield iron-rich caps and sulfate-bearing surface materials. These features are appropriate candidates for Sentinel-2 analysis because their spectral signatures span the visible to the shortwave infrared [8, 9].

The surface expression of mineralization in the region is strongly influenced by weathering. Ores and mine waste rich in pyrite can oxidize, forming goethite, hematite, jarosite, gypsum, amorphous iron hydroxides, and other secondary minerals. These components do not equate to fresh ore; rather, they serve as significant exploration indicators due to their potential spatial association with gossans, oxidized sulfide caps, mine-related deposits, or acid mine drainage products [7]. This location serves as a natural testing ground for correlating remote sensing data with underlying mineral-system dynamics.

This study primarily examines the principal CRMs and base-metal relationships, which encompass Cu, Pb-Zn-Ag, pyrite-sulfur-complex sulfides, Fe-Mn-Ti, Au-Ag-As, and associated elements. These relationships are treated with caution. Sentinel-2 does not directly identify most metals, especially when they occur as minute grains or as replacements within other minerals. Spectral responses are used to delineate proxy minerals and alteration products [3, 5]. Interpretation is more reliable when spectral evidence aligns with geological maps, documented mineral occurrences, and soil geochemical data from the Geochemical Atlas of Spain and associated datasets produced by the Geological and Mining Survey of Spain (IGME).

Vegetation and water significantly limit spectrum analysis and interpretation in this region. Vegetation can obscure the reflectance of bedrock and soil, whereas water bodies can provide significant absorption and deceptively low-reflectance areas. Consequently, both were eliminated before spectral analysis. The remaining open or inadequately covered surfaces were considered the most reliable regions for BR and LSU interpretation. This masking procedure is simple yet crucial, as it enables the resulting maps to depict geological and mineralogical variations rather than land-cover interference.

