GIS-Driven mineral exploration: Enhancing geological insight through aeromagnetic integration

Kawtar Benyas[1]*, *Assia* Idrissi[2], *Abdelmounim* Qarbous[3], *Slimane* Sassioui[1], *Abdellatif* Aarab[1], *Abdellah* Lakhloufi[1] *and Rajaa* Aitali[4]

[1] Laboratory of Analysis and Modelling of Water and Natural Resources, Mohammed V University, Rabat, Morocco.
[2] Department of Earth Sciences, Faculty of Sciences, Mohammed V University, Rabat, Morocco.
[3] Department of Geology, Regional Centre for Education and Training Professions RSK, Rabat, Morocco.
[4] Geophysics and Natural Hazards Laboratory, GEOPAC Research Center, Scientific Institute, Mohammed V University, Rabat, Morocco.

Abstract. The *Rehamna* Variscan massif, located in the western *Moroccan* Meseta, is known for its geological complexity and mining potential, requiring detailed investigation to uncover its hidden resources. This study combines spatial analysis with aeromagnetic geophysical prospecting methods, using Geographic Information Systems (GIS), which are effective for integrating spatio-temporal data and organizing research phases. The goal is to demonstrate that incorporating aeromagnetic data into GIS enhances the detection and analysis of geological structures, thus facilitating mineral prospecting. This integration identified a significant bipolar magnetic anomaly, similar to that of the *Hajjar* mine, indicating favorable geological structures for mineralization. It also helped map faults and other geological discontinuities, revealing new target areas for in-depth mineral exploration, particularly for precious metals. The findings highlight the effectiveness of GIS in mineral prospecting in geologically complex regions. However, interpreting the data requires expertise in geophysics and geology to improve model accuracy. This combined approach allows for more precise analysis and better planning of mining exploration efforts.

Keywords: GIS, aeromagnetic geophysics, mineral exploration, *Rehamna* massif, geological analysis.

1 Introduction

The variscan *Rehamna* massif, situated in the western part of the *Moroccan* Meseta, stands out as a geological formation of significant importance due to its structural complexity and mineral wealth. Formed during the Hercynian orogeny, this massif is a geological mosaic of diverse rocks and structures, shaped over millions of years of tectonic and magmatic activity.

* Corresponding author: benyas.kawtar@gmail.com

The intricate interactions among these varied lithological units have created a terrain that is favorable for the accumulation of mineral resources, making the region a focal point for mineral exploration. To thoroughly understand the geological intricacies of the *Rehamna* massif and to enhance the likelihood of uncovering new mineral deposits, more advanced and integrated exploration techniques are required.
This paper introduces an innovative approach for mineral prospecting in the Hercynian *Rehamna* massif by leveraging aeromagnetic geophysical data and incorporating them into a Geographic Information System (GIS). Aeromagnetic data capture the variations in the Earth's magnetic field caused by differences in the magnetic properties of underlying rocks. Integrating these data into a GIS permits a sophisticated spatial analysis and three-dimensional visualization of magnetic anomalies and geological structures. This integration helps identifying potential areas for mineral exploration and enhances our understanding of the complex geology of the *Rehamna* massif.

2 Geological framework

The *Rehamna* massif is located in north-western *Morocco*, in the western part of the *Moroccan* Meseta, between the cities of *Casablanca* and *Marrakech* (Fig. 1). Geologically (Fig. 1), the Hercynian *Rehamna* massif, is a geological region of remarkable complexity and mineral wealth. The first geological explorations were carried out by [1]Gigout in 1951 and were followed by in-depth studies by researchers such as [2]Hoepffner et al. (1975) and [3]Aghzer and Arenas (1998), who provided a detailed understanding of the stratigraphy and tectonic deformation of the massif. The base of the massif consists of Precambrian felsic volcanic formations, as described by [4]Hoepffner (1974) and confirmed by more recent research by [5]Pereira et al. (2015). These formations support a succession of varied Paleozoic sedimentary deposits, including detrital and carbonate facies extending from the Lower Cambrian to the Visean.
The Hercynian orogeny profoundly modified the region through several tectonic phases of deformation, identified as D1, D2 and D3. These processes have been well documented by researchers such as [6]Chopin et al. (2014) and [7]Wernert et al. (2016). In addition, the interactions between metamorphism, tectonics and magmatism have been examined at depth, revealing intense regional metamorphism and significant magmatic intrusions at the end of the Hercynian cycle, contributing to the current geological structure of the massif and the formation of hydrothermal mineral deposits. The region's post-Paleozoic sedimentary cover is dominated by Cretaceous and Mio-Plio-Quaternary deposits, with a minor Triassic presence that is often eroded, as highlighted by [8]Hoepffner et al. (2005) and [7]Wernert et al. (2016).
Overall, the Hercynian *Rehamna* massif illustrates the complexity of geological processes, ranging from Precambrian stratigraphy to Hercynian tectonic phases, enriched by metamorphism and magmatism (Fig. 1). These features make the massif a major area of interest for geological research and ongoing mining exploration**.**

