Copernicus data to boost raw material source management: Illustrations from the RawMatCop programme

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Abstract

Earth Observation (EO) data can become an essential tool in the transformation of a raw materials sector that aims to reconfigure its model of operation. The high demand for the mineral resources necessary for the transition to a carbon neutral and circular economy conflicts with the increasing difficulties of finding new deposits. As the sector heads towards embracing circularity and reducing the environmental impacts, a clear focus has been set on developing appropriate tools to boost the efficiency of mineral resource management, both technologically and economically. In this scenario, the Sentinel satellites of the European Copernicus program come into play. Despite being satellites considered medium resolution, they provide great temporal and spatial coverage in a continuous record, which makes them tools with great potential for the raw materials sector. However, the lack of applications in the raw materials sector suggests that these technological advances have remained underrated by sectoral actors. The RawMatCop program was designed to bridge this gap. This program, co-funded by the European Commission and EIT RawMaterials, aims to develop applications and promote the use of Copernicus data in the raw materials sector to contribute to a safe and sustainable supply of mineral resources. The presented applications can be grouped into three categories covering the whole mining cycle from exploration to exploitation and post-mining. Two of the presented case studies cover the study of primary sources including exploration of Iron Oxide Copper Gold mineralisations to identify high-potential mining areas and mapping of informal gold mining and its environmental impacts. Another project focused on secondary sources tackled data applications for grade mapping and sample optimisation in mining residues. And the forth project focused on monitoring ground stability related to mining activity. The results demonstrate the high cost-effectiveness of Sentinel 1 and 2 in extending ground-based measurements to larger areas, especially when these are hard-to-reach areas. Finally, the presented projects examine the industrial and social impacts of technological innovations, as well as contribute to the achievement of prominent European Union policy objectives and the United Nations Sustainable Development Goals.

Keywords

Critical raw materials, Copernicus, Sentinel, mining residuals, exploration, mineral resources, ground instability, small-scale mining

1. Introduction

The increasing demand for raw materials globally, specifically for Critical Raw Materials (CRMs), has positioned the management of the material supply chains as a priority in the agenda of the European commission (EC) (Ferro and Bonollo, 2019). CRM classification by the European Union (EU) depends on meeting two main parameters: economic importance and supply risk (Martins and Castro, 2019). Many of the identified CRMs are essential in the European Green Deal and different sectors such as green mobility, electronics, health, steelmaking, defense and space exploration (COM, 2019). The provision of CRMs is crucial in these sectors not only due to their contribution to production costs, but also given sustainability considerations (Ferro and Bonollo, 2019). Historically, the main source of raw materials in Europe has been mining activities within the continent. However, over the last decades, mining exploration and extraction activities have diminished considerably in Europe due to growing concerns over the environmental impacts. Moreover, production costs are lower outside of Europe. These developments have, nonetheless, been at odds with the vital role of mining to fuel the growing demand for raw materials (EC, 2008, 2017). Multiple factors, such as low public acceptance following reported negative environmental and social impacts, have influenced the development of mining activities, especially in the EU (EC, 2016; Mancini and Sala, 2018). Re-opening abandoned sites, exploring new mineral sources, recycling and substitution of materials could represent strategic solutions to meet the high demand for CRMs. Hence, since 2008, the EC through the Raw Materials Initiative, presented new strategic implementations to foster sustainable supply from European sources; to make sure to have access of international markets of raw materials and enhance the resource efficiency and recycling (EC, 2008). To reach the presented objectives, different solutions within projects are presented. Developing a modern technologically-advanced small-scale mining concept is one of the solutions, which can be considered to support the raw materials value chain in the EU (Sidorenko et al., 2020). Specific attempts are done to ensure the reasonable and sustainable critical raw materials supply for the strategic Action Plan on Batteries, including cobalt artisanal mining (Mancini et al., 2021). Besides, there are several strategies which focus on improving the material efficiency, with design, substitution, reusing and recycling the materials (Karakaya et al., 2021). In all presented projects, the strategies that address cleaner and more efficient mining are directly linked to advanced technologies that monitor mining activities and their impacts. These technologies include, notably, use of diverse sensors to collect real-time data, advanced mining equipment, and the use of remote sensing techniques acquired using various platforms such as satellites and drones.

The growing role of satellite imagery in different sectors is expected to have a considerable impact on the future of societies and economies, with the market predicted to grow from $350 billion to $2.7 trillion over the next three decades (WEF, 2020). Copernicus, a greatly ambitious Earth Observation (EO) data source, has been identified as a priority by the EC regarding mineral resource management (Jutz and Milagro-Pérez, 2018). It is a programme that provides accurate, timely and easily accessible information to improve environmental impact monitoring, better understand the effects of climate change, and enhance resource management. Copernicus provides vast amounts of data corresponding at medium spatial resolution in six thematic categories that contribute to a more sustainable future: i) land management, ii) marine environment, iii) atmosphere, iv) emergency response, v) security and vi) climate change. The programme is directed by the EC, in partnership with the European Space Agency (ESA). ESA manages the data collection by 30 satellites, and is responsible for the overall Copernicus initiative, setting requirements and managing the services (https://www.esa.int/ESA). The Sentinels are six types of satellites that host optical and radar sensors and aim to meet the practical demands of the Copernicus programme since 2014.

The adoption of Copernicus data throughout the mining cycle could be decisive for sector's contribution to the achievement of the goals set forth by the European Green Deal (COM, 2019). Firstly, in the context of the Green Deal, the uptake of satellite technology, within and beyond the raw materials industries, can be transformational for the European economy, supporting the transition to a new circular economy model and driving sought-after job creation and growth. The use of satellite imagery across European industries will lead to the development of value-added resources and services, helping create new market segments, strengthening the innovativeness of industrial players and generating business opportunities.

Secondly, the anticipated proliferation of Copernicus uptake across Europe can help strengthen the EU's digitalisation capacity and equip the labour force for the ongoing digital transformation. The ambition for Europe to champion a robust digital transition strategy has been codified in "A Europe fit for the Digital Age" (EC, 2020a), one of the high-level European Commission priorities between 2019-2024, as well as in the Green Deal (COM, 2019).

Therefore, the satellite technology, specially, the global and frequent coverage of Copernicus imagery can help safeguard a sustainable supply of critical raw materials coming both from inside and outside of the EU. As an example, to facilitate the sustainability of mining with a minor environmental impact with specific attention to the necessity of the CRMs exploration (Tejado-Ramos et al., 2021), or in general characterize the large-scale geological formations with high precision and their changes through time (Booysen et al., 2021).

