Mineral prospectivity mapping: a potential technique for sustainable mineral exploration and mining activities – a case study using the copper deposits of the Tagmout basin, Morocco

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ABSTRACT

Mineral prospectivity mapping (MPM) based on the principle of geometric mean was applied to stream sediment geochemical, fault density, and aeromagnetic data from Tagmout basin, Morocco to determine new areas for optimizing copper exploration. The application of a fuzzy operator using stream sediment data, factor analysis, and fault density map, allowed weights to be assigned to these parameters so that the MPM function can process them to indicate the most favorable zones of copper mineralization. The model’s accuracy as evaluated using a normalized density index (Nd with value 1.22) shows the reliability of the method. The potential copper concentration areas represent 8.22% of the entire basin of which 30% are concentrated in the western portion of the basin and other significant areas are in the southwest and northeast portions. The results indicate that MPM is a powerful technique for planning exploration programs that aim for sustainable mining activities.

Introduction

Prospecting for mineral deposits is a challenging process given that the majority of the large-scale deposits have already been located. The remaining deposits may have smaller geochemical and/or geophysical signatures, be located beneath cover rocks, and/or there is a lack of geological information that makes ore deposits difficult to detect. One technique to overcome these difficulties is to use mineral prospectivity mapping (MPM) to determine regions for more detailed exploration. Mineral prospectivity is a computer-based method that integrates a wide range of geo-information that includes geophysical,
geochemical, geological, and remote sensing (e.g., multispectral satellite data) to determine spatial associations between these data sets with potential ore deposits (Bonham-Carter et al. 1989; Zuo 2020). Several mineral prospectivity methods can be divided into either knowledge-driven or data-driven techniques or combinations between these two end-members (Zuo 2020).

Most mineral prospectivity methods are multi-criteria decision-making (MCDM) routines that are procedures of deciding the best outcome choice from many possible alternatives (Zhang and Liu 2010). In many cases, decision criteria reported by a decision-maker is often inaccurate for several reasons such as the weights are expressed in precise numbers, gaps in data, limited knowledge and insufficient capacity of the decision-maker, or because the decision-maker has an imprecise or inadequate level of information processing in the domain of the problem (Xu and Cai 2010; Wu and Zhang 2011). Accordingly, a fuzzy operator has been used in routines to solve MCDM problems and generate weights for decision criteria (Zadeh 1965; Xu and Cai 2010) and thus, a final decision model. The decision model can then be used to describe the imprecise decision and provide a better way to manage uncertainty in decision making (Wu and Zhang 2011).

In recent years, various methods have been used in MPM, including the data-driven index overlay technique (Yousefi and Carranza 2016), Boolean logic MPM technique (Carranza et al. 2008; Yousefi and Carranza 2016), fuzzy operators (Yousefi and Nykänen 2016), and the expected value MPM method (Yousefi and Carranza 2015a). Yousefi and Carranza (2015b) proposed the geometric average prospectivity model to generate continuously weighted evidential maps. This method provides a number of advantages including a) reduce the uncertainty associated with bias in feature weights and distance intervals to imprecisely estimated features, b) providing fuzzy weights of continuous values into the evidence maps which are assigned without the use of the known mineral occurrences locations, and c) they can also solve the problem of using different values of evidence layers in the same unit (Yousefi and Carranza 2015b).

The evaluation of prospectivity models is a critical problem in defining exploration targets. In this regard, fractal methods (Mandelbrot 1983) can be used with geometric support to estimate the spatial characteristics related to the mineral deposits, such as geochemical anomalies (e.g., Cheng et al. 1994; Cheng 2007; Carranza et al. 2008; Carranza 2010; Afzal et al. 2010, 2016; Zuo 2011a, 2011b; Kouhestani et al. 2020; Pourgholam et al. 2021; Shabbazi et al. 2021; Shamseddin Meigooni et al. 2021), geological structures (e.g., faults) (Carranza and Sadeghi 2010) and geological units (Zuo et al. 2009). Fractal models have been used to classify exploration evidence layers and target areas for prospectivity modeling of minerals (Almasi et al. 2015; Yousefi and Carranza 2015a, 2015b). Many studies have proposed the fractal models using concentration-area (C-A) and prediction-area (P-A) to determine the evidential map capacity with the known mineral occurrences, and determine predictive ability that can be used as an evidential map weight and for selecting thresholds to yield binary predictor maps (e.g., Yousefi et al. 2014; Yousefi and Carranza 2015b, 2016).