3 Data and methodology

The aeromagnetic data has been provided to us, in the form of residual field maps. They are the product of the airborne magnetic survey carried out by the Airborne Magnetism Campaign (C.A.G., 1970), which was commissioned by the *Moroccan* Directorate of Mines and Geology. To process the available digital data, we used Geosoft Oasis montaj 7.0.1 and Arcgis 10.1 software. The analysis of the airborne magnetic data enabled us to highlight the various magnetic components of the bodies likely to be mineralized and their spatial positioning. The residual magnetic field (Fig. 2) was reduced to the pole using the *Fourier* transform (Fig. 3).

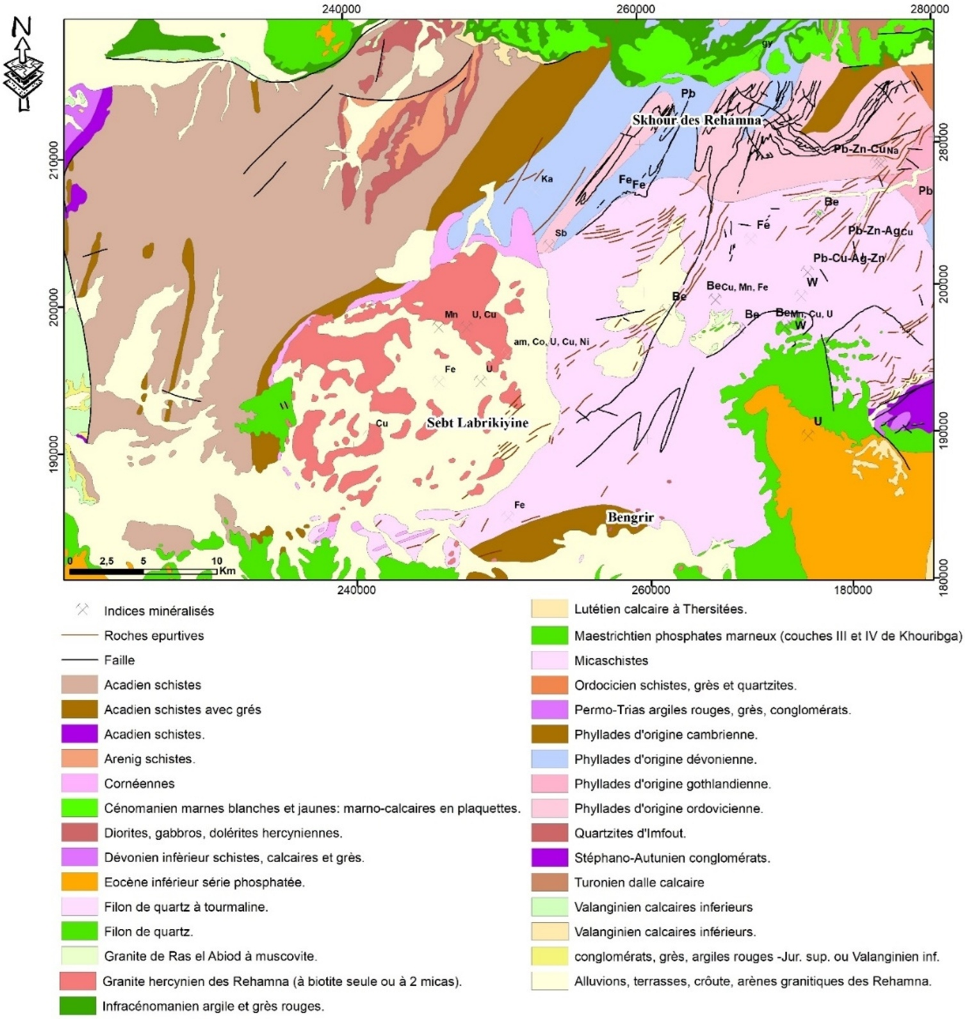

Fig. 1. Geological setting of the Hercynian *Rehamna* massif

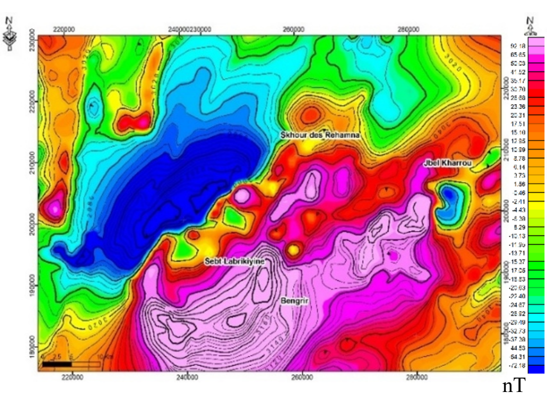

Fig. 2: Residual magnetic field map of the large bipolar anomaly in the *Rehamna* massif

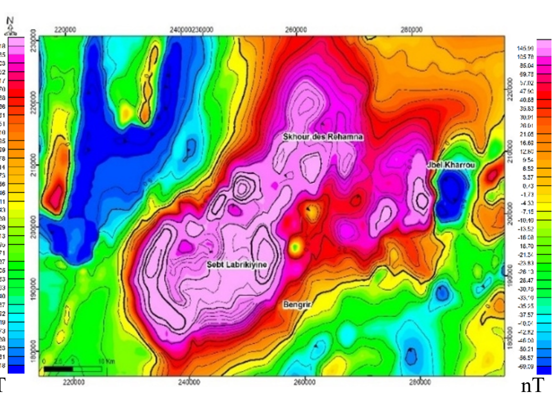

Fig. 3: The reduction to the pole of the bipolar anomaly of the *Rehamna* massif

 https://doi.org/10.1051/e3sconf/202560701001

3.1 Upward continuation

Upward continuation is considered as a clean filter, regarding that it produces almost no side effects that would require the application of other filters to correct. In order to separate anomalies due to surface sources from those due to deep