Finally, enhancing the adoption of Copernicus data can improve greatly the transparency of sectoral operations. The free, open access nature and high-resolution characteristics (spatial and revisit time) of Copernicus has the potential to transform the availability of information on activities related to the raw materials' value chain. This can have considerable implications for sectoral actors, specifically regulatory bodies, consumers and industry. Copernicus can provide an unmatched tool for public authorities to monitor mining activities and ensure compliance along European and foreign supply chains. This is of uttermost importance to EU decision-makers and the EU public, whether concern over conditions supply chains originating outside of the EU is high. Likewise, the accessibility and volume of the data can make it an extraordinary and reliable source for consumers and society as a whole to become informed and empowered in the green transition. Moreover, the availability of reliable, comparable, and verifiable information can be extremely beneficial for relationships between the mining industry and local stakeholders. It directly contributes to building trust and obtaining a Social Licenses the Operate (SLO) which refers to the acceptance of an extractive activity by the local community and stakeholders (Leena et al., 2019).

The RawMatCop programme is the focus of this paper. It is a collaboration between EIT Raw Materials and the European Commission extending from 2017 until mid-2021. Among various programme activities, RawMatCop funded a diverse collection of short research projects at the intersection between EO and the raw materials sector. Such projects provide a solid foundation for the development of digital competences and skills among sectoral stakeholders, ultimately supporting the European Data Strategy's goal to make Europe a leader in a data-driven society (EC, 2020b). The objective of this paper is to present a selection of these projects, to illustrate the various successful cases, and to examine the contribution of such activities to technological innovations, to the European Union policy objectives, and to the United Nations (UN) Sustainable Development Goals (SDGs). RawMatCop's projects have utilized EO data in different pilot sites (see Fig.1), during the period. These projects explore different applications, highlighting the importance of using EO data for the safe and sustainable supply of mineral resources. The use of Copernicus data, freely available Sentinel-1 (radar) and Sentinel-2 (multispectral optical) and their applications to different fields, benefits, and limitations are addressed.

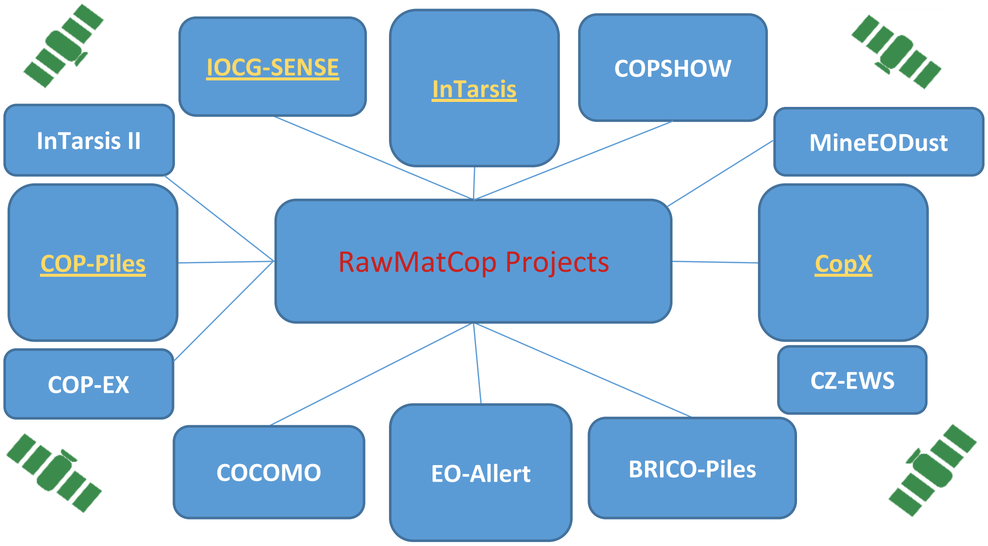


Fig. 1. RawMatCop Project constellation (2017-2021). The four projects described in this paper are Cop-Piles, IOCG-SENSE, CopX and InTarsis (highlighted).

2. Materials and methods

In this paper, four projects are presented as they demonstrate the potential of Sentinel data (Sentinel-1 and Sentinel-2) for the mineral resource sector. The "COP-Piles: Sample optimisation in stockpiles/tailings, for grade mapping of raw materials" project explored the characterisation and mapping of raw materials in mining residues and sample optimisation using Copernicus data (Sentinel-2). The importance of using satellite data is highlighted for the characterization of mining residues by geostatistical tools. Similarly, the "IOCG-SENSE: Integration of space-borne remote sensing data with geophysical and geological data for exploration of Iron Oxide Copper Gold (IOCG) mineralisation" project focused on IOCG exploration and on the optimum procedures for integrating space-borne remote sensing data with other geoscientific data. The project relied on Sentinel-2 data from the High Arctic with excellent geological exposure and minimum data interpretation problems caused by vegetation cover. Project "CopX: Geospatial mining transparency through Copernicus and MapX" employed Sentinel-2 multispectral optical data for the detection and mapping of small-scale informal mining and its environmental impact over a study area. It developed an approach that will be implemented to cover the region of Antioquia, Colombia. The research for this project was carried out in collaboration with the United Nations Environment Programme (UNEP) and UNEP/GRID-Geneva. Finally, the "InTarsis: A ground monitoring system combining Sentinel-1 and seismic" project examined the importance of ground stability control for safe and sustainable mining. InTarsis deliverables included an automated web tool to improve the monitoring capacity of the mining stakeholders. As an additional result, this project helped bridge the gap between complex Sentinel-1 data and partners in the mining sector through training sessions using a user-friendly platform. All topics are of great importance to the sector and have the potential to be implemented in future projects.

2.1 COP-Piles project

Background and objectives: The COP-Piles project explored raw materials mapping and sample optimisation in mining residuals, using geostatistical analysis (Matheron 1971) and Earth Observation data. This research is of strategic importance since it focuses on the recovery of CRMs from mining residuals. The depletion of in-situ reserves, paired with the increasing need to use lower grade materials and with advances in recovery and processing technologies, have driven the recent revaluation of stockpiles and tailings (mining residues) as material sources (Kasmaee et al. 2010 and 2018). Moreover, the rise of environmental and legal barriers to access primary mineral sources across the world (this is notably the case in the European Union) have led to a growing economic interest in the processing of secondary raw materials and resampling of mining stockpiles and other forms of mining waste (Tiess, 2010, Blengini et al., 2017). Recently, environmental aspects have resulted in a generalized search for more effective management systems of mining residuals in mining sites which consider waste as a valuable potential future resource (Garbarino et al., 2020). Therefore, there is a growing need to characterise mining residuals (grade and tonnage calculation) in order to assess the feasibility of their "re-use" or "re-mining".

