Gold-Copper Prospectivity Mapping in Masara Gold District, Eastern Mindanao, Philippines through the Analytical Hierarchy Process (AHP) Approach

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Abstract: *Gold-copper prospectivity mapping was conducted in the Masara Gold District of Eastern Mindanao using the Analytical Hierarchy Process (AHP). AHP methodology provides a structured framework for evaluating the significance of various geological parameters, including lithology, alteration zones, soil geochemistry, and magnetic anomalies. By conducting pairwise comparisons among these criteria, weights were assigned that reflect their relative importance in mineral exploration. The credibility of expert judgments was assessed through the consistency ratio, ensuring the reliability of the results. Reclassified criteria maps and mineral prospective maps were generated after AHP, which illustrate the spatial distribution of mineral potential across the study area. The analysis revealed significant areas with high potential for copper and gold deposits, particularly around potassic alteration zones, indicating a strong likelihood of porphyry copper mineralization. The study emphasizes the importance of understanding geological contexts in guiding exploration efforts and resource allocation. By integrating remote sensing data and GIS approaches, the research enhances the ability to distinguish mineral signatures, facilitating informed decision-making in gold-copper exploration. The generated mineral prospective maps serve as valuable tools for stakeholders, enabling them to focus their investigations on areas with the highest potential for mineralization. This can potentially contribute to the ongoing efforts in sustainable resource management and provides a framework for future exploration initiatives in similar geological settings.*

Keywords: Gold-copper prospectivity, Analytical Hierarchy Process, Mineral Exploration, Masara Gold District

1. INTRODUCTION

The exploration of mineral deposits is a critical endeavor in the mining industry, particularly in regions rich in resources like the Masara Gold District in Eastern Mindanao, Philippines which is one of the five (5) major gold-producing mineral districts in the country (Fig. 1) [1].

Understanding the geographic relationship between mineral deposits and their geological characteristics is essential for effective exploration strategies. Previous studies have highlighted the importance of mapping in ore exploration, which provides vital information about geological settings and mineralization patterns [2].

Analytical Hierarchy Process (AHP) is a popular decision-making tool that is widely used in other fields of sciences such as agriculture [3, 4]. Employing AHP to evaluate the significance of various geological parameters, including lithology, alteration zones, soil geochemistry, and magnetic anomalies can enhance mineral exploration efforts.

There exists a vast challenge of identifying high-potential areas for copper and gold deposits more efficiently in Mindanao Island, particularly the Masara Gold District (Fig. 2). Traditional exploration methods often lack a systematic approach to assess the relative importance of different geological factors, leading to inefficient resource allocation. Therefore, a more structured framework is vital for decision-making in mineral

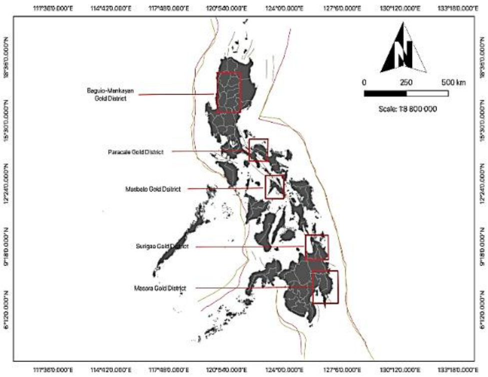

Fig. 1. Five major gold-producing districts in the Philippines. Adapted from [1].