sources, we carried out a theoretical calculation by applying the "Upward continuation (UP) Filter" [9]. The magnetic anomaly map reduced to the pole is upwarded. The expression of the upward continuation operation (1) is of the following form [10]Sailhac (1999), based on Green's identities:

$$U(x,y,Z0-\Delta Z)=\frac{\Delta Z}{2\pi}\iint \frac{U(x',y',0)}{\left((x-x')^2+(y-y')^2+\Delta Z^2\right)^{\frac{3}{2}}}\,dx'dy' \qquad (1)$$

With $\Delta Z>0$
Where Z0 is the aircraft elevation and ΔZ the reference plane.

4 Results and discussion

The integration of aeromagnetic geophysical data into GIS identified significant magnetic anomalies and geological structures favorable for mineralization. A large bipolar magnetic anomaly was detected (Fig. 4), similar to the one at the *Hajjar* mine [11] (Fig. 5), suggesting the presence of favorable conditions for the formation of mineral deposits (Fig. 4 and 5). This discovery suggests that the *Rehamna* massif may host geological structures conducive to mineralization.
In addition, mapping of geological discontinuities has identified several faults and fractures that could play a crucial role in locating mineralization [12], [13]. These discontinuities are often conduits for mineralizing fluids, and their identification is essential for targeting areas with high mineral potential.