This work aims to evaluate the potential of locating additional copper deposits within Tagmout basin in eastern Morocco where several large copper deposits currently exist. Prospectivity models include fractal and geometric averaging methods that will be used to determine higher concentrations of copper occurrences. The models (Figure 1) incorporate geological, geochemical data from stream sediment samples and geophysical (magnetic) data to determine and identify anomalies associated with copper deposits. These anomalies will then be categorized according to their potential as targets for prospecting geology and geophysics in more detail for copper mineralization.
The first data layer to be set in the study model is the geological layer (i.e., geological setting). The Tagmout basin, which is located in the Anti-Atlas Mountains, covers an area of 822 km² and is located in the northwestern Draa Basin of Eastern Morocco (Figure 2a). The Anti-Atlas consists of a series of inliers where igneous and metamorphic rocks of Paleoproterozoic and Neoproterozoic age are exposed (Kouyaté et al. 2013). Most of these inliers lie between or along the South Atlas Faults and the Anti-Atlas Major Fault (Figure 2a). The Proterozoic rocks were formed during the Paleoproterozoic Eburnian orogeny and the Neoproterozoic Pan-African orogeny. The Tagmout (or Tagmout Tin Ouayour) basin is located within the contact zone of the Ighrem inlier which is a basin characterized by abundant carbonate and siliciclastic formations (Figure 2b) (Pouclet et al. 2007). The basin was formed during the late stages of the Pan-African orogeny where extension occurred after accretion of volcanic arcs that once covered the entire Anti-Atlas range. The resulting basins have been interpreted to be pull-apart basins where siliciclastic sediments filled the basins (Pouclet et al. 2007). After the formation of the basins, a marine
transgression caused the deposition of carbonates during the Cambrian. Later Cambrian extension resulted in the deposition of transgressive sediments above the Cambrian sediments and Neoproterozoic lithologies (Pouclet et al. 2007).
**Proterozoic basement formations**

The oldest lithostratigraphic unit within the study area is the Paleoproterozoic Zenaga Complex that forms a basement comprising granites, mica schists, sandstones, shales, and gneisses, where the siliciclastic and metamorphic rocks lie adjacent to the granites (Oudra et al. 2005). The Neoproterozoic rocks lie directly on top of the Paleoproterozoic units where the contact is considered to be tectonic since there is a brittle-ductile transition shear zone (Oudra et al. 2005). The Neoproterozoic rocks include Ourty Group overlain by Ighrem Group. The Ourty Group includes quartzites and carbonate units (Oudra 1988; Oudra et al. 2005), while the Ighrem Group is composed of conglomerates and volcanic-detrimental formations that were deposited in a basin formed during the later portions of the Pan-African orogeny (Oudra et al. 2005). The Upper Neoproterozoic is composed of conglomerates, sandstones, and volcanic units overlain by pelites and volcanic breccia (Choubert and Faure Muret 1973). The Upper Neoproterozoic rocks are directly located on quartzites of the Ourty Group (Oudra 1988).

**Paleozoic units**

The Paleozoic units lie unconformably over the Neoproterozoic rocks and include Adoudou and Lie-de-vin formations. The Adoudou Formation has been divided into several subunits including volcanoclastics and siliciclastic rocks of the Basal Series, and the overlying Lower Limestones which include the Tamjout Dolomite (Choubert 1963; Algouti et al. 2001; Benssaou and Hamoumi 2001) (Figure 2c). The Lie-de-vin Formation includes purplish-red pelites interspersed with carbonate beds and overlying subunits of the Upper Limestones and the schistose Limestone Series (Choubert 1963; Algouti et al. 2001; Benssaou and Hamoumi 2001). All of the above units have been dated to the Lower Cambrian (Choubert 1952; Boudda and Choubert 1972; Benziane et al. 1983; Benssaou and Hamoumi 2001) and were deposited in an intracontinental basin that formed during the rifting of the West African Craton (WAC) at the end of the Neoproterozoic (Soulaimani et al. 2003). Northeast-trending dolerite sills and dikes intrude all of the above units and are related to the opening of the Atlantic Ocean in the Triassic/Lias period (Sahabi et al. 2004).

