Litho-structural framework of mineralization along the Ait Atmane fault zone (High Atlas, Morocco): Insights from remote sensing and field data

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Abstract. Geological mapping through remote sensing is an essential method for georesource exploration. This study focuses on mapping structural lineaments in the Ait Atmane region, located at the limite between the Central High Atlas and Eastern High Atlas sub-domains. The area is characterized by a Meso-Cenozoic sedimentary cover. The primary objective is to analyze the distribution of fractures associated with the Ait Atmane fault and their relationship with Pb-Zn±Fe mineralized structures, aiming to identify metallotects for mining exploration. To achieve this, Sentinel-2A and ASTER images and ASTER GDM data were utilized to extract structural lineaments. After correcting the images, data processing centered on the automated detection and extraction of structural lineaments. Validation of the results was carried out through comparison with Google Earth imagery, existing geological maps and field observations. The findings show four predominant fractures systems: NW-SE, NE-SW, and ENE-WSW, affecting Jurassic and Cretaceous formations along the Ait Atmane fault. The Pb+ Zn ± Fe mineralization occurs in veins hosted in Pliensbachian reef limestone formations and is carried by faults trending ENE-WSW and ESE-WNW with a subvertical dip. This research highlights the critical role of structural controls in the localization and distribution of mineral resources along the Ait Atmane Fault Zone.

Keywords: Remote sensing, Lithological discrimination, Fractures, High Atlas, Morocco.

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1 Introduction

The Ait Atmane area, located at the junction of the Central High Atlas and Eastern High Atlas ranges, extends from the easternmost part of the Central High Atlas to the western section of the Eastern High Atlas within the Ziz Valley. This region is traversed by the N°21 national road connecting Midelt to Errachidia and is geographically bounded by the High Atlas Mountains to the north, the pre-African trough to the south, Jbel Dermchane to the east, and Jbel Izeft to the west. A prominent geological feature of the region is the Ait Atmane fault, which exhibits a general orientation of N70 with a steep northward dip and thrust movement towards the south. The fault's lateral displacement varies significantly, increasing progressively from east to west [1, 2, 3, 4].

The Ait Atmane region contains several Pb-Zn-Fe mineral indices along the fault, primarily hosted within Lower and Middle Lias carbonate formations. While some of these mineral indices have been historically mined, others are currently exploited by artisanal miners, making this region a key economic resource for the Errachidia province.This study aims to use remote sensing techniques to map the lineaments and lithology of the Ait Atmane region and validate these findings through fieldwork. By identifying the structural features and mineralized zones associated with the Ait Atmane fault, this research seeks to provide critical insights for future mineral exploration while advancing the understanding of structural controls on mineralization distribution.

2 Materials and Methods

The methodology adopted in this study integrated multiple approaches to achieve comprehensive results. Digital mapping, utilizing remote sensing techniques, was instrumental in extracting valuable geological information, particularly for identifying lineaments using Landsat, Sentinel, and ASTER satellite images. Various processing methods, such as Principal Component Analysis (PCA) and directional filters, were applied to enhance lineament visualization and clarity [5, 6, 7, 8].

The processed data layers were overlaid onto topographic and geological maps, as well as Google Earth images, enabling the integration of remote sensing data with field observations to produce comprehensive synthetic lineament maps [8, 9]

Validation and evaluation of the results were conducted using pre-existing geological data [1], field observations, and laboratory analyses. These included the creation of cross-sections, structural measurements, and petrographic analyses of thin sections under optical and metallographic microscopes (Fig. 1). This multi-faceted approach ensured the reliability and accuracy of the findings.