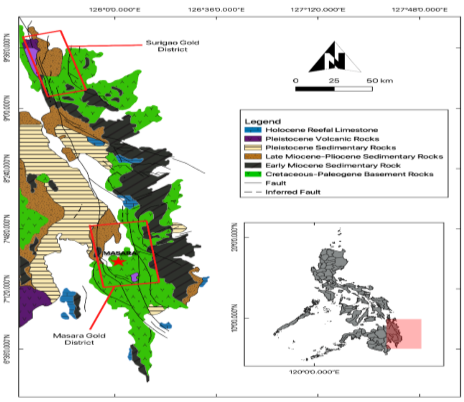

Fig. 2. Regional geologic map of Eastern Mindanao. Adapted from [5].

exploration to prioritize geological parameters based on expert assessments [2]. Key geological parameters in mineral exploration must be evaluated to generate mineral prospectivity maps that illustrate the spatial distribution of mineral potential. This can then provide a comprehensive reference for future exploration activities in the region, which will contribute to a more informed decision-making process in mineral prospecting.

2. MASARA GOLD DISTRICT

The Masara Gold District has presented considerable development prospects for porphyry copper and epithermal gold deposits since its discovery in 1937. However, the area wasn't thoroughly explored until 1975, when porphyry copper potential was discovered [5].

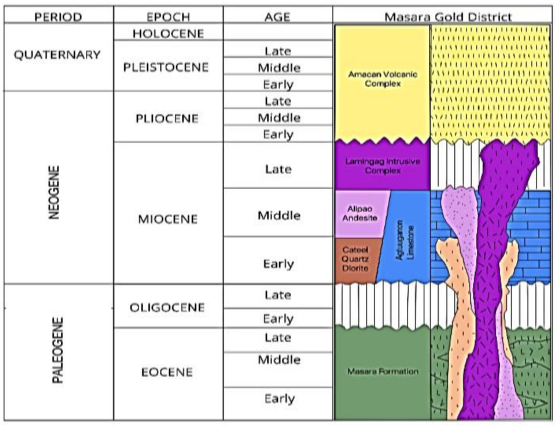

Fig. 3. Stratigraphic column of the Masara Gold District. Adapted from [5].

The Masara Gold District is located in Eastern Mindanao in Maco, Davao de Oro, at the southern end of the Pacific Cordillera (Fig. 2). The district is surrounded by a NW trending structural corridor that is connected to the Philippine Fault Zone (PFZ). Currently being mined by Apex Mining Co., Inc. (AMCI) are epithermal gold deposits (Masara epithermal gold) and porphyry copper deposits (e.g., Kurayao and Teresa prospects). There have also been a few isolated reports of skarn deposits and sediment-hosted deposits [5].

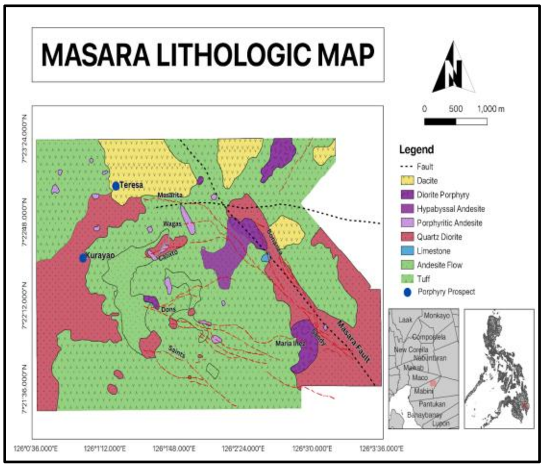

Fig. 4. Lithologic map of the Masara Gold District. Adapted from [6].

The district is made up of various geologic units, with the Eocene Masara Formation as the basement overlain by the Early to Middle Miocene Agtuuganon Limestone (Figs. 3 & 4). Composite stocks of several intrusives cut across these units, such as the Early Miocene Cateel Quartz Diorite, the Middle Miocene plagiophyric Alipao Andesite, and the late Miocene Lamingag Intrusive Complex (LIC) which is composed of fine-grained andesite, diorite porphyry and quartz diorite stocks. The Amacan Volcanic Complex, the youngest unit, is unconformably overlain on all others. The units of the Masara Formation, the Cateel Quartz Diorite, the Alipao Andesite, and the LIC, respectively, host mineralization and accompanying hydrothermal alteration [6].