**Ore geology**

The Anti-Atlas of Morocco has several world-class metallic ore deposits and over 200 known copper deposits that were formed by a variety of ore deposition mechanisms that include sedimentary exhalative deposits, vein deposits, volcanogenic massive sulfides, and epithermal processes (Bouabdellah and Slack 2016). The majority of these deposits are located within Neoproterozoic and Cambrian units overlying Paleoproterozoic rocks or along with the transition between these Neoproterozoic and the Cambrian units (Bourque et al. 2015). The copper mineralization is mostly epigenetic and is related to several tectonic events including rifting at the end of Proterozoic and compression during the Hercynian orogeny where a thermal event created conduits for the fluids or rifting during the Atlantic Ocean opening (Bouabdellah and Slack 2016). There are 10 known copper deposits near and within the study area (Figure 2b). The most important copper deposits include the Alous, Assif Imider, Aménayo, Tizert, Amadouz, Talat N’Ouamane, and Akiout deposits. These deposits are located within Late Neoproterozoic and Early Paleozoic lithologies. A number of these deposits occur within
or near volcanic structures (sills, intrusions, or dikes) which suggest a relationship between hydrothermal activity and later Neoproterozoic volcanic episodes or a margin basin (Pouit 1966; Chabane and Boyer 1979). The Tizert and Amadouz copper deposits are emplaced within Cambrian lithologies and have a more controversial origin, but are more likely related to the Atlantic Ocean opening or Varisican compressional tectonics (e.g., Pouit 1966; Soulimani 1998; Oummouch et al. 2017). The Tizert and Amadouz copper deposits were formed by synsedimentary processes (Bourque et al. 2015) within Late Ediacaran Basin Series sediments that are found within the Igherm inlier (Figure 2a) (Oummouch et al. 2017; Poot et al. 2020). The ore zones within the sedimentary rocks are 200 and 400 m below the surface and are located mostly along the Cambrian basin’s margin adjacent to the Proterozoic basement highs (Oummouch et al. 2017). Additionally, the known mineralization occurrences are found near strike-slip faults that may have acted as a path for the ore-rich fluids (Oummouch et al. 2017) which deposited ore disseminated chalcopyrite, chalcocite, and bornite. Furthermore, the deposits have undergone supergene enrichment that formed significant deposits of azurite, malachite, and covellite (Poot et al. 2020).

The study area has several regions that contain polymetallic mineralization (Cu, Pb, and Zn) stratiform synsedimentary (Talat N’Ouamane). The mineralization is located within the Late Ediacaran Adoudou Formation either in the Base Series near the contact with the Precambrian substratum or higher in the carbonates bed of the Tamjout member. Rare occurrences are found in the Lower Limestone series, but they are always within the terrigenous facies with carbonates cement and/or in purely carbonates facies (Pouit 1966). The mineralization is present only in the base formation when its thickness reaches between 10 and 60 meters within low regions in the paleotopography of the underlying basement.

**Spatial data**

**Stream sediment samples**

Stream sediment samples were collected at 172 sites (Figure 2b) and were analyzed for their As, Cu, Pb, Ni, and Cr concentrations (Table 1). These elements are considered to be good indicators for potential copper deposits (Yang et al. 2009; Parsa et al. 2016). The sampling strategy and error-control procedures follow Johnson et al. (2001). Generally, only second and third-order tributaries were sampled (Figure 2b). Each sample consists of five samples collected along the stream’s living bed. 2 to 5 cm of the surface layer is removed to avoid wind contamination. Dry sediments are sifted through a 2 mm mesh Nylon. The samples were analyzed by an X-ray fluorescence spectrometer (XRF) type Spectro X-LAB 2000. Quality control is done by inserting standard samples during each analysis session and randomly inserting control samples. The XRF ED is calibrated using several samples of international standards.

**Geophysical data**

Magnetic data were acquired in 1999 by Géoterrx-Dighem for the Moroccan Ministry of Energy and Mines. Flight lines were spaced 500 meters apart and were oriented N15° to N315°. The draped survey had an average ground clearance of 30 meters with the data collected using a cesium magnetometer that has a sensitivity of 0.01nT. The raw data were processed by removing noise and diurnal variations and detecting closing errors.
Table 1. Representative geochemical analyses of the studied stream sediments in ppm.

