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Remote sensing insights into subsurface-surface relationships: Unveiling geological structures and landforms at copper deposits

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Abstract
This review article delves into the transformative role of remote sensing techniques in elucidating subsurface-surface relationships at copper deposits. Understanding these connections is key to accurately finding and describing copper deposits, helping to make mineral exploration and extraction more efficient and sustainable. The purpose of this study is to provide a complete review of the use of remote sensing to characterise geological and topographical features in copper-rich areas by synthesising current research and technical advances. It explores key contributions from recent literature and case studies, shedding light on the intricate interconnections between subsurface geology and surface features. While remote sensing offers significant benefits, such as higher accuracy and broader coverage compared to traditional methods, it also faces limitations, including resolution constraints, the need for ground-truthing, and poor penetration in vegetated areas, necessitating complementary techniques. Through critical analysis, the article aims to offer valuable insights to researchers, geologists, and industry professionals engaged in mineral exploration and resource management. Ultimately, this review strives to serve as a vital resource, fostering informed decision-making and promoting sustainable practices within the dynamic realm of copper deposit exploration and exploitation.

Keywords
Landforms, copper deposits, mineral exploration, remote sensing, GIS, geological structures, sustainable practices, industry professionals.

1 Introduction

The exploration and understanding of mineral deposits, particularly copper, necessitate a comprehensive grasp of the intricate relationships between subsurface geological structures and surface manifestations (Pour et al., 2013). Remote sensing technologies have emerged as powerful tools in this endeavour, revolutionising our ability to unveil the complexities inherent in such subsurface-surface connections (Ganguly, 2023). This review seeks to thoroughly examine the current state of knowledge regarding the application of remote sensing techniques in delineating and characterising subsurface-surface relationships at copper deposits.

Copper, a crucial metal with diverse industrial applications, often occurs in deposits characterised by complex geological settings (Savini et al., 2021). Reflecting on the significance of this vital metal in the global economy, the International Copper Study Group's recently released 2023 Statistical Yearbook sheds light on world copper supply and demand data for the 10 years from 2013 to 2023 (ICSG, 2023). Through a critical analysis of relevant literature and case studies, this review aims to highlight the specific methodologies and technological innovations that have enhanced our understanding of subsurface-surface relationships in copper-rich environments (Damoah-Afari et al., 2023; Jung et al., 2022). Doing so aims to bridge the gap between theoretical insights and practical applications, providing a valuable resource for researchers, geologists and industry professionals involved in mineral exploration and resource management (Pour et al., 2023; Sahbeni et al., 2023).

The intricate landscapes of copper deposits, with their intricate interactions between geology, hydrology, and ecology, are complex environments that require an intricate understanding to inform sustainable practices and strategic decision-making within mineral resource exploration. By integrating remote sensing technology, we can unravel the intricate details of these landscapes, enabling us to navigate the intricate connections between copper deposits and their surroundings and ultimately facilitate more informed and effective decision-making within the dynamic field of mineral resource exploration. The importance of remote sensing in this area is becoming more widely acknowledged as pressure mounts to create novel technologies and techniques with less of an adverse effect on the environment (El-Desoky et al., 2023; Sabins, 1999).

2 Fundamentals of remote sensing

The fundamental principles of remote sensing encompass various aspects, including sensors, platforms, data acquisition and image interpretation (Dharaiya & Aditya, 2022). Key fundamentals of remote sensing encompass the following:

- **a) Electromagnetic spectrum**, which contains a range of energy wavelengths, is essential to remote sensing. Throughout the spectrum, different materials interact with energy in unique ways and either reflect or emit it.
- **b) Types of remote sensing:** Passive (detect natural radiation) or active (emit energy, measure response).
- **c) Platforms:** Platforms are carriers that house satellites and ground-based systems, among other remote sensing equipment.
- **d) Sensors:** Remote sensing sensors gather data from the electromagnetic spectrum, including optical (cameras), thermal infrared, microwave (radar) sensors, and more.
- **e) Resolution:** Remote sensing data has spatial, spectral, temporal, and radiometric resolutions.
- **f) Data acquisition:** There are an array of methods for gathering remote sensing data. One is through passive optical systems, which catch sunlight reflected off the Earth's surface. Another is through active systems, which send and receive signals (e.g., radar).
- **g) Image interpretation:** Interpretation involves analysing remote-sensing images to extract meaningful information. This may include identifying land cover types, monitoring changes over time or assessing environmental conditions.
- **h) Applications:** Remote sensing is applied in agriculture, forestry, environmental monitoring, urban planning, disaster management, and more.
- **i) GIS integration:** Data collected by remote sensing is frequently incorporated into geographic information systems (GIS) for the purposes of spatial analysis and forecasting.
- **j) Data analysis techniques:** Various techniques, such as image classification, change detection, and spectral analysis, are employed to extract meaningful information from remote sensing data.

Understanding the principles is critical for the effective and precise application of remote sensing technologies in various fields. The field of remote sensing is continuously developing due to technological advancements, which opens new avenues for scholarly investigation and practical applications (Navalgund et al., 2007; Yang, 2020). Figure 1 is a diagrammatic presentation of remote sensing applications (Lasheen et al., 2023).