Case study and data: The COP-Piles project has used data from an active case study in Greece. The Bauxite mining Residues (BR) is located 136 kilometers from Athens in the gulf of Corinth. The material contained within the residue is red mud from an aluminum processing plant which piles since 2010 daily (around 2700 tones per day). The red mud residues contain aluminum, iron, vanadium, and titanium. Different groups of data were collected for the research including: in-situ samples (daily data of grades), Sentinel-2 images (to monitor the piling procedures and remote sensing studies), and a stereo image acquired by the PLEIADES satellite (acquisition date: 2019-05-23 with the resolution of 0.5 meter) (see Fig.2).

Research approach: Remote sensing analysis (spectrum view, histogram and correlations of bands, band ratios and classification approaches) was performed on Sentinel-2 images presenting materials which were piled between March and July (2019). Daily data corresponding to the months of March to July was used to map the strategic metals grades (iron, aluminum and vanadium). Data belonging only to two months was selected as reference data since during this shorter period only one thin layer of materials was piled in the BR and overlap of materials could be avoided. Hence, it was possible to monitor materials piling within two Sentinel images (an image at the end of April presenting piled materials during March and April, and the second image at the end of July presenting piled materials during June and July). To map grade variability, conditional Gaussian co-simulation was used using the Turning bands algorithm (Lantuejoul, 2002; Journel and Huijnregts, 1991). In-situ samples acquired during two months (transformed into Gaussian variable) were considered as the conditional variable and band-ratios (Laterite band-ratio for aluminum, ferrous silicate band-ratio for iron and band-5 for vanadium) (Van der Werff and Van der Meer, 2016), were considered as auxiliary variables. Grade maps of iron, aluminium and vanadium from different simulation realisations were obtained showing the materials variability during March-April and June-July (Kasmaee et al., 2021; Bruno et al., 2021). The stereo image of PLEIADES was used for validation and the BR volume of the identified digital elevation model (DEM) (see Fig.2).

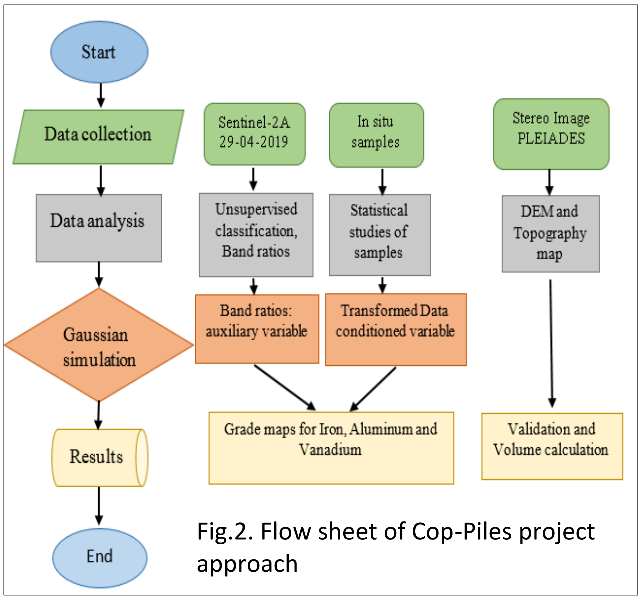


Fig.2. Flow sheet of Cop-Piles project approach

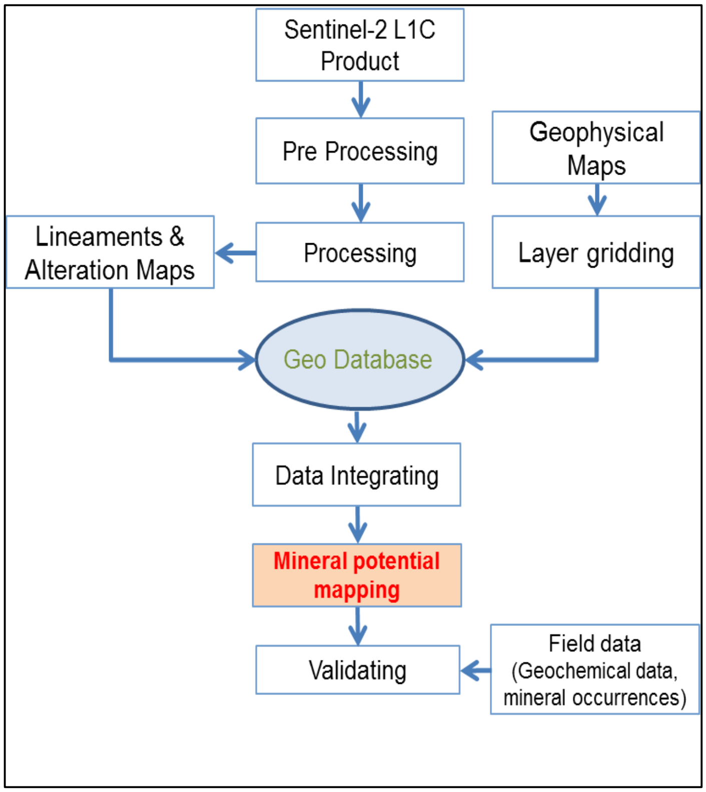
2.2 IOCG-SENSE Project

Background and objectives: This project established optimum procedures for the integration of space-borne remote sensing data with other geoscientific data and information for Iron Oxide Copper Gold (IOCG) mineral exploration. Due to the economic importance of these deposits given their attractive size and content of major raw materials, the relevance of IOCG deposits has continuously increased over the last two decades, placing them among the most important classes of ore deposits. Accordingly, IOCG deposits play an important role in the global raw materials market (Kolb and Stensgaard, 2009; Sandrin et al., 2009) and there is great demand-driven pressure to increase their supply globally.

The data procedures developed in this project were verified and evaluated based on data from Greenland. Using Greenland as a case study can contribute to increase the feasibility of exploration investments in a mineral-rich but challenging area. Mineral exploration in Greenland is in general very challenging and can lead to high investment costs due to the logistical issues arising from the lack of transportation infrastructure, the large size of the study area and adverse weather conditions. These adversities can be discouraging for investors. Improving the capacity to focus exploration on high potential areas is therefore of outmost importance, since it can help avoid wasting resources on areas with low mineral potential, thereby reducing investment risks. An important objective of the project was consequently to evaluate how Sentinel-2 data can be utilised to guide field exploration teams in their work and increase the efficiency of fieldwork.