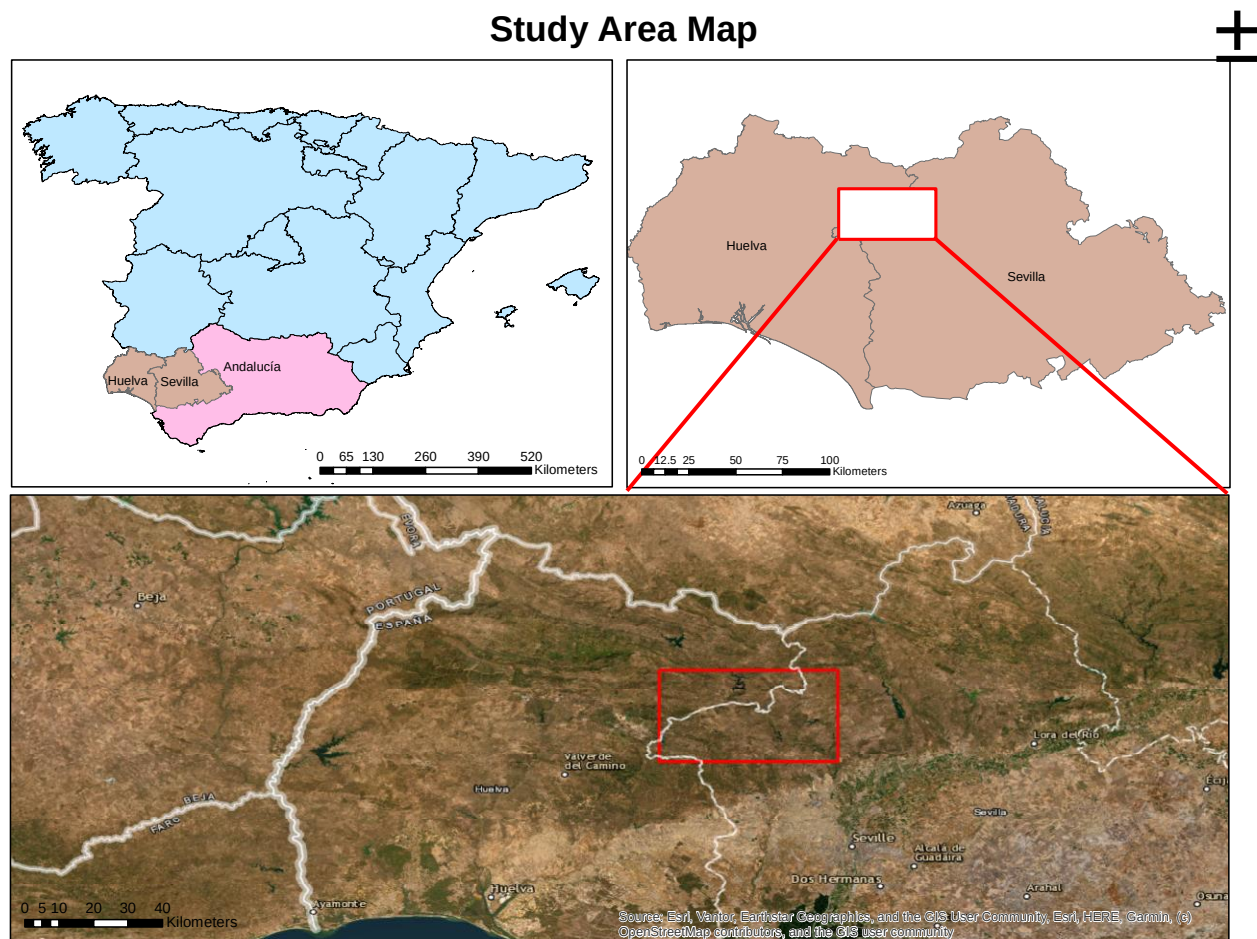


Fig. 1. Study Area Map

3. Methodology

3.1 Data

The Level-2A imagery from the Sentinel-2 satellite was obtained on August 13, 2025, with minimal cloud cover. Level-2A data provide bottom-of-atmosphere reflectance, making them suitable for geological spectral research after spatial and spectral preprocessing. The analysis includes bands from the visible, near-infrared, red-edge, and shortwave-infrared channels, which are relevant to iron oxides, hydroxyl-bearing alteration minerals, clays, and composite surface materials. All selected bands were resampled to a uniform 10 m spatial grid to enable pixel-by-pixel band ratios and spectral unmixing.

Preprocessing was performed within the GIS and remote sensing frameworks. Sentinel-2 bands were stacked, subset to the designated area, and filtered to remove low-quality pixels. Water bodies and vegetation were then masked using threshold-based filtering and visual inspection.

This step was taken to enhance the reliability of geological interpretation, as vegetation and water can obscure the spectral response and mask the fainter fingerprints of exposed rocks, oxidized minerals, and alteration products.

The geological reference information included regional and local geological maps, such as the IGME geological map framework for the Sevilla-Huelva sector and the IGME Mineral Resources Database. These datasets provided a lithostructural framework for analyzing the spatial distribution of BR and LSU abnormalities. They were used to evaluate the geological plausibility of spectral anomalies, including ferric-iron anomalies near recognized gossanous surfaces, mine wastes, structural corridors, or VMS-related lithologies.

Geochemical data from soil samples served as an independent validation layer. In the IPB, soil geochemistry is particularly significant because weathered sulfide systems can produce multi-element anomalies at or near the surface. The Geochemical Atlas of Spain provides standardized datasets for shallow and deep soil layers, enabling comparisons of spectral results with elemental distributions. This study used geochemical evidence to assess whether the observed spectral anomalies aligned with expected trends for Cu, Pb-Zn-Ag, Fe-Mn-Ti, Au-Ag-As, or pyrite-sulfur-complex sulfides. Endmember spectra for LSU were selected from the USGS spectral library. Given Sentinel-2's relatively broad spectral bands, the endmember set was kept small while maintaining geological relevance. This selection reflects anticipated alteration and weathering processes in a VMS terrain rather than an effort to identify specific ore minerals.

3.2 Methods

The workflow followed five methodical steps: Sentinel-2 preprocessing, water and vegetation masking, BR mapping, LSU abundance mapping, and integration with geological and geochemical data. The objective was not to produce a single automated response but to build a coherent set of evidentiary layers to support early-stage decision-making. Regions where BR anomalies, LSU abundance patterns, geological formations, favorable lithologies, and geochemical anomalies converge were designated as higher-priority targets for field exploration.

BR analysis was utilized to improve mineralogical indicators. Ratios were computed on a pixel-by-pixel basis by dividing the reflectance of one Sentinel-2 band by that of another. The numerator and denominator were selected to enhance the visibility of the expected absorption and reflectance contrasts of the target material. The products were treated as comparative indicators. Elevated values informed the geological interpretation, although they were not regarded as direct tests or as quantitative estimates of mineral abundances [10, 12].

Table 1. Sentinel-2 band ratios used for lithological and alteration interpretation [10]

Target	Sentinel - 2 Band ratio	Geological importance
Ferric iron	Band 04 / Band 03	Enhances ferric iron minerals and red-yellow oxidation products, such as goethite, hematite, and jarosite, on surfaces.
Iron oxide / Oxidation	Band 04 / Band 02	Highlights iron-stained surfaces, ferruginous mine wastes, gossanous materials, and weathered sulfide products.

Linear Spectral Unmixing (LSU) was used to estimate the relative abundance of specified endmember groups within each Sentinel-2 pixel. Each pixel spectrum was modeled as a linear combination of reference spectra, with a residual term. The endmembers were not treated as pure minerals in the field; instead, they were classified as representative spectral groups. This approach is appropriate for the research area, as most pixels consist of a mixture of rock, soil, secondary minerals, and weathered mining detritus [9, 17]. The LSU utilized spectra indicative of sulfate-rich and iron-hydroxide substances.

Validation and integration were carried out qualitatively yet systematically. Initially, each BR and LSU layer was meticulously examined against geological maps and established mineral-resource sites. The regional distribution of anomalies was analyzed in relation to soil geochemical data. Third, regions where independent evidence coincided were recognized as promising. This integration phase was intentionally cautious: single-layer anomalies were considered potential markers, but consistent coincidences across spectral, geological, and geochemical data were deemed more compelling evidence for field prioritization.