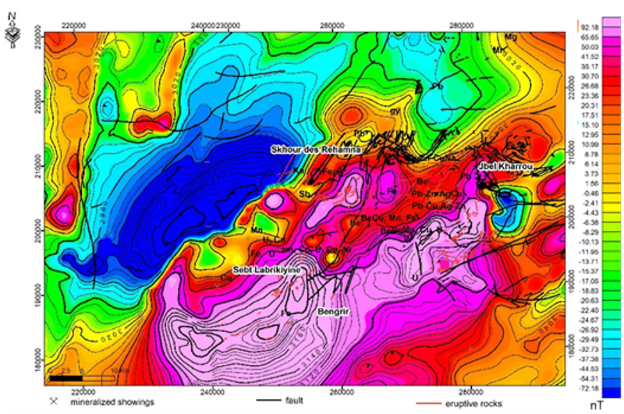

Fig. 4: Superposition of the bipolar anomaly of the *Rehamna* massif and mineral showings and geological faults

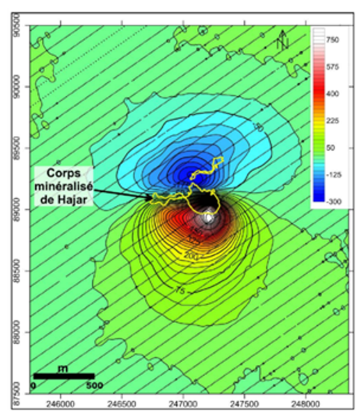

Fig. 5: Residual magnetic field map of the *Hajjar* mine [11]

The target areas identified for deep exploration are mainly located in regions where magnetic anomalies are most pronounced. These zones also show overlap with existing mineral showings, reinforcing the hypothesis of their high mineral potential.
For a more in-depth analysis, the reduced to the pole magnetic field map was upward continued to different altitudes: 500 m, 1000 m, 2000 m, 18000 m, and 30000 m (Fig. 5). These continuations help mitigate the effects of superficial anomalies and better visualize the

deep sources of the same magnetic anomaly across various depths, providing a more comprehensive view of its vertical extent.
At 500 m and 1000 m: These altitudes allow for the reduction of interference from surface structures and highlight the deeper anomaly related to shallow geological structures. The maps show extensive areas of anomalies, which could correspond to granitic magmatic intrusions around *Sebt Labrikiyine* and *Bengrir*.
At 2000 m: This altitude emphasizes the deeper components of the magnetic anomaly. The continuation of the anomaly indicates the presence of significant magnetic bodies at depth, which could reflect magmatic reservoirs or zones of concentrated ferrous minerals at intermediate levels.
At 18000 m and 30000 m: These very high-altitude continuations help visualize anomalies associated with regional or deep crustal geological structures. At these levels, the maps reveal regional trends of this magnetic anomaly, which may be linked to variations in the Earth's crust composition or large-scale structural weaknesses. This deep anomaly could be related to large-scale mineralized systems or major tectonic structures influencing the formation of mineral deposits.

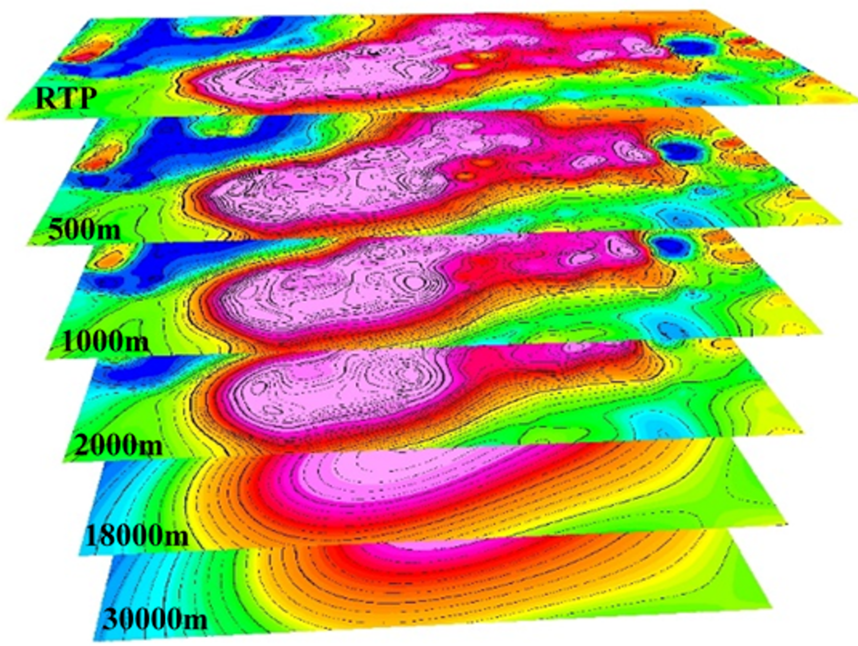

Fig. 5: 3D presentation of upwardly-extended maps (500m, 1000m, 2000m, 18000m and 30000m) in ArcScene.