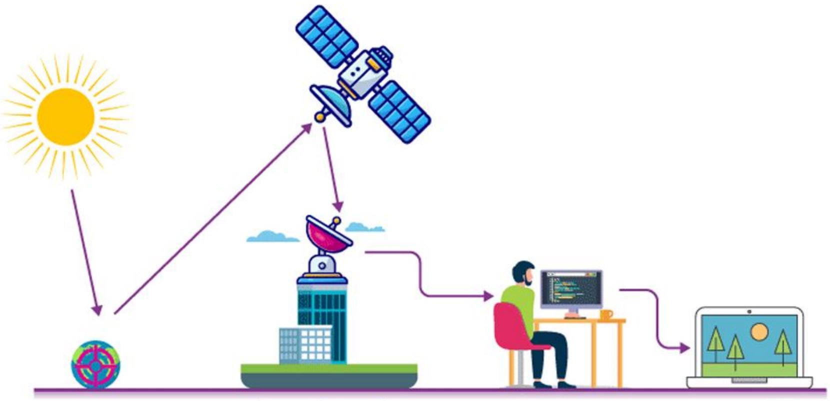

Fig. 1: Remote sensing technique (Lasheen et al., 2023).

Remote sensing is very useful in collecting data, even in areas inaccessible to human beings. Based on the platform, remote sensors are classified as airborne or spaceborne. Airborne sensors are mounted on aircraft like helicopters, balloons or UAVs, flying at low altitudes. This allows for the acquisition of high-resolution data but with limited coverage. Spaceborne sensors aboard satellites provide synoptic views that cover large areas but at a coarser resolution. Based on the recording type, remote sensor data are collected passively or actively using analogue or digital remote sensing instruments, ideally simultaneously as the in-situ data (Gautam & Mehta, 2015; Mahnaz et al., 2023).

2.1 Principles of remote sensing in geological studies

Geological applications in remote sensing exploit diagnostic spectral reflectance signatures and textural patterns to map surface distributions of rocks, soils, vegetation and water indicative of subsurface conditions (Brandmeier & Chen, 2019). Several unique capabilities make remote sensing highly suited for geological applications like structural mapping, lithological discrimination, hydrothermal alteration identification and geomorphological analysis (Sahbeni et al., 2023). Geological applications of remote sensing images include interpretation of the regional tectonic framework and lithology distribution (Ruisi et al., 2011). Multispectral and hyperspectral sensors facilitate the identification of geological materials based on diagnostic absorption features related to chemical composition. This enables lithological and alteration mapping (Kokaly et al., 2017). Optical, thermal and radar data provide information from the surface, as well as the shallow subsurface, due to variable penetration capacities, revealing obscured geological structures (Gojiya et al., 2023). Remote sensing plays a crucial role in geological studies by providing valuable information about the Earth's surface and subsurface features. Here are some key principles and applications of remote sensing in geological studies:

2.1.1 ***Spectral signatures***

There are different spectral fingerprints, or patterns of energy reflectance, for each type of rock. A wavelength-dependent spectral signature is an item's ratio of incident to reflected radiation energy. Geologists can detect and map different types of rocks and minerals by using remote sensing tools that can pick up these signals at different wavelengths. Spectral signatures obtained from remote sensing can be input into expert systems and machine learning algorithms to automate lithological and mineral mapping over large areas (Brandmeier & Chen, 2019; Sabins, 1999). Multi-temporal spectrum data can detect weathering, hydrothermal alteration, and other geological processes that change surface mineralogy (Bournas et al., 2015). This aids in the identification of sites with increased mineral prospectivity.

2.1.2 Lithological mapping

Maps of lithological units can be created using remote sensing data, particularly from optical and infrared sensors. Certain minerals and rock types have distinctive spectral properties that can be recognised and distinguished using image processing techniques (Van der Meer et al., 2014). Integration of remote sensing-derived lithological maps with other geospatial data in GIS provides critical information for geological modelling and analysis. Analysis of spectral variations within lithological units gives insights into subsurface compositional complexity that can guide drilling or sampling strategies (Wei, 2020).

2.1.3 Mineral exploration

Remote sensing is widely used in mineral exploration. Over time, geological mapping methods have evolved, and nowadays, the combination of remote sensing data and advanced data analytics, such as machine learning, is gaining much attention. This combination helps geologists overcome common challenges of traditional methods, such as subjective judgment, that can provide reliable maps and avoid wasting money on prospecting in barren regions. Certain minerals exhibit characteristic spectral reflectance patterns in different wavelengths. This allows geologists to identify potential mineral deposits and map their distribution. Integrating remote sensing data with other geospatial datasets in GIS software provides an enhanced understanding of geological contexts for detected mineral anomalies and improves exploration targeting (Liu et al., 2023; Ruisi et al., 2011; Shirmard, 2022). This can reveal new sites of interest for follow-up sampling or drilling. Automated analysis of remote sensing data, using machine learning, has accelerated global-scale mapping of mineral prospectivity to aid companies in the acquisition of new licenses (Damoah-Afari et al., 2023; Folkes, 2017; Navalgund et al., 2007; Yusoff et al., 2015).