4. Results

4.1 Band ratio results

The Sentinel-2 band ratios of Fe-bearing ores, namely Band 04/Band 03 and Band 04/Band 02, serve as supplementary indicators of the oxidized, iron-rich surface expression of the study area. This interpretation aligns with the region's geology, which lies within the Iberian Pyrite Belt, a globally significant VMS province. Mineralization is dominated by pyrite, and extensive weathering has produced substantial gossans, ferruginous mining by-products, and acid mine drainage precipitates. In this context, these ratios do not immediately indicate new ore; rather, they identify supergene and environmental by-products of sulfide oxidation that surround or adjoin the ore system at the surface. Their anomalies are expected to show the strongest correlation with the IGME resource groups Fe–Mn–Ti, Pyr–S–Complex Sulfides, Au–Ag–As, and Pb–Zn–Ag, as these groups are frequently associated in the region with gossanized caps, pyrite-dominated mining operations, and ferric secondary minerals formed during oxidation. They may also indirectly support the interpretation of copper occurrences where copper-bearing sulfides appear as oxidized caps or ferruginous mine-land surfaces.

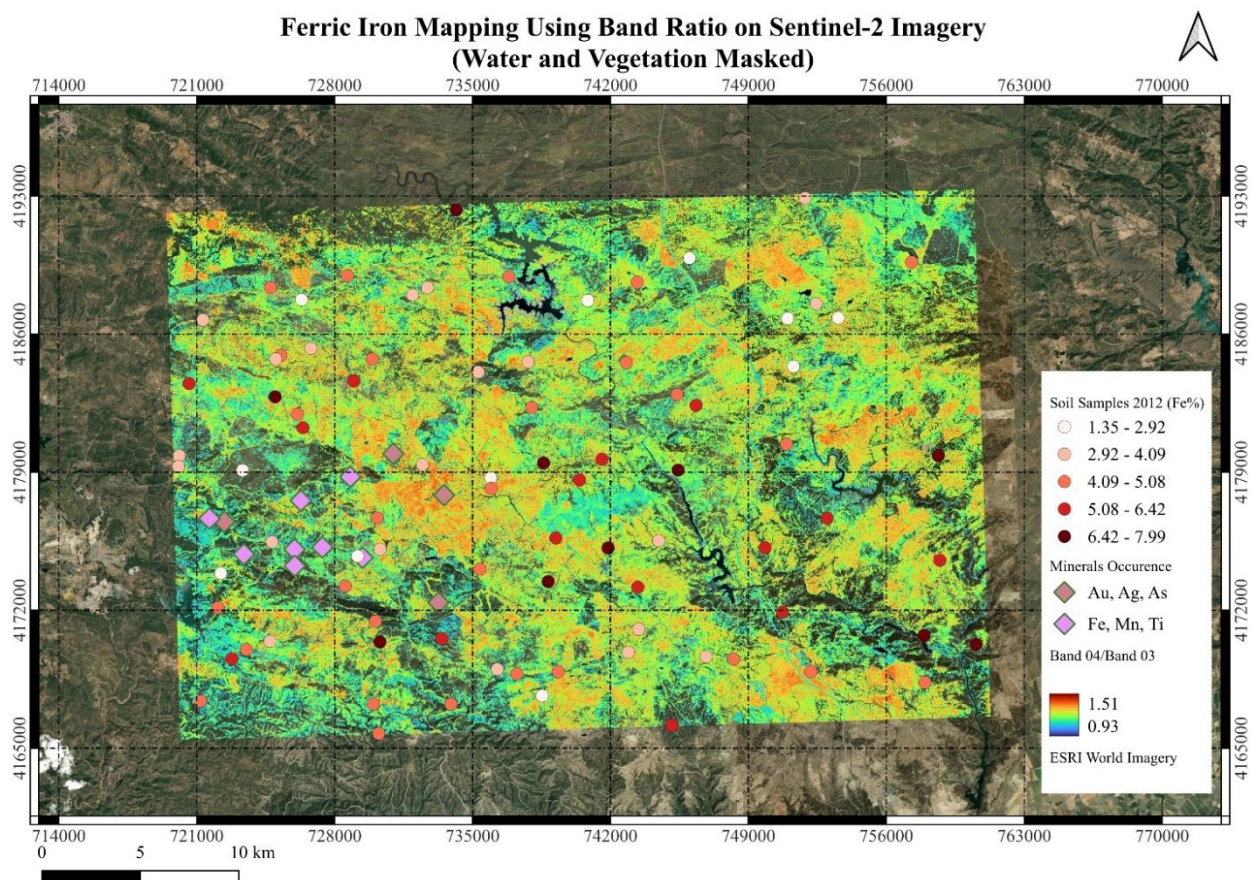


Fig. 2. Ferric iron mapping using the Band 04/Band 03 ratio on Sentinel-2 imagery