Fig.3. Flow sheet of IOCG_SENSE project

Since the differences in spectral absorption characteristics of many minerals are subtle, selecting an efficient method to extract the spectral signature is essential. Extraction a set of meaningful spectral signatures or features from the original data could improve the process of classification. Several methods for feature extraction and dimensionality reduction of multi- and hyperspectral data in mineral exploration field exist. For example, principal component analysis (PCA), band ratio, wavelet transform, and linear discriminant analysis (LDA), among others, have been introduced in the literature (Abdolmaleki et al., 2018).



Case study: The area selected for examination in Greenland is Inglefield Land in Northwest Greenland. Inglefield Land has been subject to a number of investigations with the aim of providing data for mineral exploration (Dawes, 1999). A combined airborne magnetic and transient electromagnetic survey was performed 1994 followed by work in 1995 including geological investigation, mineralisation studies and regional geochemical survey. Geological research was also carried out in Inglefield Land in 1999 by the Geological Survey of Denmark and Greenland (GEUS). The objective was to complete the 1: 500 000 geological map and follow up the work on known and newly fund mineral occurrences in the area (Thomassen et al., 2000).

Research approach: In this research project, two tiles of Sentinel-2 Level 1C data covering the study area were utilised. After preprocessing the satellite data, principal component analysis, band ratios and filters were used to produce evidential remote sensing layers. Geophysical data (magnetic and electromagnetic) were combined with Sentinel-2 data to obtain information at depth (Rasmussen et al., 2003). **A** Fuzzy Analytic Hierarchy Process (FAHP) was applied to calculate the weights of each evidential layer and then fuzzy operators were used to integrate those values (Abedi et al., 2013). The final product, in the form of a prospectivity map, can be employed to generate a specific map to guide successful and optimised exploration activities. These maps can identify optimised areas for mineral exploration, increasing the efficiency of the process by integrating a new technological development (freely accessible Copernicus data). Finally, the map produced by the project was validated using results from previous research which included soil samples of the study area and had identified mineral occurrences and mapped high concentration of Fe sulfide. Fig.3 outlines the research and methodology approach employed in the project.

2.3 CopX project

Background and objectives: “CopX: Geospatial mining transparency through Copernicus and MapX” is a project that aimed to provide new insights from Sentinel-2 data on the detection and mapping of small-scale informal mining and its environmental impacts. The results of the project were integrated into MapX (https://mapx.org), an online open platform for mapping and visualising geospatial data on natural resources (collaboration with UNEP and UNEP/GRID-Geneva). The project contributes to the important debate on the sustainable use of natural resources. Small-scale mining occurs in various parts of the developing world, providing a livelihood to many households in poor and rural areas (Carstens, 2017). Unfortunately, these activities have major environmental and social impacts. Particularly in Colombia, informal mining activities lie at the heart of the country’s complicated armed conflict (Power, 2002; Rettberg and Ortiz-Riomalo, 2016).

Case study and data: CopX focused on the mapping of informal alluvial small-scale gold mining or placer mining in Colombia. Field visits to mining sites in the municipalities of El Bagre and Zaragoza in the department of Antioquia along with stakeholder meetings were carried out in December 2018 and March 2019. This knowledge was utilised in the processing of Sentinel-2 data in order to train the machine learning approaches and to obtain insights into the needs of the decision-makers.

Research approach:
The work carried out within CopX aimed to first assess the possible use of Sentinel-2 data to identify mining sites and distinguish them from other bare soil areas in the region. Such identification has been previously carried out using multispectral Landsat data in combination with airborne acquisitions (UNODC, 2018). However, Sentinel-2 had not been utilised or assessed for such an application prior to the CopX project. The second objective of CopX was to achieve an in-depth understanding of the development dynamics in mining areas through the study site.

The mine-detection procedure involved the use of field knowledge and an understanding of the mining process, particularly knowledge that each excavation requires a mining pond that is used in the mining process. Thus, CopX utilised a novel approach that aims at detecting mining ponds along with their corresponding excavated bare soil and tailings. This approach included the supervised classification of Sentinel-2 data followed by a post-classification procedure to correctly identify bare soil that is in the vicinity of isolated water bodies (Ibrahim et al, 2020). Supervised learning was carried out using a support vector machine classification approach of Scikit-learn in Python (Pedregosa et al, 2011), and post-classification analysis was carried out using the GeoPandas package (Kelsey et al., 2020) in Python. To understand the temporal dynamics in the area, change detection was used along with a sequential pattern mining analysis by Sequential PAttern Discovery using Equivalence classes (SPADE) (Zaki, 2001). This was implemented by the “arulesSequence” package in R Programming (Diaz and Buchta, 2019). SPADE allowed the identification of changes and trends annually and seasonally since 2016 (the start of the Sentinel-2 mission). Figure 4 shows the flowchart of the work. As project CopX aimed to achieve its objectives, it faced a major challenge in the preprocessing of Sentinel-2 data and the detection of clouds and shadows in the study area. Thus, in the scope of CopX, an approach was developed for the identification of pixels affected by clouds and shadows over Antioquia, Colombia (Ibrahim et al., 2021).