<table>
<thead>
<tr>
<th>Sample</th>
<th>x</th>
<th>Y</th>
<th>As</th>
<th>Pb</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
</tr>
</thead>
<tbody>
<tr>
<td>AL11</td>
<td>23164.60283</td>
<td>347109.69684</td>
<td>43.00</td>
<td>0.00</td>
<td>24.00</td>
<td>27.00</td>
<td>48.00</td>
</tr>
<tr>
<td>AL15</td>
<td>230374.69777</td>
<td>338855.72313</td>
<td>28.00</td>
<td>0.00</td>
<td>23.00</td>
<td>27.00</td>
<td>43.00</td>
</tr>
<tr>
<td>AL21</td>
<td>233070.07435</td>
<td>352072.51020</td>
<td>0.00</td>
<td>0.00</td>
<td>21.00</td>
<td>52.00</td>
<td>143.00</td>
</tr>
<tr>
<td>AL28</td>
<td>227704.73950</td>
<td>353813.60256</td>
<td>27.00</td>
<td>0.00</td>
<td>19.00</td>
<td>26.00</td>
<td>52.00</td>
</tr>
<tr>
<td>AL3</td>
<td>230835.02067</td>
<td>339103.98360</td>
<td>47.00</td>
<td>0.00</td>
<td>33.00</td>
<td>26.00</td>
<td>46.00</td>
</tr>
<tr>
<td>AL30</td>
<td>232508.78450</td>
<td>336537.57442</td>
<td>34.00</td>
<td>0.00</td>
<td>18.00</td>
<td>26.00</td>
<td>45.00</td>
</tr>
<tr>
<td>AL33</td>
<td>245538.46166</td>
<td>34211.21757</td>
<td>37.00</td>
<td>0.00</td>
<td>17.00</td>
<td>29.00</td>
<td>40.00</td>
</tr>
</tbody>
</table>

(continued)
Additional data processing included removing the 1999 International Geomagnetic Reference Field (IGRF) to generate residual magnetic field data (RMF). The RMA map was digitized and gridded at a spacing of 125 m to produce RMF data (Figure 3a). To remove the dipolar effect of the Earth’s magnetic field, the RMA data were reduced to pole (RTP) (Figure 3b) (Pham et al. 2020a, 2020b).

**Fault data**

The majority of the copper deposits within the Igherm inlier and surrounding areas are associated with faults that have acted as conduits for the passage of metal-rich fluids to upper crustal levels so they can be deposited in geochemical favorable regions (Levresse et al. 2016; Oummouch et al. 2017; Ouchchen et al. 2021). Thus, faults are an important

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**Table 1.** Continued.