Band 04/Band 03 is a well-established indicator of ferric iron, signifying surfaces rich in Fe^{+3} minerals such as goethite, hematite, and jarosite, which are characteristic of gossans, spoil heaps, and ferric-stained drainage sediments in the study region (Fig. 2). Band 04/Band 02 provides a more comprehensive assessment of iron-oxide staining, typically emphasizing reddish to yellowish exposed surfaces affected by significant sulfide weathering (Fig. 3). When Band 04/Band 03 and Band 04/Band 02 produce simultaneous anomalies, the defined areas can be interpreted with greater confidence as zones of substantial ferric enrichment and marked oxidation. In fact, these responses are most relevant to the Fe–Mn–Ti group. However, the spectral signal is primarily affected by Fe-bearing phases rather than by Mn or Ti specifically. The corresponding paired response is highly pertinent to the occurrence of Au–Ag–As, as these commodities in the Iberian Pyrite Belt are generally associated with oxidized gossan environments and weathered sulfide caps, rather than with spectrally distinct primary minerals at the surface. The three iron-bearing ratios collectively illustrate the oxidized surface characteristics of the mineral system, highlighting gossan caps, ferruginous waste, acid-mine-drainage-affected drainage, and iron-stained surface materials that are spatially linked to the primary mineral resource groups in the study area.

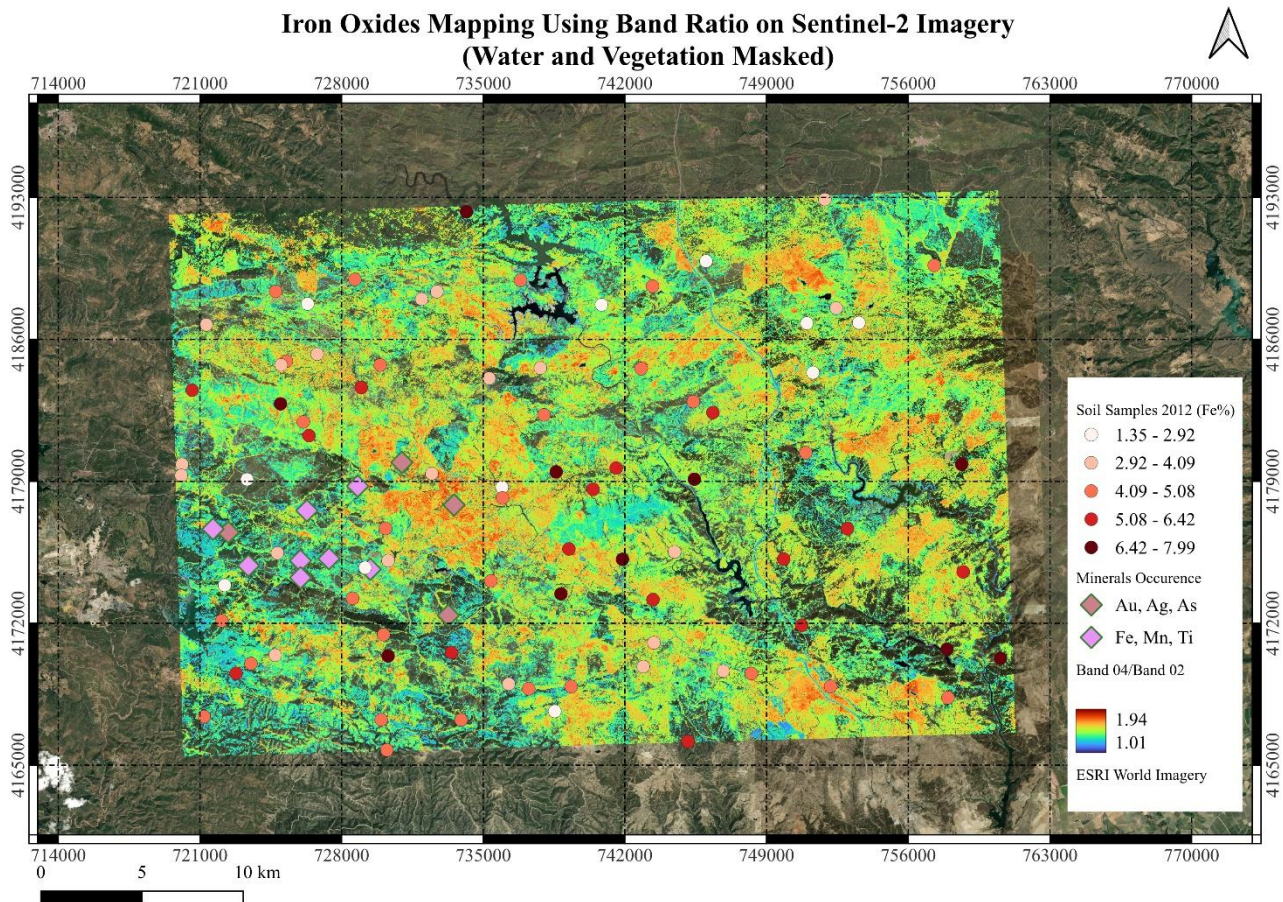


Fig. 3. Iron oxides mapping using the Band 04/Band 02 ratio on Sentinel-2 imagery

By comparing the BR results with geological and geochemical data, the most promising areas were identified where multiple ratios produced overlapping anomalies. Areas exhibiting concurrent ferric-iron anomalies were considered more reliable than those characterized by a single ratio. The most pronounced Band 04/Band 03 and Band 04/Band 02 anomalies occur in the western section of the study area, particularly around coordinates 728000-736500 E and 4173500-4182000 N, where elevated ferric-iron responses align with documented Au-Ag-As occurrences and with soil samples showing moderate to high Fe concentrations. A second anomalous belt is observed between 754000-761000 E and 4172500-4181000 N, where many Fe-rich soil samples corroborate the interpretation of oxidized surface material, despite less continuous mapping of mineral occurrences. In the eastern sector, elevated values are noted around 756000-759000 E and 4170000-4173000 N, as well as locally near 755000 E and 4189000-4191000 N. The latter areas are considered follow-up targets due to their robust spectral response, although their correlation with known mineral occurrences is less pronounced.