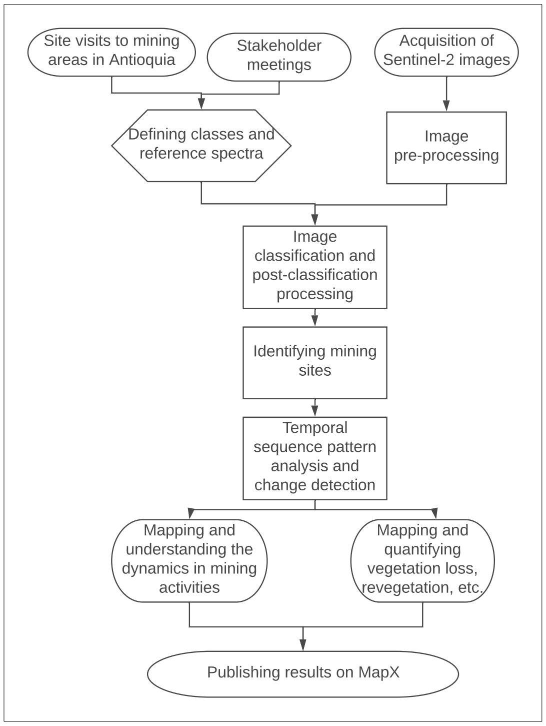


Fig. 4. Flowchart of the CopX project

2.4 InTarsis project

Background and objectives: The extractive industry must ensure a sustainable and safe supply of mineral resources, and one of the main hazards it has to deal with is ground instability. Earthworks, digging and pumping change soil mechanical properties and can provoke landslides and collapses that could have serious consequences economically, environmentally and in terms of loss of human life. The overall objective of the project is to contribute to a safe and sustainable extraction of mineral resources by improving the control over the integrity of the mining facilities. From a regulatory point of view and also following their own interests, mining companies are obliged to strictly control stability within their facilities, especially with regards to tailings-dams and open-pits. Terrestrial-monitoring systems are limited to discrete measuring-points (inclinometers, extensometers or GPS monitoring). These techniques are very precise but not suitable for covering large areas, especially when access is difficult or risky. By contrast, satellite data provides regular good resolution measurements even in remote sites.

Sentinel-1, which is in orbit since 2014, has shaken up the Synthetic Aperture Radar (SAR) world offering a wide range of opportunities, including ground motion monitoring at a scale useful for engineering work. By means of the interferometry of SAR images (InSAR), several studies show the capacity of Sentinel-1 to measure millimetric deformation in mines and civil constructions such as dams, roads, and bridges (Alex Hay-Man et al. 2017, Fernandez et al. 2016, Riccardi P. et al. 2017). The power of Sentinel-1 data for monitoring ground motion at the mining scale lies in its sensitivity, zero-cost, high revisit time, ubiquity and automation. However, this technology is rarely used by the mining sector due to the complex processing required. InTarsis is a project led by the CSIC that aimed to bridge this gap, standardising the use of radar images and improving the monitoring capacity in the sector by means of an automated algorithm that reduces processing requirements to a minimum.

Case study and data: The pilot site is located in Minas de Riotinto, an emblematic area with mining activity going back for more than 5000 years (Tornos F., 2006). Ore deposits are related to the Iberian Pyrite Belt massive sulfides, a vast Hercynian structure of 250 x 30 km covering Spain and Portugal. After the site was abandoned in 2001, activity in the Riotinto mine resumed in 2015, but only in the eastern open pit. The western pit (Atalaya pit) remains inactive. The study focuses on the historical Atalaya pit and surroundings where several instability problems have been identified such as landslides, subsidence, and collapses of galleries (Marzan et al. 2018). Our specific objective is to demonstrate that Sentinel-1 data is a tool that the mining companies can integrate and normalise for monitoring ground instabilities.

Research approach: To achieve the objective of InTarsis, a monitoring algorithm is being implemented to automate the processing of every new Sentinel-1 image (available every 6 days) and provide an update of the deformation field (see Fig. 5). The algorithm works in three main steps. First, a regular query of the Copernicus catalog is performed and new images are downloaded. Then, the processing loop is relaunched including the new images. Finally, the results are plotted and examined for velocity and coherence changes, and when thresholds are surpassed alerts are displayed. The algorithm was based on the free GMTSAR software of InSAR processing. It is being tested in the Riotinto mine demonstrating the capacity to monitor surface deformation at a mining scale with millimetric precision.

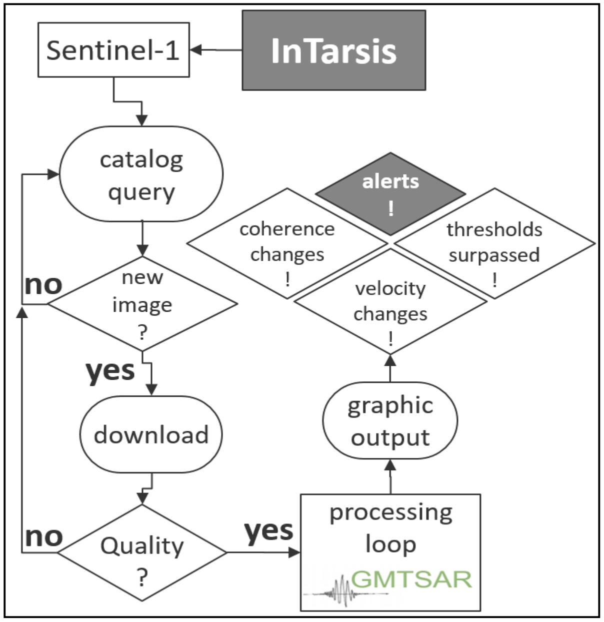


Fig. 5. Flowchart of the InTarsis algorithm

These four projects of the RawMatCop program have developed appropriate tools to improve the usability of Copernicus data in the mining sector. Despite all projects are based on the use of Sentinel-1 and 2 images, different methodologies have been developed according to the specific objectives of each project (Fig. 2 to Fig. 5). Considering that the main objective of the RawMatCop program was to promote the use of Copernicus data in the mining sector, the acquired capacities of researchers and the improvements achieved have led to the ideation and realization of different free courses, to share knowledge and to improve the capacities of mining stakeholders in Earth Observation technologies.

3. The Global Initiatives

The United Nation Sustainable Development Goals is the UN's comprehensive document for sustainable development, covering environmental, social, and economic objectives for future societies (UN General Assembly, 2015). Due to the sensitivity of mining activities and their relation to the global existential risk if the SDGs are not achieved, an awareness supporting SDGs in any project is essential (Cernev and Fenner, 2020).

Many of the SDGs for 2030 can only be attained with the contribution of minerals and metals in different industrial sectors (Mancini and Sala, 2018). The projects presented in this paper highlight how Copernicus data can be applied to improve practices in the raw materials sector in the areas of exploration, environmental impact mapping, tailing valorisations and the prevention of landslide hazards. In this process, several SDG goals have been supported (Fig.6).