<table>
<thead>
<tr>
<th>Sample</th>
<th>x</th>
<th>Y</th>
<th>As</th>
<th>Pb</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
</tr>
</thead>
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<tr>
<td>GR69</td>
<td>231904.33132</td>
<td>35516.86665</td>
<td>36.00</td>
<td>3.00</td>
<td>60.00</td>
<td>30.00</td>
<td>59.00</td>
</tr>
<tr>
<td>GR70</td>
<td>226320.27206</td>
<td>34238.49213</td>
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<td>23.00</td>
<td>20.00</td>
<td>28.00</td>
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<tr>
<td>Pel1</td>
<td>213510.61225</td>
<td>34654.90071</td>
<td>36.00</td>
<td>0.00</td>
<td>173.00</td>
<td>22.00</td>
<td>46.00</td>
</tr>
<tr>
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<td>211884.88542</td>
<td>34653.26927</td>
<td>27.00</td>
<td>0.00</td>
<td>17.00</td>
<td>28.00</td>
<td>47.00</td>
</tr>
<tr>
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<td>345106.13485</td>
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<td>0.00</td>
<td>16.00</td>
<td>41.00</td>
<td>102.00</td>
</tr>
<tr>
<td>Pel15</td>
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<td>358406.63636</td>
<td>13.00</td>
<td>0.00</td>
<td>16.00</td>
<td>35.00</td>
<td>148.00</td>
</tr>
<tr>
<td>SA24</td>
<td>249724.61499</td>
<td>351270.28305</td>
<td>43.00</td>
<td>26.00</td>
<td>22.00</td>
<td>28.00</td>
<td>35.00</td>
</tr>
<tr>
<td>SA3</td>
<td>250822.63452</td>
<td>355876.68810</td>
<td>22.00</td>
<td>0.00</td>
<td>18.00</td>
<td>28.00</td>
<td>53.00</td>
</tr>
<tr>
<td>SA4</td>
<td>255148.58067</td>
<td>35082.93651</td>
<td>22.00</td>
<td>0.00</td>
<td>16.00</td>
<td>28.00</td>
<td>53.00</td>
</tr>
<tr>
<td>SC1</td>
<td>212524.18046</td>
<td>345716.41561</td>
<td>10.00</td>
<td>0.00</td>
<td>115.00</td>
<td>30.00</td>
<td>64.00</td>
</tr>
<tr>
<td>SC12</td>
<td>210966.22887</td>
<td>347725.43403</td>
<td>31.00</td>
<td>0.00</td>
<td>13.00</td>
<td>45.00</td>
<td>118.00</td>
</tr>
<tr>
<td>SC2</td>
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<td>78.00</td>
<td>49.00</td>
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<tr>
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<td>345089.66986</td>
<td>32.00</td>
<td>0.00</td>
<td>76.00</td>
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</tr>
<tr>
<td>SC5</td>
<td>232127.07979</td>
<td>353324.45820</td>
<td>3.00</td>
<td>0.00</td>
<td>36.00</td>
<td>53.00</td>
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</tr>
<tr>
<td>SC6</td>
<td>233018.28488</td>
<td>353007.09441</td>
<td>8.00</td>
<td>0.00</td>
<td>27.00</td>
<td>50.00</td>
<td>148.00</td>
</tr>
</tbody>
</table>

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**Figure 3.** a. Residual magnetic anomaly (RMA) map. b. Reduction to the pole (RTP) of magnetic anomaly map. c. The tilt angle of the RTP data. d. Three-dimensional Euler deconvolution depths using a structural index of 0 superimposed the TDR angle derived lineaments. e. Rose diagram showing the orientation of the lineaments obtained the tilt angle method. Copper deposits are shown as triangles in Figures 3a, 3b, and 3c.
parameter in locating potential economic copper deposits. The known faults were digi-
tized for their latitude and longitude from geological maps (Gasquet et al. 2008;
Oummouch et al. 2017) (Figure 2a, 2b).

**Data-driven methods**

**Factor analysis**

Factor analysis (FA) is a multivariate analysis process (Afzal et al. 2016; Daviran et al.
2020; Ghezelbash et al. 2020) that can be used to generate significant multi-element
anomalous signatures and to reduce the number of negative variables (Yousefi et al. 2012,
2014). Principal component analysis (PCA) can be used as a FA method with varimax
rotation (Kaiser 1958) to reduce the number of variables in a dataset while preserving as
much information about the dataset as possible (Filzmoser et al. 2009). During the PCA
process, eigenvalues are calculated with the larger eigenvalues containing more variance
(i.e., more information). While there are no specific techniques to determine how many
eigenvalues to use in a study, Helvoort et al. (2005) and Yousefi et al. (2014) have shown
that eigenvalues are greater than 1 contain sufficient information to be able to discrimi-
nate geochemical anomalies. Additionally, threshold values greater than 0.5 for loadings are
considered sufficient to extract significant anomalous multi-element geochemical signa-
tures (Yousefi et al. 2014). Factor analysis requires a normal or symmetrical data distribu-
tion; however, the stream sediment geochemical data are compositional and are not
independent of each other (Filzmoser et al. 2009; Zuo et al. 2013). Thus, a log-transforma-
tion which is a normalization process was performed to generate symmetric data distribu-
tions (Cheng et al. 1994; Zuo 2011b; Wang et al. 2019).

**Geochemical mineralization probably index of the geochemical anomalies**

The stream sediment geochemistry was analyzed using the Geochemical Mineralization
Probability Index (GMPI) was introduced by Yousefi et al. (2014) and is a probability
method that develops classes using a stepwise FA. First, the distribution of geochemical
anomalies is analyzed by determining their factorial scores (FS) and then, converted into
an interval [0, 1] by applying a logistic function. This transformation of the stream sedi-
ment geochemical data into a logistic space generates a higher degree of differentiation
between the geochemical anomalies and improves the forecast rate of potential mineral
deposits (Parsa et al. 2016). The GMPI equation is:

\[
GMPI = \frac{e^{FS}}{1 + e^{FS}}
\]  

(1)

where FS is the factor score of every sample used in the FA (Yousefi et al. 2012, 2014)
and e is the exponential function. The GMPI of each multi-element association was
then calculated.