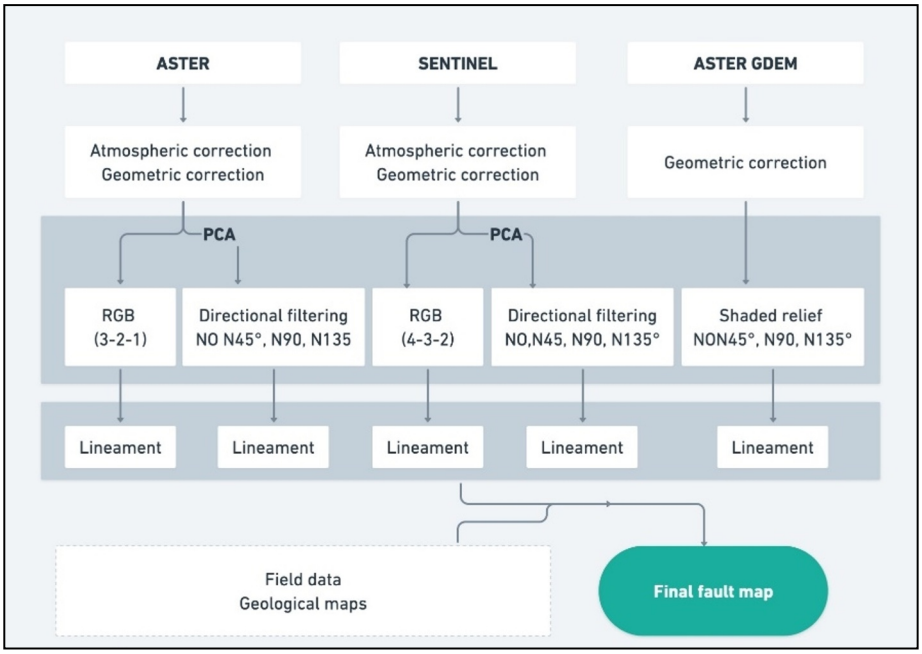

Fig. 1. Flowchart of study's approach.

2. Results

3.1 Analysis of Structural Lineaments

The integration of lineaments extracted from satellite imagery processing led to the creation of a synthetic map that revealed a variety of lineament orientations. The map shows a clear dominance of N-S, NW-SE, and NNE-SSW trends (Fig. 2), highlighting the key structural features influencing the region's geological framework.

The statistical analysis of satellite imagery, particularly the color composites generated from Sentinel-2A and ASTER images, enabled the quantification and characterization of lineaments based on their number and length as extracted by each method. The Sentinel-2A data proved particularly effective for identifying shorter and more discontinuous lineaments.

The rose diagram of the extracted lineaments indicates that the dominant directional family in the region ranges from E-W to ENE-WSW. While some of these lineaments align closely with the primary trend of the Ait Atmane fault, others are oriented perpendicularly or obliquely, reflecting the structural complexity of the region. The lengths of the lineaments predominantly fall within the range of 500 m to 3000 m, demonstrating a well-distributed representation of the region's structural features.