By following the anomaly through these different altitudes, it is possible to trace its continuity and better understand the geometry and depth of its sources. This provides crucial information for deep mineral exploration in the *Rehamna* massif, indicating potential targets for significant mineral discoveries.

5 Conclusion

This study demonstrates the effectiveness of integrating aeromagnetic geophysical data into a GIS for mineral exploration in geologically complex regions such as the *Rehamna* massif.

The combined approach of aeromagnetics and GIS not only enables precise detection and analysis of geological structures but also improves the planning of future mineral exploration campaigns. Identifying magnetic anomalies and geological discontinuities provides valuable clues for targeting deep zones with high mineral potential. However, precise interpretation of these data requires in-depth expertise in geophysics and geology. The use of this integrated approach could be extended to other regions in the search for new mineral deposits.

Funding
The authors state that no funding was received for this research and affirm that there are no potential conflicts of interest associated with this article.

Author Contribution
All authors (Kawtar Benyas, Assia Idrissi, Abdelmounim Qarbous, Slimane Sassioui, Abdellatif Aarab, Abdellah Lakhloufi , and Rajaa Aitali) reviewed and approved the final manuscript. Kawtar Benyas contributed to the study design, data analysis, and drafting of the manuscript. Abdelmounim Qarbous provided supervision and critical revisions, while Assia Idrissi assisted with data interpretation and visualization. Slimane Sassioui contributed to the methodology and technical validation, Abdellatif Aarab supported fieldwork and data acquisition, Abdellah Lakhloufi ensured methodological consistency and reviewed the results, and Rajaa Aitali contributed to the literature review and manuscript editing.

Ethics approval and consent to participate
Not relevant.

Consent for publication
All authors have given their consent for the publication of this article.

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

Acknowledgement
We would like to express our sincere gratitude to the Ministry of Energy and Mines, as well as the Directorate of Geology, for providing us with the aeromagnetic data necessary for this study. Their valuable contribution has played a crucial role in the progress of our research work.

References

[1] M. Gigout, Etudes géologiques sur la Méséta marocaine occidentale (arrière-pays de Casablanca, Mazagan et Safi), Thèse de Doctorat, Paris, (1951).

[2] C. Hoepffner, D. Jeannette, P. Jenny, A. Michard, et A. Pique. Relations entre une tectonique de decrochement et un metamorphisme a disthene dans le massif hercynien des Rehamna (Maroc), *Bulletin de la Societe Geologique de France*, vol. S7-XVII, nº 3, p. 421-429, sept. 1975, doi: 10.2113/gssgfbull.S7-XVII.3.421.

[3] A. M. Aghzer et R. Arenas. Evolution m&amorphique des mQtap&tes du Massif hercynien des Rehamna (Maroc): implications tectonothermales, *Journal of African Earth Sciences*, vol. 27, nº 1, p. 20, 1998.

[4] C. Hoepffner. Contribution à la géologie structurale des Rehamna (Meseta marocaine méridionale), Le matériel paléozoïque et son évolution hercynienne dans l’est du massif, avril 1974.

[5] M. F. Pereira, M. El Houicha, M. Chichorro, R. Armstrong, A. Jouhari, A. El Attari, N. Ennih and J.B. Silva. Evidence of a Paleoproterozoic basement in the Moroccan Variscan Belt (Rehamna Massif, Western Meseta), *Precambrian Research*, vol. 268, p. 61-73, oct. 2015, doi: 10.1016/j.precamres.2015.07.010.