These results indicate that oxidation and alteration processes are spatially correlated, as anticipated near VMS-related mineralization in the IPB. The primary limitation of BR analysis is its sensitivity to spectral ambiguity. Soils rich in iron, mining wastes, and naturally ferruginous rocks may produce similar responses. Similarly, clay-rich alterations and non-mineralized clayey soils may exhibit spectral overlap. Consequently, the BR maps were not used as independent evidence. They were regarded as rapid, clear indicators that facilitate further interpretation and field validation.

4.2 Linear spectral unmixing results

LSU is characterized by a integration of Gyp+jar+ill BRCM1 Marysvalle (Natural intimate mix of quartz, albite, gypsum, natrojarosite, pyrite, illite/muscovite in altered andesitic lavas near a hydrothermal feeder zone – a great analog for acid-sulfate/jarositic caps over sulfides), goethite-rich phyllite CU91-236A (Natural phyllite with substantial goethite developed by weathering/alteration – very gossan-like spectral behavior), and Fe-hydroxide SU93-106 amorph (Natural amorphous Fe-hydroxide – works as a generic "ferric mud" spectrum) spectral signatures provided by the United States Geological Survey (USGS) spectral library. The spectra indicate a prevalence of Fe-oxide/sulfate gossan. The analysis of satellite images demonstrates the

relative contributions of sulfate-rich material, crystalline Fe-oxyhydroxide-bearing material, and less-crystalline iron hydroxides across the three channels. This combination has geological significance for the study area, as jarosite, gypsum, goethite, and Fe-hydroxides indicate sulfide oxidation within the IPB, particularly in areas where pyrite-rich ores have undergone extensive weathering under acidic conditions.

The overlays in Figures 4 and 5 were purposefully separated to avoid conflating distinct validation layers on a single map. Figure 4 focuses on the Fe-Mn-Ti resources occurrence layer, highlighting the geographical correlation between the LSU response and the presence of iron-bearing minerals. Figure 5 shows the occurrence points of Au, Ag, and As, which serve as pathfinder indicators for gossanized polymetallic mineralization. This distinction clarifies that Figure 4 assesses the iron-rich surface manifestation, whereas Figure 5 examines the association of the same oxidized surface material with indicators of precious metals and pathfinder elements.