**Fuzzy weighting of fault density**

Faults are an important component in determining the location of many ore deposits
(Afzal et al. 2019). Faults and fractures can provide conduits for the movement of metal-
rich fluids, circulation of hydrothermal fluids and will aid in determining the location of
the ore deposits (Micklethwaite et al. 2010; Afzal et al. 2019). Thus, adding fault traces
determined from geological mapping or inferred from geophysical data to a data-driven database will increase the probability of locating ore deposits. Fault trace density (FD) was thus used to aid in predicting the location of ore deposits (Yousefi and Nykänen 2016). Several investigations have used a high FD as an indicator of copper mineralization (Pirajno 2010; Chen et al. 2011; Yousefi and Carranza 2015c).

To further analyze the FD data, a logistic function was used to convert continuous FD data to the range [0, 1] (Nykänen et al. 2008). By using the logistic conversion, the distinction between different classes of evidence data can be improved (Yousefi and Carranza 2015c). The following logistical transformation function was used to calculate FD values in a fuzzy space:

\[ F_{FD} = \frac{1}{1 + e^{-s(FD-i)}} \]  

Where \( F_{FD} \) and FD are the transformed values and values to be converted in the interval [0, 1] range, respectively (Yousefi and Carranza 2015c), i is the inflection point, and s is the slope. The i and s are defined by Yousefi and Nykänen (2016):

\[ i = \frac{2\ln99}{\max(FD) - \min(FD)} \]  
\[ s = \frac{\max(FD) + \min(FD)}{2} \]

Using Equation (2), a fuzzy score map of the FD data was created (Figure 5).

**Integration of weighted layers**

In MPM, the integration of weighted evidence maps requires the use of functions that use a weight indicating the importance of each evidence map to provide the model that indicates the mineral potential target (Bonham-Carter 1994; Porwal et al. 2006; Ghezelbash et al. 2019a, 2019b). To accomplish this integration, we used the geometric average model to combine the map of fuzzy scores of two layers related to the significant mineralization, namely GMPI (Figure 5b) with the FD data (Figure 6), and to delineate the most prospective target zones for further exploration of the copper mineralization (Wang et al. 2007). The geometric average is the statistically average value when calculating a single average from several geodatabase evidential layers with geometrical support (Yousefi and Carranza 2015b). To calculate the geometric average function for copper mineralization, \( G_{ACu} \), the following equation was used (Yousefi and Carranza 2015a):

\[ G_{ACu}(F_{GMPI}, F_{FD}) = \left( \prod_{i=1}^{2} F_i \right)^{1/2} = \sqrt{F_{GMPI}F_{FD}}^2 \]  

where \( F_{GMPI} \) and \( F_{FD} \) are the fuzzy scores of indicator values from the corresponding evidential maps, that were calculated using fuzzy operators (Parsa et al. 2016; Farahbakhsh et al. 2019; Roshanravan et al. 2020). The corresponding geometric average prospectivity map is shown in Figure 7a.
Creating evidence layers

Geochemical signature

A two-step FA was applied for extracting component stream sediment geochemical signatures. In the first step, factors F1 and F2 representing Ni–Cr and Cu–Pb multi-elements association, respectively, with positive loading are shown in Table 2. In the second step, As is considered to be a noisy element and was omitted from the dataset and further analysis. Therefore, the positive loads in F1 and F2 only take into account Ni–Cr and Cu–Pb multi-element association, respectively (Table 2). The total variance for the Ni-Cr association increased from 44.52% in the first-step F1 to 49.77% in the second-step F1, while variances for Cu-Pb increased from 27.63% in the first-step F2 to 31.07% in the second-step F2. Consequently, the FA successively reduced the number of factors and increased the intensity of the anomaly (as reported by Yousefi et al. 2012).