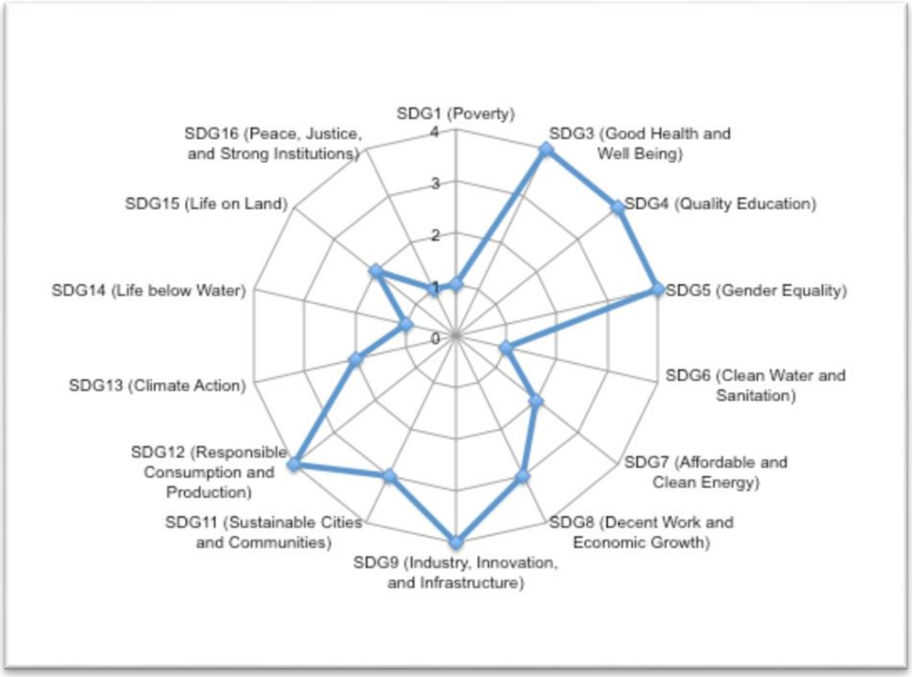


Fig.6. An overview of contribution to SDGs by the four projects COP-Piles, IOCG-SENSE, CopX, and InTarsis

All projects support SDG8 (Decent Work and Economic Growth) and SDG9 (Industry, Innovation, and Infrastructure) through the use of state-of-the-art Copernicus data to extract insights for the raw materials community. Furthermore, they contribute to SDG3 (Good Health and Wellbeing) and SDG12 (Responsible Consumption and Production) by tackling topics such as waste management, non-invasive mineral exploration, informal mining and is impacts, and improving the control over the integrity of mining facilities. The contribution of each project to specific SDGs is summarised in Table 1:

Table 1. Supported SDGs by RawMatCop projects and their applications

Project	SDGs	Explanation

COP-Piles	SDG8 (Decent Work and Economic Growth) SDG9 (Industry, Innovation, and Infrastructure) SDG11 (Sustainable Cities and Communities)	To support the reassessment of waste as a new source of raw materials; To reduce, recycle, revaluate and reuse of landfill mining residuals; To increase the economic potential of mining wastes and reducing their negative environmental impact; To integrate Sentinel data and Geostatistical modeling contributions
IOCG-SENSE	SDG7 (Affordable and Clean Energy) SDG8 (Decent Work and Economic Growth) SDG9 (Industry, Innovation, and Infrastructure) SDG13 (Climate Action) SDG15 (Life on Land)	To identify the high potential areas for mineral deposits in exploration campaigns; To use Sentinel data and Machine Learning (ML) techniques contributions; non-invasive and non-destructive approaches developments; To shift to the clean energy technologies
CopX	SDG1 (End Poverty) SDG8 (Decent Work and Economic Growth) SDG9 (Industry, Innovation, and Infrastructure) SDG11 (Sustainable Cities and Communities) SDG16 (Peace and Justice; Strong Institutions)	To improve the management systems of extractive resources and livelihoods of the concerned rural communities; To mitigate the environmental impact of extractive activities affecting the water quality and vegetation loss
InTarsis	SDG7 (Affordable and Clean Energy) SDG8 (Decent Work and Economic Growth) SDG9 (Industry, Innovation, and Infrastructure) SDG11 (Sustainable Cities and Communities) SDG13 (Climate Action) SDG15 (Life on Land)	To have a positive impact on the supply of mineral resources to sustain our new technology-based economy; To deployment the clean energy technology by providing safer and more sustainable mineral resources; to reduce the environmental impacts by improving monitoring capacity; To control the global warming by reducing mining risk and improving mineral supply efficiency

Moreover, the structure of the RawMatCop programme includes the delivery of short courses (https://eitrawmaterials.eu/eit-rm-academy/rawmatcop/rawmatcop-academy/) for sectoral actors to share and disseminate the results of all research projects. This enables a clear contribution of the programme to SDG4 on quality education. Notably, the four presented projects among others collaborated for the delivery of a four-day practical course from 2017 to 2021 (six editions, two in presence and four online), with participants from industry, research, academia, the public and the non-profit sectors. The main objective was to provide state-of-the art training in the use of remote sensing and Copernicus data for the raw materials sector.

Finally, RawMatCop, contributes to SDG5 (Gender Equality) through active presence and contribution of women researchers who remarkably represented 50% of team of 2018-2019 and 43% for the whole program 2017-2021, confirming the notable presence of women in the value chain of the Copernicus programme (Jagaille et al., 2020). This accomplishment is particularly noteworthy since mining has not been traditionally an equal-opportunity sector for genders (Tekinbas and Deonandan, 2021).

4. Results and Discussions

In all presented projects, results demonstrate the great potential of Sentinel-1 and 2 data to improve profitability, safety, and impact reduction of mining activity. It is also to be mentioned the importance of integrating spatial observations with ground base data (reflectivity, lab analysis lithology, GPS, infield samples, geophysical data, etc.). This integration is necessary to calibrate the satellite images with ground truth points and thus be able to extend the local measurements to the coverage provided by the image (swath of 100 km and 250 km for Sentinel 1 and 2 respectively) in a cost-effective way. This is a huge improvement that Sentinels can bring to an exploration or monitoring plan.

In the COP-Piles project, the collection of the available data, the preliminary statistical analysis and the remote sensing studies created the possibility to map metal-grade variability for the bauxite residues of Greece. Three main metals were chosen for grade mapping due to their high concentration inside the bauxite residuals and also given their prominence in European CRMs strategies. Iron and Aluminum were chosen since they have a higher concentration within the bauxite residues and are strategically important for processing plants. In addition, Vanadium was choosing as it is a CRM and given it is of strategical importance for the European Union. Hence, the V_2O_5 grade map was fundamental to evaluate the possibilities of recovering CRMs from bauxite residues in Greece. The main outputs of the COP-Piles project were the grade variability maps for Iron, Aluminum and Vanadium (see Fig.7) in a temporal range from March to July 2019. What's more, throughout the research process not only grade variability maps were created but also the piling of materials during the five months of study was monitored. The use of remote Copernicus data was fundamental in the project, since in-situ sampling from mining residuals was costly and challenging.