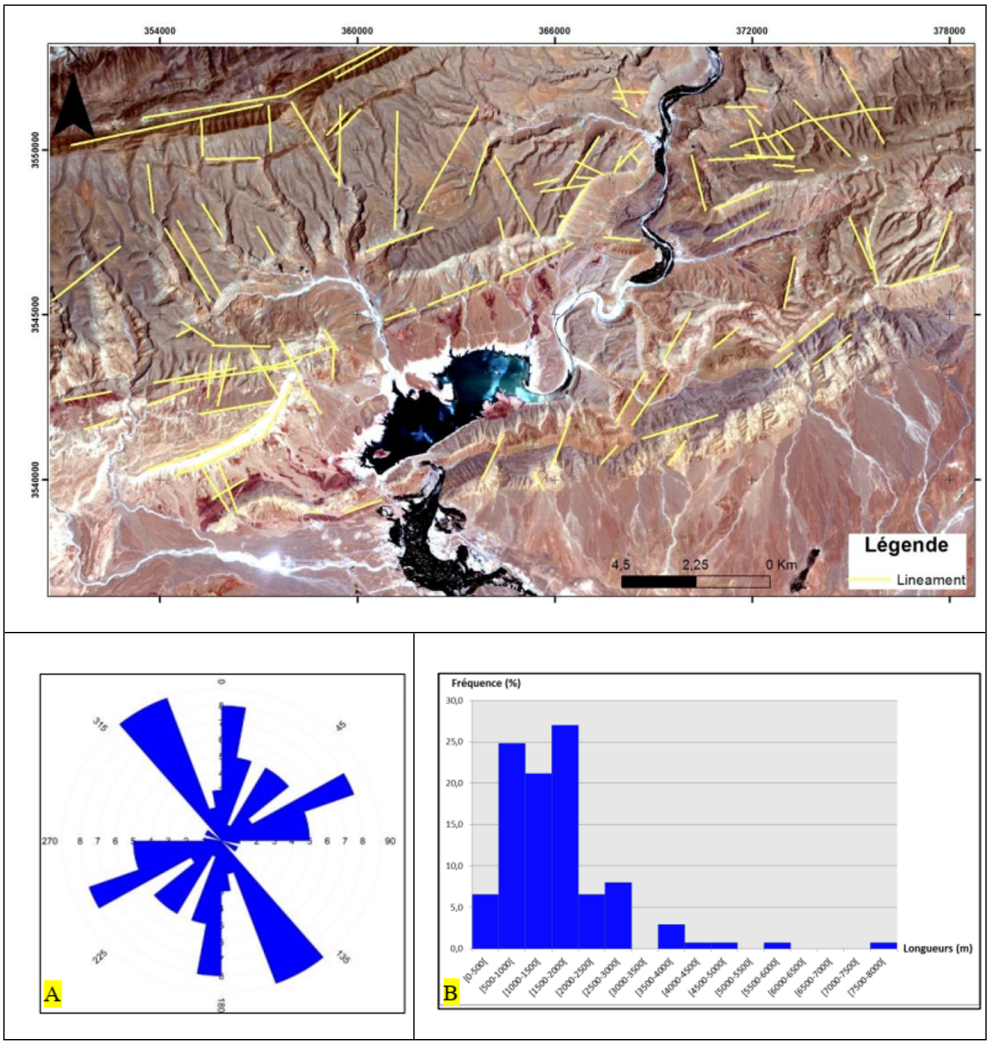

Fig. 2. A) Synthetic map of extracted lineaments in the Ait Atmane Area; B) Rose diagram of lineaments in the Ait Atmane (B) Length frequency diagram.

3.2 Geological Interpretation of lineaments

Field measurements of fault orientations closely match the lineaments extracted from satellite image processing, with the exception of the NW-SE direction. These fractures can be classified into two main fault families: normal faults oriented N-S to NE-SW and reverse faults oriented ENE-WSW to E-W (Fig. 3A & B).

Most normal faults display discontinuous fillings, which are often composed of white calcite, dolomite, iron oxides, or, in some cases, galena mineralization, either disseminated or occurring as veinlets in smithsonite.

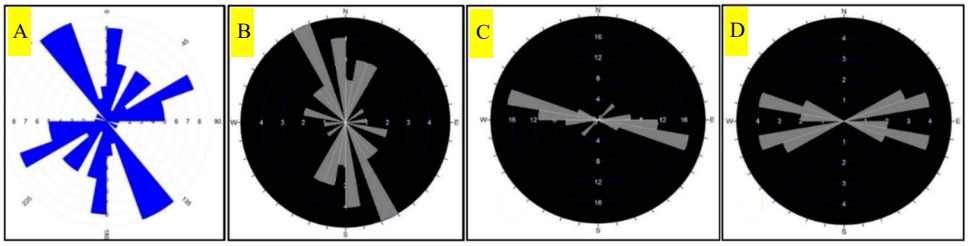

Fig. 3 Preferential orientation of the main features in the Ait Atman area: A) Lineaments from remote sensing; B) measured faults (C) iron-bearing mineralized veins; D) lead-zinc mineralized veins.

The Ait Otmane region is characterized by significant mineralization of lead, zinc, and iron oxides, primarily hosted within grayish limestone formations with marly joints, exhibiting a reef-like appearance, and dating back to the Pliensbachian age.

Lead-zinc mineralizations often appear as speckled or veined patches, with galena displaying average orientations ranging from N70 to N100 and exhibiting a subvertical dip. These orientations suggest that the galena and smithsonite mineralization at Keba are controlled by the main Ait Atmane fault and its branches. In some locations, the mineralization follows a normal fault geometry. The veins typically range in size from 0.2 meters to 0.5 meters. Lead mineralization is occasionally found along the periphery of iron oxide veins, indicating a reactivation of the fault hosting the mineralization.