The FS obtained from the FA was used as a multi-element anomaly indicator. The FS has been used to create maps to identify geochemical anomalies that indicate mineralization or sources of geochemical contamination (Helvoort et al. 2005). FS values that have 95% of cumulative percentile as the background samples and threshold separating anomaly (Yousefi et al. 2014) were used in our analysis. The FS Ni-Cr (Figure 4a) and FS Cu-Pb (Figure 4b) distribution maps show the range of FS values within the Tagmout basin. The yellow to orange regions represent regions with anomalies that may contain higher levels of copper.

The distributions of the GMPI for the Cu–Pb and Ni-Cr associations are shown in Figure 5. To increase the intensity of the anomalies for copper mineralization, some multi-element associations can be omitted, even though they may be considered as evidence of copper mineralization. For this reason, the GMPI Ni-Cr results were excluded from our analysis, as they relate to certain lithological formations such as dolerite, gabbro, and quartzite, and the known copper deposits within the Anti-Atlas do not occur within these lithologies.

Faults density basing on magnetic data

The RTP signature of the Tagmout basin contains short and long wavelength anomalies with the highest amplitude anomalies occurring over possibly buried mafic Proterozoic rocks similar to those outcropping in the Igherm inlier (Ouchchen et al. 2021) in the southern portions of the study area (Figure 5b). Within the NW part of the study area, the northeast-trending magnetic maximum corresponds to a Jurassic-age dolerite dike, outcropping in the Ighrem inlier (Figure 2b). The other magnetic maxima located in the central and eastern parts of the study area also may be related to buried Proterozoic rocks but the linear nature of the central anomalies suggests that these may be related to linear structural features (i.e., fault systems). Magnetic data can help in determining lineaments.

Table 2. Matrix of rotating components of the first and second steps.

<table>
<thead>
<tr>
<th></th>
<th>First step</th>
<th></th>
<th></th>
<th>Second step</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Elements</td>
<td>F1</td>
<td>F2</td>
<td>F3</td>
<td>Elements</td>
<td>F1</td>
</tr>
<tr>
<td>As</td>
<td>-0.816</td>
<td>0.119</td>
<td>-0.078</td>
<td>Pb</td>
<td>-0.535</td>
</tr>
<tr>
<td>Pb</td>
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<td>0.566</td>
<td>-0.526</td>
<td>Cu</td>
<td>-0.086</td>
</tr>
<tr>
<td>Cu</td>
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<td>0.833</td>
<td>0.531</td>
<td>Ni</td>
<td>0.881</td>
</tr>
<tr>
<td>Ni</td>
<td>0.799</td>
<td>0.430</td>
<td>-0.283</td>
<td>Cr</td>
<td>0.960</td>
</tr>
<tr>
<td>Cr</td>
<td>0.939</td>
<td>0.211</td>
<td>-0.063</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eigenvalues</td>
<td>2.532</td>
<td>1.259</td>
<td>0.649</td>
<td>Variance (%)</td>
<td>49.768</td>
</tr>
<tr>
<td>Variance (%)</td>
<td>50.646</td>
<td>25.175</td>
<td>12.975</td>
<td>Cumulative variance (%)</td>
<td>49.768</td>
</tr>
</tbody>
</table>
with significant magnetization contrast (Salem et al. 2008) and therefore allow for a better understanding of the structural framework (Austin and Blenkinsop 2008, 2009; Salem et al. 2008; Henson et al. 2010; Pham et al. 2021b, 2021d). The cause of these lineaments could be the contact between rock units, faults, or fracture zones (Pham 2020, 2021d). To aid in determining lineaments within the magnetic data, derivative methods are commonly used including horizontal and vertical derivatives (Pham et al. 2021c, 2021d). Horizontal and vertical derivatives can produce large and small amplitude anomalies making interpretation of deeper sources difficult. Thus, the tilt angle derivative (TDR) was developed (Salem et al. 2008) which uses a ratio between the amplitudes of the vertical derivative and the total horizontal derivative that overcomes this problem. Figure 5c shows the TDR map of the RTP data.