2.1.4 Alteration zone detection

Remote sensing can detect alteration zones associated with mineral deposits. Due to recent extensive studies, remote sensing has proven to be helpful in detecting alteration zones and, consequently, mineral explorations. Hydrothermally altered rocks are often associated with many ore deposits, which have specific spectral features that are identifiable in multispectral remote sensing data (Bournas et al., 2015; Cathles & Smith, 1983; Ciampalini et al., 2014). Mineral composition changes caused by hydrothermal alteration result in distinct spectral signatures that can be determined using remote sensing data (Fu et al., 2023). High spectral resolution remote sensing systems can identify specific clay and sulphate minerals that are indicative of hydrothermal alteration related to buried mineralisation. This allows to focus on specific targets within larger regional alteration footprints. Temporal analysis of vegetation stress and health, using remote sensing, aids identification of alteration zones containing phytotoxic minerals at depth (Bahrami et al., 2021; Hewson et al., 2021).

Understanding these principles and applying remote sensing techniques in geological studies enables geologists to gather information efficiently, make informed decisions and contribute to the broader understanding of the Earth's geological processes (Ruisi et al., 2011). Techniques like photogrammetry, LiDAR, and radar interferometry yield high-precision digital elevation models and assist in structural and geomorphological mapping. Global DEMs of the Earth and coverage of the Earth's sea floor and ice caps have fostered terrain modelling at broad spatial and temporal scales. In some respects, this trend returns morphometry to its origins in the quantitative generalities sought by von Humboldt and his successors, but with a sophistication and emphasis on geologic processes that were absent from the older work (Pike, 2002).

2.2 Types of remote sensing technologies relevant to copper deposits

A variety of remote sensing systems and techniques have emerged over recent decades that hold great potential for analysing and mapping copper deposits based on their unique surface expressions. According to Pour et al. (2023), systems like AVIRIS, Hyperion, and EnMAP acquire high spectral resolution images in hundreds of narrow, contiguous bands spanning visible to infrared wavelengths. This allows detailed mapping of hydrothermal alteration minerals associated with copper deposits based on spectral signatures (Van der Meer et al., 2014). Thermal infrared sensors, like TIMS, ASTER, Landsat and ECOSTRESS, can map surface temperature variations to indicate geothermal activity, hydrothermal alterations and structural controls related to concealed copper mineralisation (Ourhzif et al., 2019). Remote sensing technologies play a significant role in identifying and studying copper deposits. Various sensors and techniques are employed to detect and characterise the geological features associated with copper mineralisation.

2.2.1 Optical remote sensing

Optical sensors, operating in the visible, near-infrared and shortwave infrared wavelengths, are widely used in copper exploration to identify and map alteration minerals associated with mineralisation. Porphyry copper (Cu) deposits are typically associated with distinct hydrothermal alteration zones, such as potassic, phyllic, and propylitic zones, which are characterised by specific mineral assemblages. The potassic alteration zone, often proximal to the mineralised core, is marked by the presence of potassium feldspar and biotite (Liu et al., 2023). This zone is typically surrounded by the phyllic alteration zone, which is dominated by quartz, sericite (muscovite), and pyrite, often overprinting the potassic zone. The outermost zone is the propylitic alteration zone, characterised by the presence of chlorite, epidote, and calcite minerals (Fu et al., 2023). The spectral response patterns of key alteration minerals can indicate processes related to hydrothermal fluid flow and copper precipitation, making them direct markers for buried copper deposits. Phyllically altered rocks are characterised using visible and shortwave-infrared (VNIR+SWIR) wavelengths by Al–OH absorption in ASTER band 6 because of molecular vibrations in muscovite, whereas argillically altered rocks have an absorption feature in band 5 resulting from alunite (Rowan et al., 2006; Van der Meer et al., 2014). Analysis of multi-temporal optical data has emerged as an important technique for alteration zone delineation, as weathering processes and hydrothermal reactions can cause temporal changes in surface mineralogy overlying copper deposits. Machine learning classification, applied to VNIR data, improves the accuracy of mineral mapping and lithological discrimination, which is important for copper exploration (Abdelouhed et al., 2021).

2.2.2 Thermal Infrared (TIR) remote sensing

Thermal infrared imaging (TIR) sensors can detect temperature anomalies associated with hydrothermal alteration zones, which are often indicative of copper mineralisation. According to their heat capacities and thermal conductivities, TIR surveys that are flown at various times of the day reveal diurnal temperature fluctuations that help identify alteration minerals (Brandmeier & Chen, 2019; Yang & Oldenburg, 2012). ASTER TIR data are important for mapping lithologies that lack distinguishing VNIR+SWIR absorption features, particularly quartz and feldspars. Fusion of TIR data with hyperspectral and topographic data in 3D environment models enhances understanding of geothermal activity in the context of subsurface geological structures (Khaleghi et al., 2020; Liu et al., 2023).

Thermal satellite imagery enables geologists to target areas of hydrothermal alterations that have higher chances of mineralisation. Analysis of thermal images from platforms like ASTER provides critical insights into the nature and extent of subsurface mineralisation. Recent advancements in thermal imaging technology have improved the detection and mapping of thermal anomalies, enabling enhanced copper targeting (Fu, 2023; Pike, 2002; Sabins, 1999).