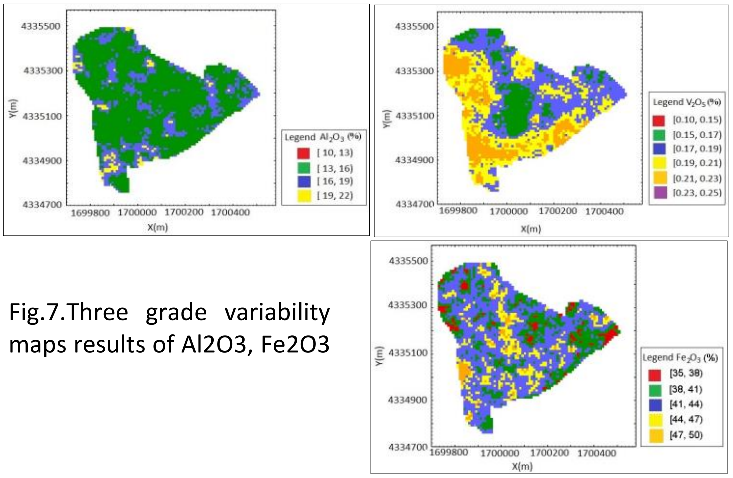


Fig.7.Three grade variability maps results of Al2O3, Fe2O3

In the contrary of COP-Piles project, in which metal grades were obtained for a small area, in IOCG-SENSE project, the main objective was to identify prospective areas in a large particular region for mineral exploration. To this end, multi-source data (remote sensing data, airborne magnetic and airborne electromagnetic data) were integrated to produce a mineral prospectivity map or a mineral favorability map. The final maps identifying the most prospective exploration areas were obtained with the integration of fuzzy operators (see Fig. 8). IOCG deposits were selected as the target of this study since they contain major resources which are prominent in the global raw material market. The main output of the IOCG-SENSE project was the delivery of cost-effective, timely and comprehensive solutions for mineral exploration. The final delivery was a prospectivity map with areas classified in three groups (high, moderate and low) according to the potential of IOCG deposits in Inglefield land. While in Fig.7, integration of Copernicus data with in-field samples created the detailed

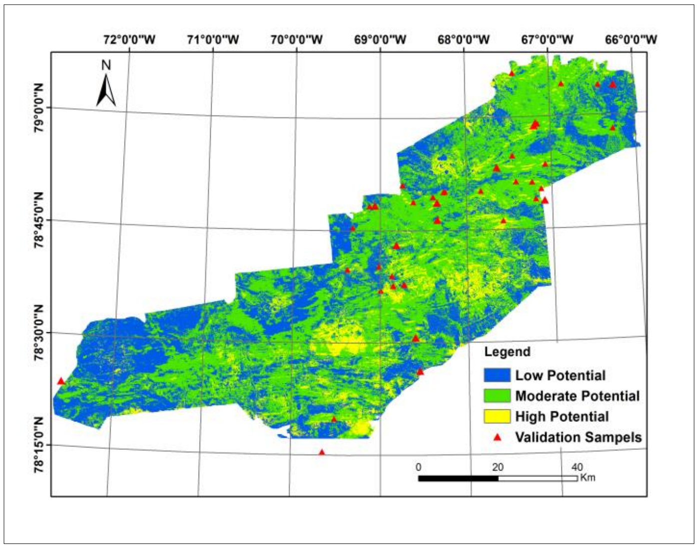


Fig.8. Prospective map based on FAHP technique in the Inglefield land

grade maps (for iron, aluminum and vanadium), the prospective maps defined the probability of IOCG potentials in a large area (Fig.8).

While targeting and monitoring in COP-Piles and IOCG-SENSE dealt with targeting spectrally distinct features in small-scale and large-scale study areas, project CopX's challenge was the lack of spectral distinction of mining bare soil and commission errors of sediment and other bare soil pixels were major. Thus, an approach targeting a unique spatial setting was considered where bare soil required the presence of small mining ponds to be considered a positively detected mining areas. The results obtained from the CopX project were diverse but of relevance to stakeholders and decision makers in the mapping of mining sites and understanding of the activity dynamics in the region. Two achievements could be highlighted. Firstly, CopX led to the creation of a methodology using free data for mapping placer mining sites in Colombia.

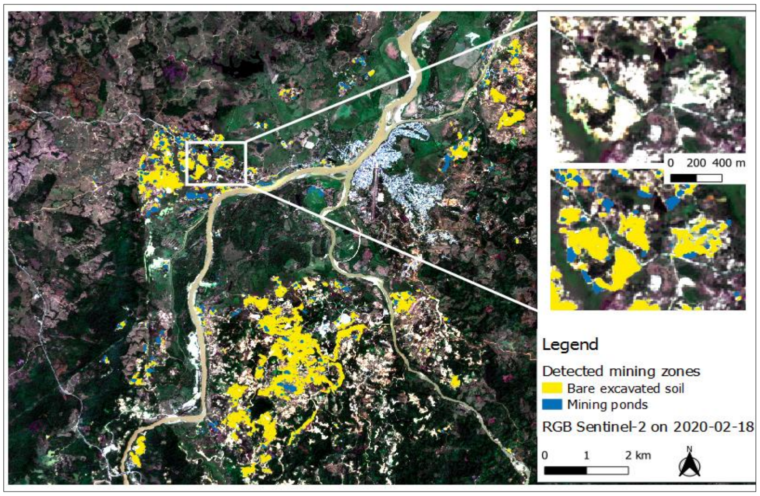


Fig.9. Alluvial mining (excavated soil with mining ponds) at the border of El Bagre and Zaragoza detected using sentinel-2 data acquired on the 18th of February, 2020.

Secondly, the project identified both mining bare soil and mining ponds. This is a novel identification approach that emphasizes the importance of including mining ponds in the calculation of surface areas affected by mining activities. Fig.9. shows a map of the detected mining sites composed of bare soil in the vicinity of mining ponds. In the investigated region, the area of mining ponds detected is equivalent to approximately 43% of the corresponding detected excavated soil.