Iron mineralization occurs as discontinuous caps along the veins, characterized by centimeter-thick, massive formations predominantly composed of limonite and goethite. The mineralized veins exhibit two primary families of orientations: a predominant direction ranging from N90 to N120, and a secondary, less pronounced family oriented around N50. The study of these mineralizations reveals three main textures: disseminated, massive, and veined. Galena is irregularly distributed within limestones and paleokarsts surrounding faults oriented ENE-WSW. Iron oxides and galena appear as massive mineralizations within faults oriented ESE-WNW to E-W (Fig. 3C & D). The veined texture is characterized by a network of fractures containing galena and iron oxides, oriented N70 to N120.

3. Discussion

4.1 Structural and Lithological Insights

The Ait Atmane fault zone, located at the junction of the Central and Eastern High Atlas domains, exhibits a complex interplay of lithological and structural factors that govern mineral distribution. Detailed structural analysis, combined with remote sensing data, reveals four primary lineament orientations: NW-SE, NE-SW, ENE-WSW, and E-W, which affect Jurassic and Cretaceous formations. These orientations align well with field observations, suggesting that the majority of fractures and faults follow these structural trends.

The structural complexity is further amplified by the variety of fault types present. Normal faults are predominantly oriented N-S to NE-SW, while reverse faults are aligned ENE-WSW to E-W. The identification of these fault families, both through satellite imagery and fieldwork, affirms the reliability of remote sensing techniques for structural mapping. The presence of both normal and reverse faults reflects a dynamic tectonic environment, characterized by alternating extensional and compressional forces that have shaped the region's geology.

4.2 Controls on Mineralization

Pb-Zn-Fe mineralization in the Ait Atmane region primarily manifests as veins and veinlets within Pliensbachian reefal limestone formations. This mineralization is hosted along faults oriented ENE-WSW and ESE-WNW, with a subvertical dip, indicating a strong tectonic control over the location and distribution of the mineralized bodies. The lithological units, particularly the reefal limestones, offer favorable conditions for ore deposition due to their structural characteristics.

The observed paragenetic sequence in the region suggests an initial mineralization phase dominated by galena (PbS) and calcite ($CaCO_3$), with occasional occurrences of sphalerite (ZnS). A subsequent supergene phase, driven by secondary processes such as oxidation and dolomitization, has led to the formation of minerals such as smithsonite, goethite, limonite, and siderite. This multi-phase mineralization process underscores the complexity of the ore-forming environment and highlights the crucial roles played by primary hydrothermal processes and secondary supergene alterations in controlling mineral distribution.

4.3 Correlation of Remote Sensing and Field Data

The integration of remote sensing data with field observations has proven to be an effective method for mapping structural lineaments in the Ait Atmane region. High-resolution Sentinel-2A and ASTER images were crucial for extracting significant lineaments, which were then validated through fieldwork and comparison with existing geological maps. The strong correlation between remote sensing data and field measurements of fault orientations highlights the reliability and precision of the remote sensing techniques employed.

The synthetic lineament map generated from the combined satellite and field data reveals dominant structural trends of N-S, NW-SE, and NNE-SSW, which align with the primary fault directions in the region. This alignment further confirms the efficacy of remote sensing in identifying key structural features that govern mineralization patterns.

4.4 Economic Implications

The detailed mapping of structural features and lithological units in the Ait Atmane region carries significant implications for future mineral exploration. Understanding the spatial distribution of fractures and faults, along with their relationship to mineralized zones, offers valuable insights for targeted exploration. The identification of ENE-WSW and ESE-WNW oriented faults as primary hosts for Pb-Zn-Fe mineralization provides clear guidance for future exploration efforts.

Additionally, the region's economic potential is highlighted by ongoing artisanal mining activities and the presence of multiple Pb-Zn-Fe mineralized sites. By delineating metallotects and elucidating the structural controls on mineralization, this study lays the foundation for more systematic and efficient exploration strategies, ensuring a more focused approach to resource discovery and development.