Combining these remote sensing technologies allows geologists and exploration teams to comprehensively study the geological context of copper deposits, from regional mapping to detailed site characterisation. Integrating multiple data sources enhances the accuracy and efficiency of copper exploration and resource assessment. Digital photogrammetry creates detailed 3D terrain models from overlapping aerial or satellite stereo imagery to assist in interpretable geological feature identification. Medium-resolution multispectral data from satellites like Landsat, Sentinel-2 and WorldView provides essential baseline information on geology and structures at regional scales (Ourhzif et al., 2019).

3. Geological structures and remote sensing

Geological structures exert critical controls on copper mineralisation by providing conduits that focus on hydrothermal fluid flow to form copper deposits. Structures, including faults, fractures, fold axes and stratigraphic contacts, localise mineralising fluids and determine sites of copper ore formation. Analysis of spatial patterns of mineral deposits and quantification of their correlation with detailed structural features are beneficial to understanding the plausible structural controls on mineralisation. Therefore, identifying and analysing surface expressions of concealed geological structures is important for successful copper exploration (Sun et al., 2018).

Through the integration of several remote sensing technologies and analytical methodologies, geologists can acquire a significant understanding of the Earth's geological formations. These insights are essential for geological mapping, hazard assessment, resource exploration and understanding the dynamic processes shaping the Earth's crust. Remote sensing enhances the targeting of copper exploration initiatives and drilling operations by identifying surface manifestations of hidden faults, stratigraphic interfaces, and fold formations that govern hydrothermal fluid movement. Integration of remote sensing structural data with borehole and field data surveying provides critical insights into the structural architecture and paleo stress history, determining sites of copper ore formation hidden beneath cover (Rajesh, 2004).

3.1. Case Studies Illustrating Structural Mapping at Copper Deposits: International, regional, and National level

Numerous case studies from around the world showcase successful applications of remote sensing techniques for revealing and analysing geological structures associated with copper deposits across diverse geographical settings (Haest et al., 2007; Lin et al., 2021; Pour et al., 2013; Ruszkiczay-Rüdiger et al., 2009). At the Dikulushi Cu-Ag sedimentary rock-hosted deposit in the Democratic Republic of Congo, ASTER satellite data analysis highlighted significant NNW and NNE trending regional structures that served as important controls on copper mineralisation (Haest et al., 2007).

In the Nantou copper porphyry district of central Taiwan, a 15-band ASTER satellite imagery study combined with field spectroscopy surveys and verification sampling was undertaken to characterise lithological alterations and structural features associated with copper mineralisation across the 10 km wide prospective area underlain by volcanic and sedimentary lithologies. Traditional studies on lithological alterations, structural features, and landform recognition relied on the visual interpretation of topographic maps and aerial photographs, which inevitably need field investigations and manual discrimination due to the limitation of technology (Lin et al., 2021; Fu et al., 2023). With the technological development of the geographic information system and remote sensing, as well as the acquisition of high-quality geospatial data, ASTER visible-near infrared (VNIR) and shortwave infrared (SWIR) band ratio analysis integrating absorption features in bands 5, 6, and 8 helped discriminate zones of argillic, phyllic, and propylitic hydrothermal alteration minerals including alunite, muscovite, and chlorite representing the geochemical halo overlaying subsurface copper enrichment. SWIR bands also highlighted intensely silicified lithoscopes (Lin et al., 2021; Ciampalini et al., 2014).

Structured principal component analysis followed by directional filtering was utilised to enhance subtle lineament expressions of regional fault and fracture patterns in the ASTER data, corresponding to conduit structures focused on metal-bearing solutions. Prominent northeast-southwest and subsidiary northwest-southeast mineralised fracture trends were evident, coinciding with strike-slip structural regimes. Integrated analysis revealed alteration anomalies concentrated around intersections of these two structural orientations, highlighting subsurface permeability pathways for ascending copper-enriched hydrothermal fluids (Ruszkiczay-Rüdiger et al., 2009; El-Desoky et al., 2022; Khaleghi et al., 2020). Verification drilling across zones delineated through the remote sensing techniques encountered planned targets showing close agreement between surface expressions and subsurface copper grades. Satellite imaging helped lithological-structural modeling guide effective exploratory drilling, demonstrating the utility of multispectral analysis in reconnaissance characterising veiled terrains to find hidden resources (Ruszkiczay-Rüdiger et al., 2009).

A remote sensing study using ASTER satellite imagery was undertaken to identify copper mineralisation in the Hashtjin region (NW Iran), located within the vast Urumieh-Dokhtar metallogenic belt known for copper deposits. Several remote sensing investigations for mineral exploration and lithological mapping have been conducted in arid and semi-arid terrains, with large exposures of geologic materials, allowing the acquisition of spectral information directly from rock–sil assemblages (Pour et al., 2013; Sun et al., 2018; Mahnaz et al., 2023). However, in tropical environments, the application of remote sensing data for geological mapping has been much more limited because of the dense, often complete vegetation cover in tropical regions. Moreover, the persistent cloud cover and limited bedrock exposures are other obstacles imposed by tropical environments (Pour et al., 2013).