[6] F. Chopin, M. Corsini, K. Schulmann, M. El Houicha, J.-F. Ghienne, et J.-B. Edel. Tectonic evolution of the Rehamna metamorphic dome (Morocco) in the context of the Alleghanian-Variscan orogeny: REHAMNA MASSIF − MOROCCAN VARISCAN BELT, *Tectonics*, vol. 33, nº 6, p. 1154-1177, juin 2014,

doi: 10.1002/2014TC003539.
[7] P. Wernert, K. Schulmann, F. Chopin, P. Štípská, D. Bosch, et M. El Houicha. Tectonometamorphic evolution of an intracontinental orogeny inferred from P-T-t-d paths of the metapelites from the Rehamna massif (Morocco), *J. Metamorph. Geol.*, vol. 34, nº 9, p. 917-940, déc. 2016, doi: 10.1111/jmg.12214.
[8] C. Hoepffner, A. Soulaimani, et A. Piqué. The Moroccan Hercynides, *Journal of African Earth Sciences*, vol. 43, nº 1-3, p. 144-165, 2005, doi: 10.1016/j.jafrearsci.2005.09.002.
[9] M. Ivan. On the upward continuation of potential field data between irregular surfaces, *Geophysical Prospecting*, vol. 34, nº 5, p. 735-742, août 1986, doi: 10.1111/j.1365-2478.1986.tb00490.x.
[10] P. Sailhac. Analyse multiéchelle et inversion de données géophysiques en Guyane Française: (in French), Thèse de Doctorat, 1999.
[11] A. Jarni, M. Jaffal, E.M. Mouguina, L.Maacha, A. En-Aciri, M. Outhounjite, A. Ouadjou, M. Zouhair, A. Radnaoui, and O. Saddiqi. Magnetic anomalies of Jebilets-Guemassa metallogenic province (Hercynian Morocco) State of knowledge and problem related to mineral exploration, *International Journal of Innovation and Applied Studies*, vol. 12, nº 2, p. 491-504, 2015.
[12] K. Benyas, A. Aarab, A. Qarbous, A. Lakhloufi, A. Manar, M. Amar, A. Idrissi et M. Elmimouni, Exploiting Aeromagnetic and Gravity Data Interpretation to Delineate Massif Deposits of Rehamna Area (Western Meseta-Morocco), *Iraqi Geological Journal*, vol. 54, nº 2C, p. 13-28, sept. 2021, https://doi.org/10.46717/igj.54.2C.2Ms-2021-09-21.
[13] K. Benyas, A. Aarab, A. Lakhloufi, A. Qarbous, A. Manar, M. Amar, A. Idrissi et M. Elmimouni, Contribution of the Airborne Magnetic Field to the Structural Study of the Variscan Granitoid of Rehamna, Morocco, *Iraqi Geological Journal*, vol. 55, nº 1A, p. 21-39, 2022, doi: 10.46717/igj.55.1A.2Ms-2022-01-21.

Journal articles

1. A. Nicolas, J.-L. Barrat, J. Rottler, Effects of inertia on the steady-shear rheology of disordered solids. Phys. Rev. Lett. **116**, 058303 (2016)
2. A. Lohrasebi, T. Koslowski, Modeling water purification by an aquaporin-inspired graphene-based nano-channel. J. Mol. Model. **25**, 280 (2019). https://doi.org/10.1007/s00894-019-4160-y
3. M. Ben Rabha, M.F. Boujmil, M. Saadoun, B. Bessaïs, Eur. Phys. J. Appl. Phys. (to be published)

Books

4. J. Couturier, Y.H. Abou and E. Grolleau, Element of nuclear safety, (EDP Sciences, Les Ulis, 2019)
5. M.N. Ozisik, Radiative transfer and interactions with conduction and convection (John Wiley and Sons, New York, 1973)

Proceedings

6. J. Rhodes, K. Smith, D. Lee, CASMO-5 development and applications, in Proceedings of the PHYSOR-2006 conference, ANS Topical Meeting on Reactor Physics, Vancouver, BC, Canada, September 10-14, September 10-14 (2006), B144

Theses

7. S. Azzaoui, SCALE-6 fuel depletion analyses: Application to the ARIANE program, Master Thesis, SCK-CEN, Belgium, 2010
8. K. Ambrožič, L. Snoj, Characterization of gamma field in the JSI TRIGA reactor, Ph.D. thesis, University of Ljubljana, Faculty of Mathematics and Physics (2020)