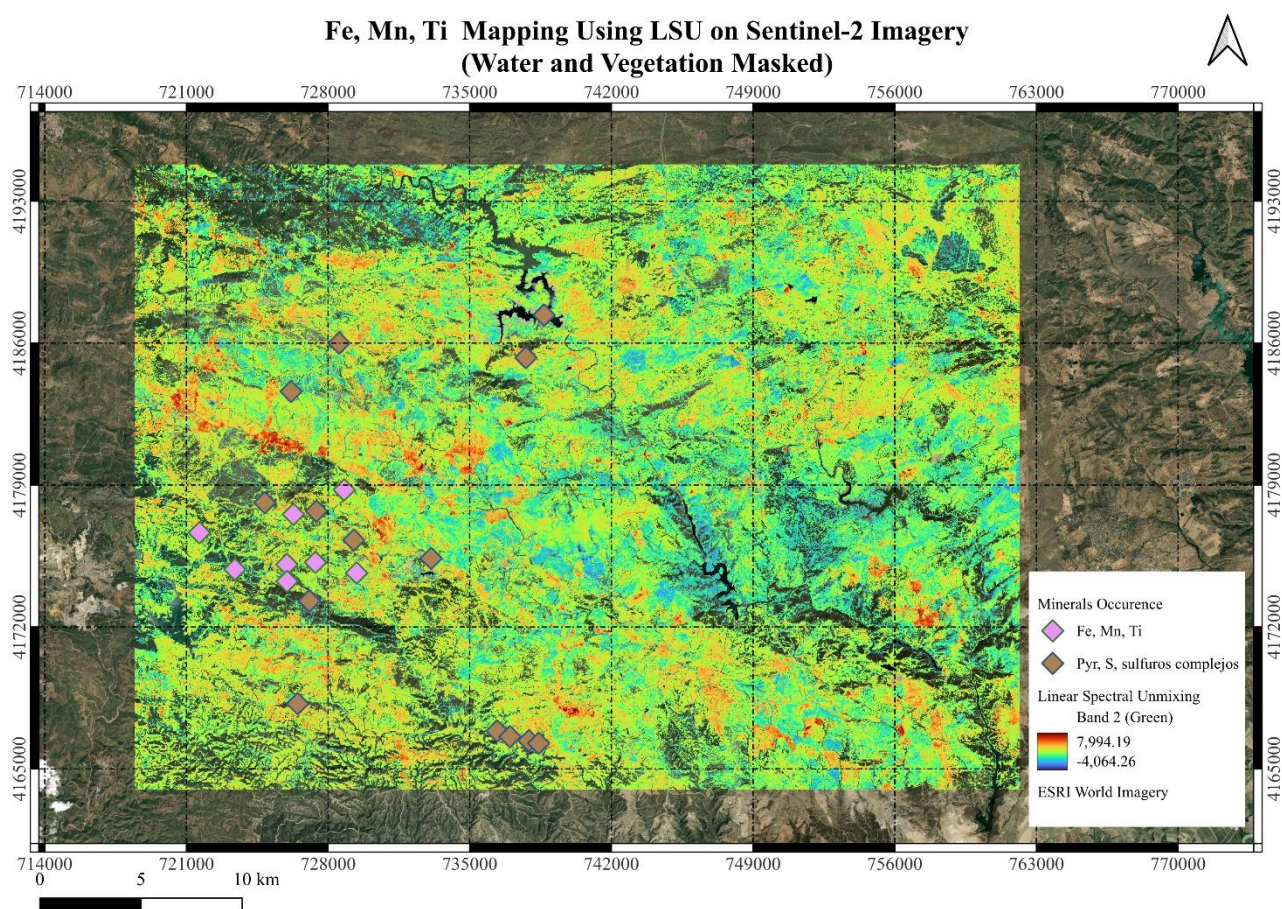


Fig. 4. Identification of Fe, Mn, and Ti deposits using the USGS spectral library for LSU on Sentinel-2 imagery

The results from these spectra are best interpreted as indicating the surface expression of gossan, iron-stained weathering zones, and other oxidized materials derived from sulfide-rich protoliths. This hypothesis is strongly supported by the widespread occurrence of pyrite, sulfur, and complex sulfides in study area, in addition to IGME's cataloging of Fe, Mn, and Ti mineral resources in the area (Fig. 4). In regions where the LSU reaction is more evident, the ground surface is typically marked by supergene iron minerals and sulfate-rich oxidation products, rather than unweathered ore or pristine volcanic host rock. Figure 4 shows the most distinct LSU response in the western to south-western sector, specifically around 721000-728000 E and 4179000-4186000 N, and in the smaller central-western zones around 731000-735000 E and 4178000-4181000 N. These regions are interpreted as oxidized, iron-rich surface materials, given their proximity to mapped Fe-Mn-Ti occurrences. Several red LSU patches do not align with mineral-occurrence locations. This is expected, as the occurrence database records distinct known deposits or possibilities, whereas LSU maps the abundance of spectral material at the surface. Therefore, rather than being verified mineral occurrences, non-coincident red zones should be understood as gossanous, ferruginous, or mine-waste/soil-related surface anomalies that require field validation.