Numerous analysis methods were implemented on ASTER spectral data, including Spectral Angle Mapper, Matched Filtering, and Principal Components Analysis to delineate argillic, propylitic, and sericitic hydrothermal alteration zones associated with porphyry copper systems (Kokaly et al., 2014; Kruse, 2010). Applications of these remote sensing techniques combined with field verification successfully mapped alteration patterns related to concealed copper mineralisation in the Kerman Cenozoic arc terrane of Iran's central Tethyan belt and the SE Anatolian orogenic belt in Turkey (Labdaoui et al., 2023; Pour et al., 2013). Integration of remote sensing data with geological, geochemical, and geophysical surveys has a high potential to detect new porphyry copper targets for exploration in the Urumieh-Dokhtar belt and specifically the relatively under-explored Hashtjin area (Pour et al., 2013).

In 2021, High-resolution IKONOS multispectral data (1m) combined with ASTER VNIR-SWIR imagery (15m pixels) was collected over the 450 km^2 Heiqia prospect area in western China to map lithological and hydrothermal alteration patterns related to copper, lead, and zinc mineralisation concealed beneath the remote mountainous terrain. False colour composites integrating IKONOS bands 1, 2, and 3 helped differentiate gossan oxide zones and jarositic argillic alterations associated with subsurface non-ferrous metallic enrichments based on characteristic colour tones following image enhancement (Lin et al., 2021; Fu et al., 2023). Two concealed Cu-Pb-Zn belts were inferred to be trending along the regional structural fabric. Belt I lies in phyllite-metagraywacke sequences with dominantly structurally controlled vein/fissure fill copper ores. Belt II occurs in dolomitised limestone hosts with mainly strata-bound lead-zinc replacements. ASTER-based lineament analysis revealed the alterations concentrated at intersection zones of the two cross-cutting structural trends. The study demonstrated immense potential in combined multispectral optical and hyperspectral thermal infrared data for reconnaissance characterisation of complicated mountainous terrains towards efficiently locating concealed non-ferrous metallic deposits through coordinated surface-subsurface feature analysis (Ciampalini et al., 2014; Fu et al., 2023).

The Gondwana region of Tibet provides an insightful case study for applying advanced spectral analysis techniques to the structural mapping of copper deposits. Although there are important porphyry copper deposits in this mineral-rich region, the associated hydrothermal alteration cannot be sufficiently mapped using present techniques (Zhang et al., 2017). A new spectral feature-enhanced principal component analysis method proves superior for extracting alteration information from ASTER multispectral imagery across the Gondwana belt. Located in the southern part of the Tibetan Plateau, the Gondwana region is remote and difficult to access, making traditional mineral exploration challenging. However, due to the region's favourable deep dynamics, it has abundant mineral resources, and world-class porphyry copper deposits in areas such as Qulong and Jiama have been recently developed (Ikponmwen & Oyibo, 2023; Liu et al., 2023; Saylam et al., 2023; Wei, 2020).

In the Saga County area, Neoproterozoic porphyry bodies visible in the remote sensing analysis correlate with known surface copper mineralisation not previously exploited. Likewise, an interpreted Paleoproterozoic fracture zone under cover in Xietongmen County presents a compelling target for follow-up sampling and drilling (Liu et al., 2023; Sahbeni et al., 2023). Large-scale alteration mapping better defines the shape and extent of these prospective zones than existing geological maps. This innovative image processing lays the groundwork for uncovering new copper enrichment zones by translating raw spectral data into relevant geological interpretation.

Additional field verification and sampling are warranted where the remote predictions imply significantly more concentrated copper than is evident superficially. This cost-effective approach for focusing exploration efforts could apply to buried porphyry systems worldwide (Liu et al., 2023; Wang et al., 2022).

Main knowledge gaps remain regarding the accurate subsurface projection of the structures visible through surface lineament expressions seen in remote sensing data analysis. The decline in the number of newly discovered mineral deposits and the increase in demand for different minerals in recent years has led exploration geologists to look for more efficient and innovative methods for processing different data types at each stage of mineral exploration (Rajesh, 2004). Different types of remote sensing datasets, such as satellite and airborne data, make it possible to overcome common problems associated with mapping geological features. Therefore, direct validation and calibration of remote sensing interpretations relative to measured orientation from field mapping, drill core, and geophysics are required to strengthen confidence in predictions of subsurface structures from surface expressions (Jones et al., 2019; Bournas et al., 2015). As sensor resolutions improve, advanced processing algorithms emerge, and integration with exploration datasets progresses, remote sensing-based structural mapping offers immense potential to guide copper exploration globally across concealed terrains lacking outcrops (Shirmard et al., 2022).

3.2 Advances in Remote Sensing Techniques for Structural Analysis

Significant advances in remote sensing technologies and analytical techniques continue to emerge, enhancing capabilities for detailed structural geological mapping to guide mineral exploration (Sabins, 1999). These developments enable more accurate and higher resolution characterisation of surface expressions related to subsurface structures controlling mineralisation. This makes it possible to have a more thorough understanding of the spatial linkages that exist between surface characteristics and subsurface geology, which in turn facilitates more informed decision-making regarding the exploration, assessment, and exploitation of resource-rich regions (Kruse, 2010). Increasing availability of very high resolution (VHR) multispectral satellite sensors like WorldView, Quickbird, and Pleiades provides imagery with pixel sizes down to 0.3 meters, assisting identification of small-scale geological structures, including meter-scale faults and fracture networks (El-Desoky et al., 2022). This section highlights some key areas of advancement in remote sensing techniques for structural geology studies.