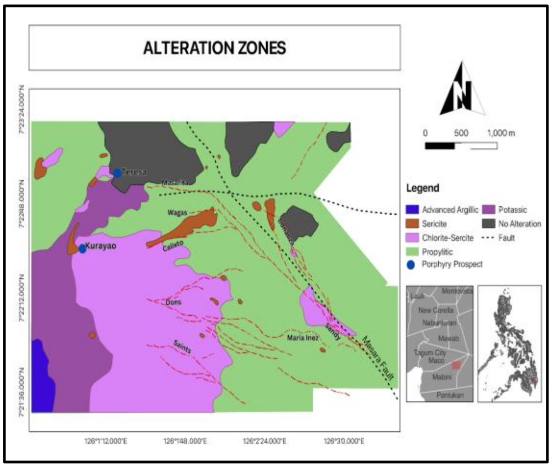

Fig. 5. Alteration zone map of the Masara Gold District. Adapted from [6].

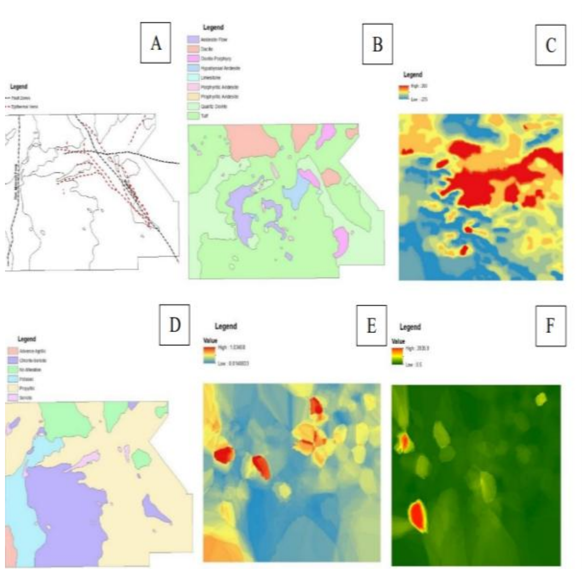

Fig. 6. Thematic layers utilized in the study [5,6,7,8].

In the Masara Gold District, gold mineralization is structurally controlled. Low- to medium-K calc-alkaline magmatism is directly related to the gold mineralization in the area. It is host to the Masara-Hijo-Amacan copper-gold deposits and is located among sizable volcanic structures in a dilatational jog of the Philippine Fault Zone. Hydrothermal mineralization and related alteration are found in the Lamingag Intrusive Complex, Alipao-Andesite, Cateel Quartz Diorite, and Masara Formation [1].

Detailed alteration mapping and mineralogical studies have revealed at least five alteration zones in the AMCI tenement area in the Masara gold district, including regional propylitic alteration, potassic alteration seen in the area's western part, chlorite-sericite zones in the area's central and eastern portions, minor sericite alteration, and advanced argillic alteration (Fig. 5). Mapped potassic alteration zone coincides with areas of mineralization with significant degrees of alteration that are situated close to epithermal veins [4].
The close association of copper mineralization with porphyry and intermediate volcanic rocks, the presence of hydrothermal alteration zones, the dispersed nature of sulfide minerals, the severe lack of massive lenses, and the volcanic arc tectonic setting of ore-bearing rocks are the main geological factors that contribute to the porphyry system. Numerous geological properties, including structural, geochemical, alteration, and mineralogical characters, can be found in porphyry copper deposits. It is well known that the formation and dispersion of the majority of mineral deposits are greatly influenced by structural variables. The scale at which hydrothermal fluids flow is substantially influenced by the joints, faults, and folds in rock units [5].

3. MATERIALS AND METHODS

Available geologic data in the Masara deposit were utilized to generate the reclassified criteria and mineral prospective maps, as well as to validate the study's results. These resources include geologic structures from [5], lithologic and alteration maps from (Figs. 4&5) [6], a magnetic anomaly map from [7], and a soil geochemistry map [8] (Fig. 6).