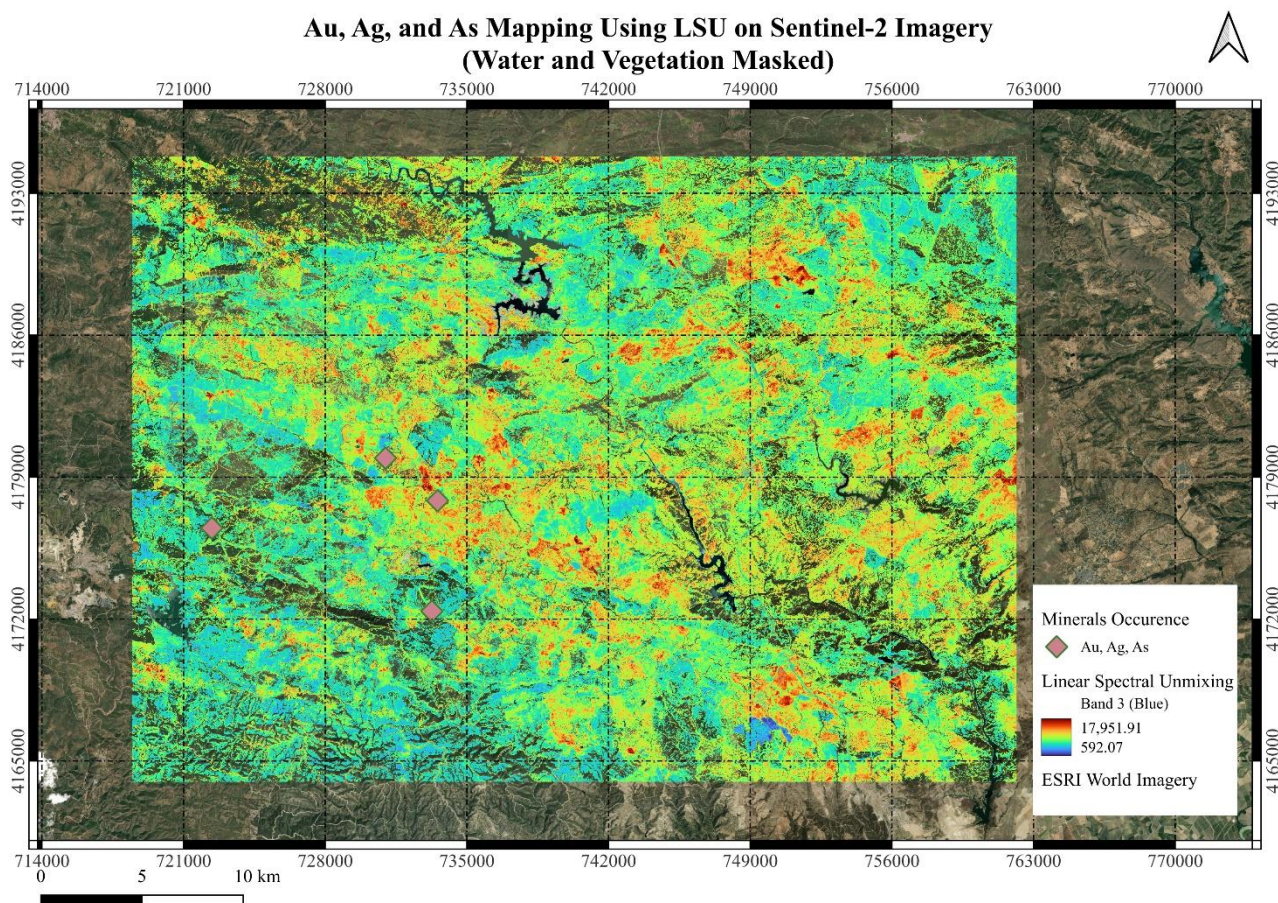


Fig. 5. Identification of Au, Ag, and As deposits using the USGS spectral library for LSU on Sentinel-2 imagery

These spectra are also relevant to the IGME resources of Au, Ag, and As (Fig. 5). The most pertinent Au-Ag-As comparison occurs in the western part of the area, specifically between 733500-742000 E and 4174500-4178000 N, where many Au-Ag-As occurrences are located within or near elevated LSU values. A secondary cluster of responses is located between 742000-753000 E and 4185000-4190000 N, where the LSU signal aligns with ferric alteration and indicates iron-rich soil. The east-west red patches, located at roughly 755000-761000 E and 4166000-4188000 N, exhibit significant surface oxidation but a paucity of Au-Ag-As mineral occurrences; thus, they are regarded as reconnaissance targets rather than confirmed Au-Ag-As prospects. In the Iberian Pyrite Belt, gossans serve as weathering products and exploration indicators, as the oxidation of polymetallic sulfides can preserve or concentrate geochemical signals associated with pathfinder and precious metals at the surface. Thus, increased LSU concentrations in this Fe-oxide/sulfate group provide the most definitive remote-sensing evidence of sulfide oxidation and the possible formation of gossan over polymetallic mineralization (Fig. 6).

Figure 6 should be viewed primarily as a comparison of the LSU response with the layers of pyrite, sulfur, and complex sulfides. The interpretation diverges from that in Figure 5 because the relevant evidence is not Au-Ag-As, but rather the weathering products anticipated above or near pyrite-rich sulfide systems. Elevated LSU responses between 720000-729000 E and 4165000-4179000 N, as well as 734000-741000 E and 4164000-4170000 N, are noteworthy when they correspond to or are adjacent to delineated sulfide occurrences. Regions with elevated LSU values that lack mapped occurrence locations are significant, as pyrite oxidation can yield jarosite, goethite, and amorphous Fe-hydroxides, even in the absence of exposed or documented primary sulfide bodies. These locations are regarded solely as proxies for surface oxidation and require field verification, portable spectroscopy, and soil or rock geochemical analysis before they are considered exploration opportunities.

The primary benefit of LSU is its ability to shift from interpreting single-ratio anomalies to mapping material groups. This is crucial for field planning. A band ratio anomaly may indicate that a surface exhibits spectral irregularities; LSU can help determine whether it is predominantly gossanous, clay-rich, chloritic, or representative of the background lithology. This distinction helps guide exploration by indicating whether to investigate a target for oxidized sulfides, hydrothermal alteration, lithological connections, or geochemical dispersion.