Remote sensing datasets have provided a new data resource to overcome problems associated with mapping geological features from field data alone. As a data-driven classification or prediction tool, neural networks have been widely applied in remote sensing data processing as well as a large number of research areas ranging from engineering to environmental science. As remote sensing resolutions and analysis workflows improve, their role will keep increasing to identify exploration targets and refine geological models. However, integration with direct subsurface measurements remains essential to maximise interpretational accuracy. All things considered, these technological developments provide immense potential to guide copper exploration globally through enhancing analysis of surface expressions related to elusive subsurface structures associated with concealed deposits across poorly understood regions (Shirmard, 2022).

4. Landforms and Remote Sensing

Terrain morphometry and associated landforms provide important clues regarding geological structures, lithological contacts, and Quaternary processes influencing copper mineralisation. The exploration of buried mineral deposits is required to generate innovative approaches and the integration of multi-source geoscientific datasets (Mahnaz et al., 2023). Subsurface structures, including faults and igneous intrusions, control landform patterns through differential erosion. Depositional landforms reveal mineralised paleochannels. Elevation data enables landform characterisation. GIS-based terrain analysis of remotely sensed DEMs enables reliable semi-automated classification of landforms using morphometric parameters like slope, curvature, and surface texture (Dewaele et al., 2006). Landforms discernible in DEMs, including ridges, valleys, cols, and saddles, may indicate structures influencing mineralisation. Depositional landforms are also mappable.

4.1 Mapping Landforms Associated with Copper Mineralisation

Landform characterisation using remote sensing-derived digital elevation models enables analysis of surface morphologies related to subsurface geological structures, lithological contacts, hydrothermal systems, and paleo-climatic influences associated with copper genesis and localisation (Lin et al., 2021). Ridges and erosional escarpments involving sedimentary strata evident in high-resolution DEMs can reveal bedding contacts, structural trends, and stratigraphic layering, which commonly control strata-bound copper deposits (Wu et al., 2023b). Linear valleys controlled by regional fault zones visible in DEMs could represent conduits for hydrothermal fluid flow and associated copper mineralisation (Dewaele et al., 2006). Various landforms identifiable through remote sensing provide valuable clues to copper mineralisation processes and deposit settings.

Linear Valleys and Drainage

Automated extraction of valley networks and drainage alignments from DEMs using hydrological analysis techniques enable the identification of structural lineaments associated with fault conduits bearing hydrothermal mineralisation. Drainage pattern analysis reveals rectilinear valley segments controlled by fracture zones that can focus on copper-bearing hydrothermal fluids. The location of geological lineaments such as faults and dykes are of interest for a range of applications, particularly because of their association with hydrothermal mineralisation. Although a wide range of applications have utilised computer vision techniques, a standard workflow for applying these techniques to mineral exploration is lacking. A framework for extracting geological lineaments using computer vision techniques consists of edge detection and line extraction algorithms for optical remote sensing data. It includes supplementary computer vision algorithms for lowering data dimensionality, eliminating noise, and improving lineament expressiveness (Farahbakhsh et al., 2020).

Landform Analysis

Geomorphic features and landforms, such as river valleys, alluvial fans, and volcanic structures, can be studied using remote sensing. This information is valuable for understanding geological processes and landscape evolution (Lin et al., 2021). Since the landforms contain abundant information on geomorphology, environment, and hydrology, landform quantification and recognition are critical procedures for geomorphological mapping and landform classification. DEMs and digital terrain analysis enable quantitative measurement of landforms to analyse relationships between geomorphology and underlying geological structures or units. Multi-temporal landform change detection with remote sensing assists in the identification of areas with heightened mineral prospectivity due to recent exposure of lithological contacts or fault zones (Ahmadi & Pekkan, 2021).

4.2 Case Examples Demonstrating Landform Analysis in Copper Exploration

Numerous case studies from global copper exploration and mining regions demonstrate the immense value provided by remote sensing-centred high-resolution landform characterisation and geomorphological analysis in understanding ore deposit localisation factors. At the Dexing copper mine in China, radar image texture and ASTER-DEM-derived morphometry identified landforms marking the spatial transition from sedimentary to igneous lithologies hosting the deposit. In Central Iran, morphotectonic analysis of drainage and DEM data revealed uplifted ridgelines and erosional valleys controlled by faults associated with copper mineralisation (El-Desoky et al., 2023; Khaleghi et al., 2020).