4. Conclusion

This study underscores the critical role of structural analysis in understanding mineralization along the Ait Atmane fault zone. The integration of remote sensing techniques with field data has proven highly effective in mapping key geological features, offering valuable insights for future mineral exploration. The identification of significant fault trends and their correlation with mineralized zones emphasizes the importance of structural controls in ore localization. This comprehensive approach not only deepens our understanding of the

region's geology but also provides practical applications for mineral prospecting and resource management in Morocco's High Atlas region.

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Author Contribution
All authors (Abdelhak Ijaajaane, Abdelkhiar Ait Ali, Souhaila Kajji, Hicham Si Mhamdi, Lahssen Baidder, and Mohammed Raji) reviewed and approved the final manuscript, with Abdelhak Ijaajaane contributing to Conceptualization, methodology, and writing original draft, Abdelkhiar Ait Ali and Souhaila Kajji providing data collection and analysis, and Hicham Si Mhamdi, Lahssen Baidder, and Mohammed Raji providing supervision, reviewing and interpreting the data.

Ethics approval and consent to participate
Not applicable.

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All the authors have agreed to publish this article.

Competing interests
The authors declare that they have no competing interests.

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5. References

1. L. Baidder, A. Kaoukaya, M. Karim, H. Ouanaimi, A. Soulaimani, A. Hafid, E.H. Abia, H. Amhoud, E.M. Ettachfini, H. Haddoumi, L. Boudad, A. Eddebbi, M. Hilali, B. Chbani, "Carte géologique du Maroc au (1/50.000) feuille Ayt 'Othmane," *Notes et Mémoires Serv. Géol. Maroc.*, 602, (2020).

Theses

2. H. Ibouh, "Du rift avorté au bassin sur décrochement, contrôles tectonique et sédimentaire pendant le Jurassique (Haut Atlas central, Maroc)," *Ph.D. Thesis*, Cadi Ayyad University, Morocco (2004).

Journal articles

3. H. Si Mhamdi, A. Charroud, M. Oukassou, A. Alali, L. Baidder, M. Raji, A. Ijaajaane, S. Elfaiz, S. Elouariti, "Enhancing the Geological Heritage of the Errachidia Area in the High Atlas, Morocco: Inventory and a Proposal for a Pedagogic and Geotouristic Trail," *Geoheritage*, 15, 1–26 (2023).
https://doi.org/10.1007/s12371-023-00813-0.
4. H. Si Mhamdi, A. Ijaajaane, S. El Ouariti, A. Charroud, L. Baidder, M. Raji, "Fold-Thrust Belt in the southern front of the Central High Atlas (Morocco): analysis and implications for the tectonic inversion of the Atlas system," *J. Struct. Geol.*, 105185, (2024).
https://doi.org/10.1016/j.jsg.2024.105185.
5. I. Bentahar, M. Raji, H. Si Mhamdi, "Fracture network mapping using Landsat-8 OLI, Sentinel-2A, ASTER, and ASTER-GDEM data, in the Rich area (Central High Atlas, Morocco)," *Arabian J. Geosci.*, 13, 1–19 (2020).
https://doi.org/10.1007/s12517-020-05736-6.
6. S. Sedrette, N. Rebaï, "Automatic extraction of lineaments from Landsat ETM+ images and their structural interpretation: Case Study in Nefza region (North West of Tunisia)," *J. Res. Environ. Earth Sci.*, 139–145, (2016).

7. H. Si Mhamdi, M. Raji, M. Oukassou, "Utilisation de la télédétection dans la cartographie automatique des linéaments géologiques du granitoïde de Tichka (Haut Atlas Occidental)," *Eur. J. Sci. Res.*, 142, 321–333 (2016).
8. H. Si Mhamdi, M. Raji, S. Maimouni, M. Oukassou, "Fractures network mapping using remote sensing in the Paleozoic massif of Tichka (Western High Atlas, Morocco)," *Arabian J. Geosci.*, 10, 1–14 (2017). https://doi.org/10.1007/s12517-017-2912-5.
9. I. Bentahar, M. Raji, "Comparison of Landsat OLI, ASTER, and Sentinel 2A data in lithological mapping: A Case study of Rich area (Central High Atlas, Morocco)," *Adv. Space Res.*, 67, 945–963 (2021).