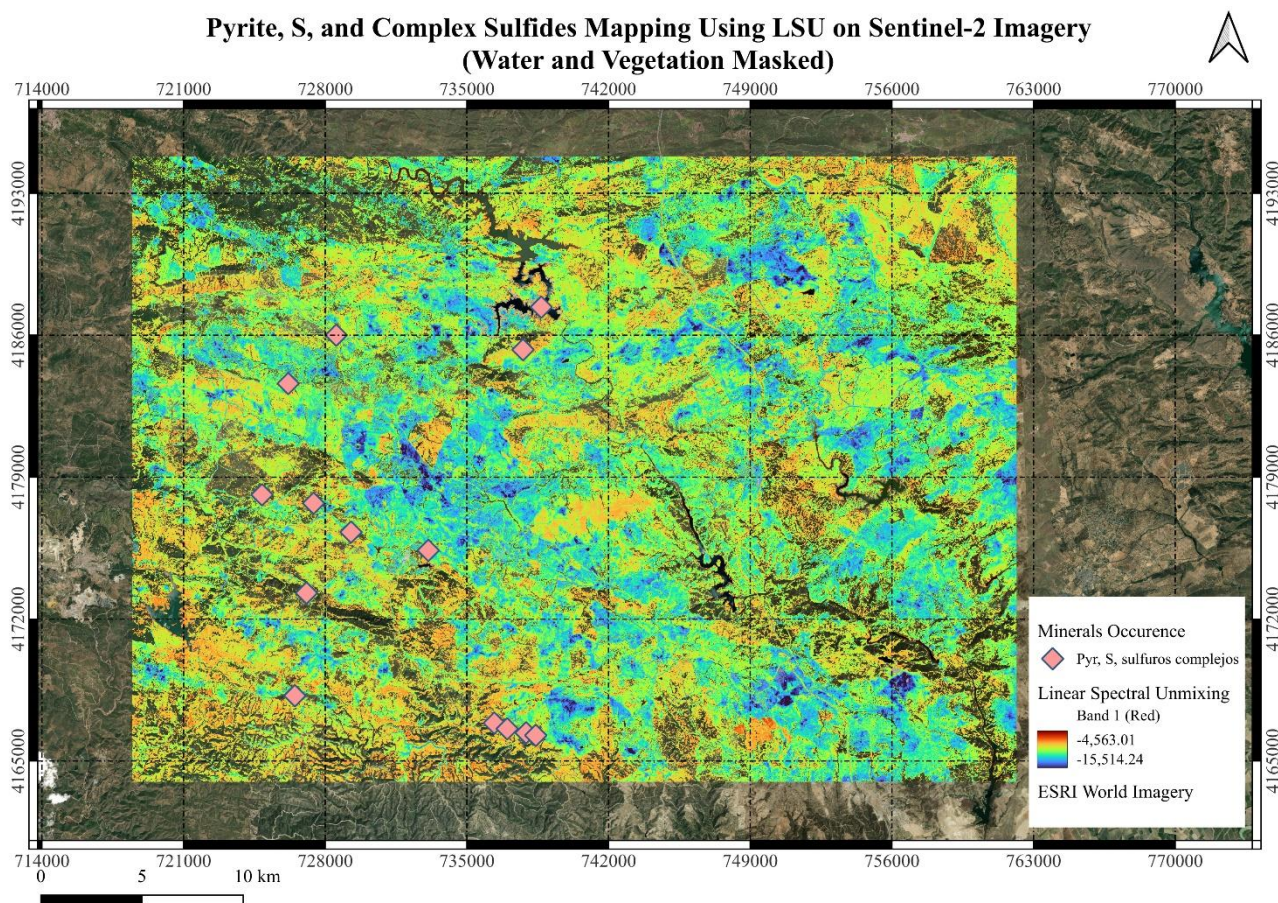


Fig. 6. Identification of Pyrite, S, and complex sulfide deposits using the USGS spectral library for LSU on Sentinel-2 imagery

The comprehensive analysis of BR, LSU, mineral deposits, and soil geochemistry reveals the following results:

- The B04/B03 and B04/B02 ratios consistently indicate ferric and iron-oxide-rich surfaces, with the most pronounced and geologically substantiated anomalies occurring in the western sector.
- The LSU identifies gossan-like materials comprising jarosite, goethite, and iron-hydroxide-rich surface mixtures; the reliable LSU targets are aligned with identified IGME's mineral occurrences.
- Figures 4, 5, and 6 illustrate distinct validation perspectives: occurrences of Fe-Mn-Ti, evidence of Au-Ag-As/pathfinders, and occurrences of pyrite-sulfur-complex sulfides, respectively. The absence of precise overlap between red LSU pixels and mineral occurrences does not negate the spectral anomaly; however, it reclassifies it from confirmed evidence to a field-validation target.
- The most prominent follow-up priorities are the western and south-western clusters, followed by the central-western anomalies. Eastern anomalies are considered lower-confidence prospects due to pronounced spectral oxidation yet reduced correlation with known mineral deposits.

5. Conclusions

This study demonstrates that Sentinel-2 imagery can provide a feasible, cost-effective, and transferable methodology for preliminary exploration of CRMs in the South Portuguese Zone of the Iberian Pyrite Belt. After masking water and vegetation, the BR analysis swiftly improved the detection of ferric iron and iron oxide patterns. LSU subsequently provided complementary sub-pixel analysis by distinguishing Fe-oxide/sulfate gossan materials. The highest exploration value emerged from integration: areas where BR anomalies, LSU abundance patterns, geological context, and soil geochemical data converged were deemed the most reliable opportunities for field study. The approach does not directly identify ore minerals or quantify metal concentrations; instead, it effectively delineates surface indicators of mineralization, alteration, and oxidation. Consequently, it can be used to refine greenfield search regions, minimize superfluous fieldwork, and facilitate mineral discovery in geologically intricate landscapes. The combined BR-LSU workflow is not intended to replace field mapping or geochemical sampling, while its value lies in ranking targets before field

campaigns, by distinguishing high-confidence co-located anomalies from lower-confidence spectral-only responses. Relating to the presented case study, the prioritization indicates to focus sampling on the western and south-western clusters, offering field guidance and cost reduction for further greenfield exploration.

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