In the Jahrum region of Central Iran, a morphotectonic investigation utilising drainage pattern analysis and land surface structural mapping using digital topographic data revealed uplifted ridgelines and erosional valleys controlled by faults and fracture corridors associated with hydrothermal alteration bearing copper mineralisation (Ruisi et al., 2011). At the Mundongwa structurally controlled vein-type copper deposits in Papua New Guinea, sophisticated remote sensing-based landform element and watershed-scale hydrological terrain analysis revealed locations of significant topographic discontinuities and zones of hydrothermal alteration directly overlaying known copper mineralisation areas, highlighting the importance of litho-structural boundaries in controlling copper deposition (Machireddy, 2023a). These examples demonstrate the various landform mapping applications that use remote sensing as a crucial analytical tool in the discovery of copper mineral systems at the regional to local scale.

5. Integration of Remote Sensing Data

Complex subsurface environments associated with copper genesis and ore formation involve multifaceted lithological, structural, hydrological, and alteration components interacting at different scales. Hence, deriving holistic insights into the geological system dynamics requires assimilating diverse remote sensing datasets sensitive to varied terrain manifestations with measured field data using suitable deposit model frameworks as guides. Hydrothermally altered rocks have received substantial attention for the cause of their potential economic implications (Bahrami et al., 2021). Optical, thermal, and microwave datasets each contribute complementary information on surface expressions of subsurface features based on interaction with different terrain properties at their characteristic wavelengths. Integrating suitable combinations using geographic information systems enables a more comprehensive characterisation of lithological domains, structural fabrics, hydrothermal alteration signatures, and land surface changes (Ruisi et al., 2011).

5.1 Challenges and Opportunities in Data Integration

Since mineral deposits with a surface expression have largely been discovered, mineral exploration is increasingly seeking deeper targets under a near-surface cover sequence. The main challenges complicating the integration of diverse remote sensing datasets with subsurface field data include complex multi-stage workflows necessitating expertise with individual technologies, interoperability issues between data formats and models, differing spatial resolutions, and post-processing uncertainties between sensors, and requisite in-depth knowledge of relevant geological concepts and processes. These factors impose significant data management, analytics, and interpretational demands spanning computer science, geospatial analysis, and geology disciplines to enable meaningful assimilation of surface and subsurface observations toward accurate subsurface inference. This necessitates multi-disciplinary collaboration and training (Dentith et al., 2019; Rajaram et al., 2009).

However, expanding computational power enables processing larger datasets, while advanced joint inversion methods integrate diverse parameters to constrain models better. Progress in spatial data infrastructure and database standards improves interoperability while increasing the availability of multi-year remote sensing time series data, which provides new opportunities (Folkes, 2017). Ongoing technology and methodology improvements must continue to tackle integration challenges to maximise the utilisation of expanding remote sensing capabilities for geology.

5.2 Advances in GIS and Remote Sensing Integration for Copper Exploration

Robust spatial database platforms like ESRI's ArcGIS Geodatabase facilitate the systematic organisation of diverse remote sensing, geophysical, and geoscience datasets to enable combined analysis and modelling towards developing integrated subsurface interpretations. Standard data models aid access, ensure consistency, and provide versioning. Multi-dimensional data cube structures optimise storage and access workflows to fuse large archives of multi-temporal data from platforms like Landsat and Sentinel to enhance subtle near-surface change detection through time. Cloud computing and distributed geo-processing systems scale computation for big data across platforms (Bournas et al., 2015; Ndatuwong & Yadav, 2014).

The foundations and core components of Data Cube are (1) data preparation, including geometric and radiometric corrections to Earth observation data to produce standardised surface reflectance measurements that support time-series analysis, and collection management systems which track the provenance of each Data Cube product and formalise re-processing decisions; (2) the software environment used to manage and interact with the data; and (3) the supporting high-performance computing environment (Chitalin et al., 2020; Lewis et al., 2017; Mccaffrey et al., 2005).

Sophisticated joint inversion algorithms that assimilate potential field, geological, spectrometric, and geochemical data enable estimating unified subsurface models consistent across parameters, better constraining deep 3D domains associated with copper deposits. Expert systems combining geological concepts with machine learning algorithms facilitate semi-automated integrated analysis to rapidly assimilate and classify complex multisensor observations, while immersive 3D visualisation aids interactive interpretation (Mccaffrey et al., 2005).

6. Challenges and Future Directions

Despite demonstrated potential across diverse applications, some persistent challenges remain impeding more widespread adoption of remote sensing technologies for copper exploration programs. Geological mapping methods and technological and scientific advances are continuously changing in other relevant fields. Mineral resources are products of geological processes, and the exploitation strategy is governed by geological factors and the environment in which these deposits occur (Ganguly, 2023; Sabins, 1999). Constraints span technological aspects like sensor resolutions or algorithm accuracies as well as non-technical factors, including data integration complexities, inadequate personnel training, and conservative industry mindsets favouring traditional methods over innovation (Calvin et al., 2015).

However, the rapid progress in remote sensing systems involving new satellite constellations, unmanned aerial vehicle deployments, improved analytics, and cloud computing promises continuing developments that could help overcome current limitations. Knowledge-driven forward models and data-driven inversion models are double-edged swords in geoscience research. Therefore, it is of utmost importance that the model outputs can be interpreted (Fu et al., 2023). Combined with increasingly routine assimilation into geoscience and mining workflows, remote sensing is poised to take on greater prominence in guiding subsurface exploration globally. However, conscious evaluation of remaining weaknesses must inform future maturation pathways to fully leverage remote sensing's potential to reveal elusive concealed copper systems through integrated surface expressions.