The InTarsis monitoring system is the unique project that focused on Sentinel-1 and established a monitoring baseline. This has been done through the analysis of the deformation field around the target zone: Riotinto's inactive Atalaya pit. Four main deformation zones were identified. Three of them related to passive waste dumps showing subtle subsidence probably due to weathering. The fourth zone was the most conspicuous (Fig. 10), which belongs to the inactive Atalaya pit. The eastern wall showed a downward movement of up to 8cm/year. This is a convergence zone between a shale contact and a fault zone that weakens the wall and divides it into blocks. On the surface, movements between blocks and landslides are observed. The results correlates very well with the ground GPS monitoring network operated by the mining company (see Fig.10). The coverage improvement with respect to GPS data provided by Sentinel-1 data is remarkable, especially in the inaccessible terraces where no safe GPS measurements were possible. The last presented application results demonstrated the important potential of Sentinel-1 images to highlight the unstable areas, monitoring the evolution of the targets and controlling new occurrences.

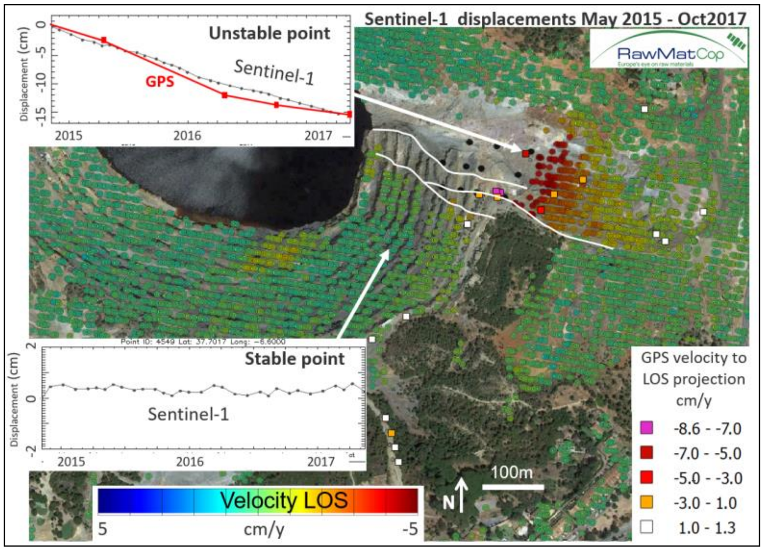


Fig.10. Inactive Atalaya pit in Riotinto. Circles in the map represent velocity values from Sentinel-1, green means stable and red subsidence. The squares are GPS ground measurements. Velocity is in LOS (line of sight) direction. The unstable area shows displacements of up to 8 cm/y. The graphs show cumulative displacement. In one of the GPS control points, the correlation (red line) is very good. Modified from Marzan et al. 2018.

The presented projects can facilitate Social License to Operate (SLO) agreements for mining activities since the open nature and high quality of Copernicus data improve transparency, efficiency and safety:

- COP-Piles results have shown that the low cost and continuous monitoring offered by Copernicus data can drive investment in the recovery of valuable materials (including CRMs) from mining residuals. This could represent a considerable investment opportunity for the more than 4.7 billion tons of mining waste and 1.2 billion tons of tailings waste (four categories of ferrous metals, non-ferrous metals, industrial minerals, and coal) stored all over European Union (Charbonnier, 2001). What's more, the robust monitoring power of Copernicus can also help shape social attitudes and reassure environmental agents of the desirability to exploit abandoned mining waste.
- In the IOCG-SENSE, the project's results can foster increased industrial investment in exploration activities by discovering local mineral deposits in the target area through the utilisation of Copernicus data. Moreover, inclusion of Sentinel data in the analysis allowed for the design of a more focused exploration programme at a reduced economic cost and also with a smaller environmental footprint compared to present day procedures. In addition to exploration companies, it is anticipated that methodologies and tools developed (e.g. the data processing algorithms) can also be of general interest for multidisciplinary researchers dealing with interpretation of geoscientific data.
- CopX project demonstrated the fundamental role of the development agencies and authorities active in the study, monitoring, planning, and creation of policies for the extractive industry. Such agencies have not yet fully tapped into the potential of Earth Observation and thus CopX aimed to provide them the means to exploit this technology through a case study evaluating informal mining and its dynamic behavior. The resulting information can contribute to suitable planning in the issuing of mining titles and licenses and in development mitigation and remediation campaigns in impacted regions.
- The InTarsis project demonstrated that Sentinel-1 is an unbiased measurement tool to improve control, safety and transparency in mining context. Therefore, InTarsis can facilitate regulatory compliance, in line with the makeover that the industry urgently needs to be accepted and viable in the future.

An additional advantage of the monitoring tools based on Sentinel data is the capacity to access the historic catalogue of images, which means that it is possible to perform analysis in the past. This will provide a picture of the situation before any intervention on a site and can be used as a reference for its restoration or for the management of potential conflicts.

5. Conclusion

Four different research projects funded by the RawMatCop Programme (2018-2019) are presented to demonstrate the potential of Sentinel-1 and 2 satellites to improve a safe and sustainable supply of mineral resource. The thematic developments cover the mining cycle from mineral resources exploration to the disposal and reuse of waste. The results show the potential of Copernicus free data for the raw materials sector. The COP-PILES and IOCG_SENSE projects demonstrate the potential of Sentinel-2 to cost-effective mapping of mineral variability at a small scale (mining residues) and at large scale (resource exploration in a remote area). On the other hand, the CopX project demonstrates the potential of Sentinel-2 to monitor informal mining activities in remote and unsafe areas and assess their impacts, contributing to efforts to mitigate affected sites and allow planning for efficient interventions. Finally, the InTarsis project demonstrates how Sentinel-1 is capable of monitoring ground stability in mining facilities, contributing to the safety of mining activities. Moreover, it’s pointed out that the ground truth measurements are required to correlate Copernicus data and together integrate into a holistic system to improve exploring and monitoring capacity of mining stakeholders.

Fig.11. Examples of contributions of Earth observation to the mining sector

In addition to being aligned with EU priorities and the UN Sustainable Development Goals, the results of the RawMatCop program highlighted the future prospective potentials in Raw Materials sector within different applications. Results demonstrated that the implementation of Copernicus data can generate profitability for the mining sector in a short period of time and can results in great added value to the sector (Fig. 11). With the EU aiming to integrate new and existing EO tools to improve best practices in the mining sector, innovation can only be expected to increase in the sector while providing new accuracy and quality measures for new EO-based products. Thus, with planned future satellite systems and their capabilities, EO-derived services will be essential for operational mining applications of the future.

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