The AHP is central to the methodology, providing a structured framework for addressing complex decision-making scenarios, (Fig. 7). This process involves pairwise comparisons of various criteria, allowing for a systematic evaluation of both tangible and intangible factors [9]. Expert interviews are conducted to gather insights, and criteria are organized hierarchically to facilitate the decision-making process. The criteria evaluated include lithology, alteration zones, soil geochemistry (for both gold and copper), and magnetic anomalies, with weights assigned based on their relative importance.

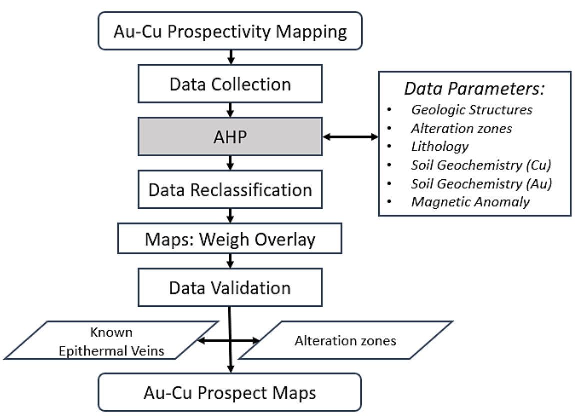

Fig. 7. Conceptual framework for the gold-copper prospectivity mapping in Masara Gold District.

To ensure the reliability of the results, a consistency check of expert judgments through the consistency ratio (CR) was utilized, which quantifies the reliability of the assessments made during the AHP process. [10] set a benchmark of 0.10 as a criterion for evaluating the validity of judgments. If the CR surpasses this threshold, it casts doubt on the trustworthiness of the judgments. In such instances, it's recommended for the decision-maker to review and amend the judgments until they reach a CR value below 0.10. Additionally, [10] proposed specific thresholds for matrices of size three and four, proposing 0.5 and 0.8, respectively, as appropriate thresholds for those scenarios.The criteria are then reclassified and mapped using a weighted overlay process, where each parameter is rated on a scale from one to five based on its relevance to mineral exploration.

4. RESULTS AND DISCUSSION

The responses to the key informant interview (KII) of Mr. Darwin Edmund L. Riguer, the exploration manager at AMCI and a Philippine Mineral Reporting Code (PMRC) Competent Person for Gold and Copper, was used after attaining a CR of 0.10. A lower CR indicates a higher level of agreement among the expert's assessments, enhancing the credibility of the results. The AHP method was employed to evaluate the significance of various geological parameters in the context of mineral exploration, specifically focusing on copper (Cu) and gold (Au) deposits.

4.1 Weights from AHP

The pairwise comparisons of parameters from the KII of the exploration manager, an expert in the field, was used to determine the relative importance of these factors. The assessed six key parameters were lithology, alteration zones, geologic structures, soil geochemistry for gold and copper, and magnetic anomalies (Fig. 8). For copper, lithology emerged as the most significant parameter, with an average weight of 33.2%, followed by alteration zones at 26.1%, and geologic structures at 14.8%. Soil geochemistry for both gold and copper, along with magnetic anomalies, were deemed less significant, with weights of 7.6% and 10.6%, respectively. For gold, geologic structures held the highest weight at 42.5%, followed by lithology at 22.3% and alteration zones at 21.7%. This ranking underscore the importance of geological features in identifying potential mineral deposits.