6.1 Current Challenges in Remote Sensing for Copper Exploration

Available multispectral satellite systems like Landsat, Sentinel-2, ASTER, and Worldview-3 provide immense regional perspective at 10 to 30-meter pixel resolutions but remain inadequate for detailed mineral exploration applications demanding sub-meter data (van der Werff & van der Meer, 2016). Hyperspatial commercial satellites are expanding higher resolution options but have high costs and inadequate spectral resolution. Similarly, airborne hyperspectral data below 5-meter Ground Sampling Distance (GSD) provides immense information richness through narrow-band mineral identification, but has limited spatial availability and remains expensive for widespread application (Bašić, 2023; Ciampalini et al., 2014; Pour et al., 2023). Tasking dedicated surveys is unviable for early exploration. Regional hyperspectral satellite missions could overcome this but lag current medium-resolution multispectral constellations.

Remote sensing relies primarily on reflected surface electromagnetic energy, restricting direct mineralogical identification to alteration assemblages or geobotanical anomalies, with limited penetration for direct subsurface detection of primary mineralisation (Elhamdouni et al., 2023). Resolving subsurface geology requires indirect geomorphic indicators and extensive field calibration. Geological and lithological classifications based on remote sensing data require a large number of data containing relevant information about different rock types at the pixel level. Subsurface imaging radar technologies remain limited. Qualitative interpretation of structures, lithologies, vegetation patterns, or landforms from remote sensing data involves inherent subjectivity adding ambiguity to subsurface projections (Pour et al., 2023). Automated classification through emerging machine learning algorithms aims to overcome this but requires extensive training data. Structured expert input is essential for final map generation and analysis.

A key challenge Involves the non-uniqueness and ambiguity of some surface manifestations discernible through remote sensing like subtle vegetation color patterns or drainage alignments, permitting multiple competing subsurface explanations. This uncertainty requires the integration of additional subsurface constraints to converge on higher confidence deposit models. Limited direct validation capabilities pose challenges confirming remote sensing-based subsurface interpretations unambiguously in the absence of confirmatory drilling or sampling outcomes (Ganguly, 2023; Mahnaz et al., 2023; Masoud & Koike, 2011; Sabins, 1999).

6.2 Future Prospects and Research Directions

Realising the immense potential value of remote sensing techniques for global copper exploration requires dedicated collaborative campaigns between miners, researchers, and space agencies to improve existing sensor specifications and data products for geoscience applications through joint tasking of upcoming commercial satellite missions (van der Werff & van der Meer, 2016). Cross-sharing of doctrine on user requirements, technological capabilities, and analytical methods is vital. Lowering acquisition costs coupled with semi-automated analytics approaches enables the promotion of systematic airborne hyperspectral surveying at regional scales across global copper belts facilitated through mining industry consortiums to maximise value and exploration insights from these rich yet expensive datasets. Processing workflows must leverage cloud infrastructures for accessibility and economies of scale through standardisation. Humans can accurately recognise the different scene categories just by seeing a few scene images. However, deep learning-based methods are either incapable of doing the same work or take a lot of time. This leads to a lot of scope for improving the existing techniques and developing new methods for scene classification (Duz et al., 2023; Gyozo & Schott, 2005; Rajaram et al., 2009).

Capability developments in AI-enabled information extraction workflows through expert systems and machine learning promise semi-automated assimilation of multisensor observations within interpretation toolkits deployed at both desktop and field tablet levels by nonspecialist mineral explorers to aid rapid prospectivity modelling. An attention operation or modelling of inter-element relationships and a multi-layer perceptron simulates relationships within an element to produce more effective results (Khaleghi et al., 2020; Kumari & Kaul, 2023; Yang & Oldenburg, 2012). However, tool transparency and trust building remain imperative through human oversight.

Conclusion

In summary, this extensive review synthesised numerous scholarly articles and books demonstrates the immense potential and already substantiated value that remote sensing technologies provide in systematically exploring for concealed copper deposits at regional to local scales by revealing meaningful geological relationships between surface expressions and associated subsurface structures, landforms, and processes involved in copper genesis. Prominent findings reveal that diverse remote sensing systems, including multispectral optical, hyperspectral, radar, and topographic sensors, enable rapid and extensive analysis of land surface materials, textures, and forms. These analyses provide critical insights into the underlying geological environments conducive to copper mineralisation, relying on measurable parameters such as lithological units, structurally controlled fluid pathways, hydrothermal alteration halos, and landform associations.

Within this context, remote sensing constitutes an indispensable and unrivalled technique within the arsenal of modern copper exploration methods, which undoubtedly will continue making meaningful contributions across diverse terrains, deposit models, and challenging environments towards pushing discovery frontiers and balancing resource opportunity with environmental responsibility through its unique wide-area reconnaissance capacities. Ultimately, the responsible path ahead involves inclusive and informed harnessing of remote sensing's immense potential, revealing elusive subsurface copper endowments through pragmatic, collaborative optimisation explicitly aligning research directions and industry adoption pathways for mutual, reciprocal improvements in tandem guiding exploration translate to equitable progress.

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