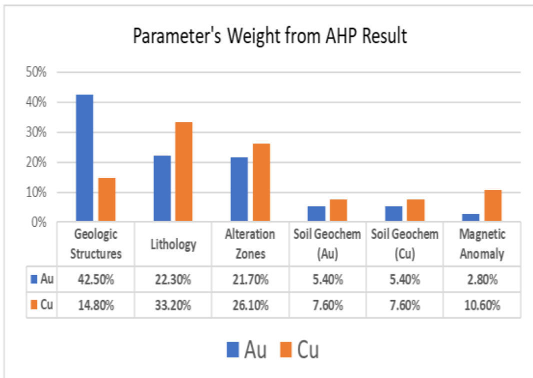

Fig. 8. Parameter's weight from the AHP

Table 1. Quantified weights for Cu

Parameters	Ave Criteria Weights	Ave Criteria Wt (%)	Rank
Geologic Structures	0.148	14.8%	3
Lithology	0.332	33.2%	1
Alteration Zones	0.261	26.1%	2
Soil Geochem (Au)	0.076	7.6%	5
Soil Geochem (Cu)	0.076	7.6%	5
Magnetic Anomaly	0.106	10.6%	4

Table 2. Quantified weights for Au

Parameters	Ave Criteria Weights	Ave Criteria Wt (%)	Rank	Parameters
Geologic Structures	0.425	42.5%	1	Geologic Structures
Lithology	0.223	22.3%	2	Lithology
Alteration Zones	0.217	21.7%	3	Alteration Zones
Soil Geochem (Au)	0.054	5.4%	4	Soil Geochem (Au)
Soil Geochem (Cu)	0.054	5.4%	4	Soil Geochem (Cu)
Magnetic Anomaly	0.028	2.8%	5	Magnetic Anomaly

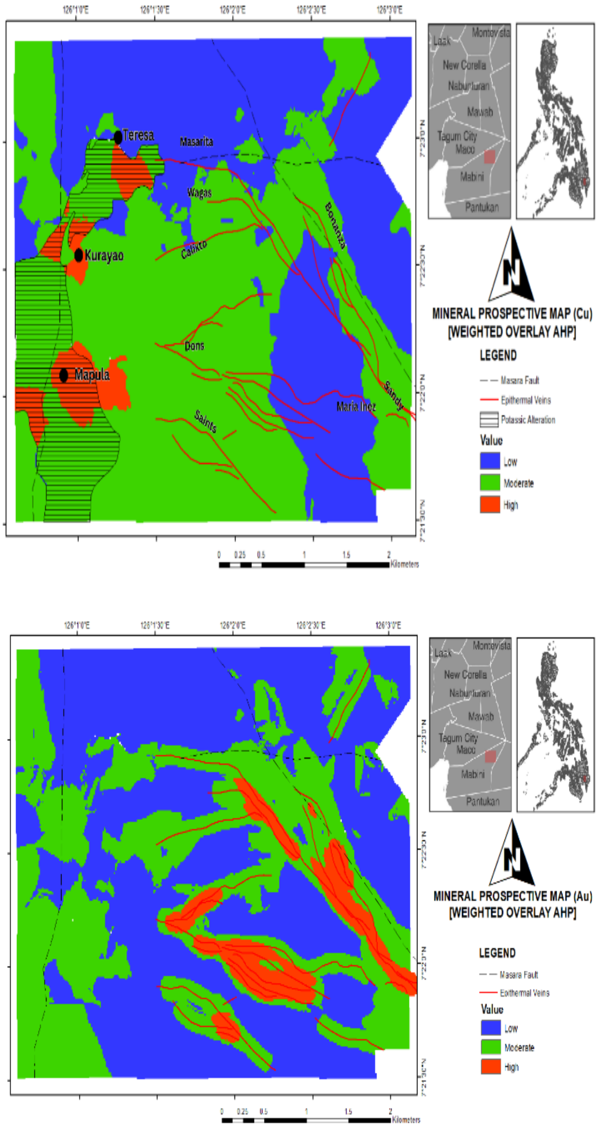

Fig. 9. AHP prospective map for Cu and Au.

4.2 Mineral Prospective Maps for Gold and Copper

The accuracy of the AHP results is contingent upon the proper assignment of weights to each criterion. The exploration geologist meticulously evaluated the individual impacts of the criteria, ensuring that the weights reflect their relevance to mineral exploration. The criteria maps were prepared for the weighted overlay process, which involved converting them into suitable formats through projection, clipping, and raster conversion.

Reclassification techniques were applied to rate each parameter's relevance on a scale of one to five, where one indicates very low relevance and five indicates very high relevance. The reclassified maps were then combined using overlay processes to produce a comprehensive map that depicts the overall relevance of the parameters (Fig. 9). These maps serve as a valuable tool for visualizing the spatial distribution of mineral potential across the study area.

The AHP methodology facilitated the generation of mineral prospective maps for both copper and gold. The AHP weighted overlay prospective map for copper (Fig. 9 top), revealing a small area of 73.10 hectares with high potential for copper deposits. An extensive area of 992.92

hectares shows a moderate likelihood of containing copper, while a larger area of 532.03 hectares indicates a lower probability. Similarly, the AHP weighted overlay prospective map for gold (Fig. 9) indicates a smaller area of 115.52 hectares with high potential for gold deposits, while an extensive area of 816.54 hectares shows a moderate likelihood of containing gold. A larger area of 665.99 hectares indicates a lower probability.

4.3 Validation

Key areas with significant copper mineral potential (Fig. 9 top), particularly around Mapula- marked in red, corresponds with the already mapped potassic alteration zones. This aligns with the general initial target of these potassic alteration zones for copper prospecting. Several areas in the high potential also coincide with the known copper prospects in the mine, such as Teresa, Kurayao, and Mapula.

The spatial distribution of prospective gold areas is closely linked to the presence of epithermal veins- some of which are already being mined. The moderate gold levels observed in adjacent areas may stem from the diffusion and dispersion of gold-bearing fluids extending beyond the primary vein structures.

The coincidence of the identified gold and copper prospects with the already known targets (e.g., potassic zones, epithermal veins), clearly underscores the reliability of utilizing AHP in mineral prospectivity mapping.

4.4 Implications for Exploration

The findings from the AHP analysis and the subsequent mineral prospective maps provide valuable insights for exploration efforts. Within the already known targets for gold and copper mineralizations (i.e., potassic alteration zones, veins), the prospective maps also allowed for a more objective and selective way of choosing the next exploration targets.

The copper prospective map has identified high priority areas even within the already existing potassic zone targets. Some of these copper prospects are not even within these zones but are adjacent, suggesting other influences for its higher copper mineralization potential. Most of the identified high gold prospects aligns with the mapped epithermal veins but has suggested key priority sites, such as the Dons and a portion of the Saints veins (Fig. 9 bottom).

By prioritizing parameters based on their significance, mineral explorationists can allocate resources more effectively and focus their investigations on areas with the highest potential for mineralization.

The emphasis on lithology, alteration zones, and geologic structures as key parameters for both copper and gold underscores the importance of understanding the geological context in mineral exploration. The results highlight the need for more detailed investigations in areas identified as having high potential, particularly those associated with these specific geological features.

5. CONCLUSIONS

In conclusion, the AHP analysis has provided a systematic approach to evaluating the significance of various geological parameters in mineral exploration. The results highlight the importance of lithology, alteration zones, and geologic structures in identifying potential copper and gold deposits. The generated mineral prospective maps serve as valuable tools for guiding exploration efforts and resource allocation.

The consistency of the expert's judgments, as indicated by the acceptable consistency ratio, enhances the credibility of the findings. The integration of the reclassified criteria maps and remote sensing data further supports the exploration process, enabling exploration geologists to make informed decisions based on the spatial distribution of the gold and copper mineralization potential.

Future exploration efforts should focus on the identified high-potential areas, leveraging the insights gained from this analysis to optimize resource allocation and enhance the likelihood of successful mineral discoveries.

6. ACKNOWLEDGEMENT

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