Figure 4. Factor score (FS) distribution of the stream sediment geochemistry data for Ni-Cr (a) and Cu-Pb (b).
Magnetic data can also be analyzed by performing a three-dimensional Euler’s deconvolution analysis which is a derivative method but also allows determining the magnetic source depth (Reid et al. 1990). Euler deconvolution has several parameters that must be defined to get reliable results including window size, structural index (a model for the source geometry based on the dominant geology of the study area), and grid interval (Reid et al. 1990). We varied the window sizes between 5 and 20 km and consistently obtained similar depths for each window. A structural index of zero was used which corresponds to a thin sheet model. The TDR and Euler deconvolution analysis indicate lineaments trend NNE-SSW, NW-SE, and E-W with depths ranging from 90 to 2471 m (Figure 5c, 5d). A number of lineaments were observed near known copper deposits. The lineaments were deduced from the magnetic derivative analysis and were added to the fault database and integrated within the FD model.

Figure 5. GMPI distribution of the stream sediment geochemistry data for Ni-Cr (a) and Cu-Pb (b).
Evaluation of the geometric average prospectivity model

After the generation of the geometric average prospectivity models, the location of known mineral occurrences (Figure 2a) is used to evaluate the results. To do this procedure, the prospectivity model values must be classified using fractal operators (Meigoony et al. 2014; Yousefi and Carranza 2015a, 2015b; Afzal et al. 2016; Sanusi and Amigun 2020). For the Tagmout basin, the fractal concentration-area (C-A) model can be used to discriminate thresholds for classifying the prospectivity values (Cheng et al. 1994). In a log-log plot, a constant slope indicates a fractal dimension, so that the threshold values can be obtained as breakpoints in the plot (Nykänen et al. 2008). Based on Figure 7b, six classes or populations are obtained from the prospectivity model. The first four populations indicate low and medium concentration anomalies and the remaining populations indicate higher concentration anomalies. Based on these results, a classified map was generated (Figure 7c) with the highest intensity anomalies (>0.62) which are located in the northeast and west parts of the Tagmout basin.

For evaluating the importance of different classes, prediction-area (P-A; Parsa et al. 2016) plots were used. In a P-A plot, the intersection points of the curve of the cumulative percentage of known Cu occurrences and the curve of the cumulative percentage of prospectivity areas can be used as the prediction rate to evaluate the prospectivity model (Yousefi and Carranza 2015a, 2016). The prospectivity model can then be used to discriminate the further area for exploration (Yousefi and Carranza 2015a, 2015c). Based on Figure 7c and the location of the known mineral occurrences, P-A plots are then prepared (Figure 7d). The intersection point in Figure 7d shows that 55% of the known mineral occurrences are predicted within 45% of the Tagmout basin.

Yousefi and Carranza (2015a) proposed that the intersection point in a P-A plot can be used to determine two indexes: normalized density (Nd) and the weight of the targeting criterion (We) (Figure 7d). Nd is the prediction rate of a prospectivity map divided by its corresponding occupied area extracted from the intersection point of the P-A plot, while We, is the logarithm of Nd. These values can be interpreted as targeting criteria where Nd > 1 and We > 0 indicate that there is a positive association with the type of
deposit that is under investigation, while values Nd\(<\) 1 and We \(<\) 0 indicate that there is a negative association (Ghezelbash et al. 2019a). If Nd = 1 and We = 0, then the mineralization is independent of the targeting criteria (Ghezelbash et al. 2019a). Ghezelbash et al. (2019a) show that if the intersection point in a P-A plot has a higher value than other targeting criteria, then this targeting criterion is more effective than other targeting criteria in locating the desired mineralization. Thus, the two values can be used to prove the effectiveness of the selected model for the mineralization type (e.g., Mihalasky and Bonham-Carter 2001). The presented results indicate that Nd = 1.22 and We = 0.20 and suggest that the used prospectivity model is effective in locating copper mineralization. Figure 8 shows the regions which predict the locations of copper deposits within the Tagmout basin based on the presented models.

**MPM: a technique for sustainable mineral exploration and mining activities - discussion**

In MPM analyzes, the generation of target zones is an important step in a mineral exploration program, as the characteristics of a specific type of mineral deposit can be related to the geological features associated with the mineralization. It is generally accepted that fault zones are important conduits that promote the circulation of metal-bearing and hydrothermal fluids (Pirajno 2010) and have been found to be especially important in the Anti-Atlas Region of Morocco in locating and forming copper deposits (Ouchchen et al. 2021). One of the critical aspects in mineral prospecting is to determine the association between geochemical and geophysical anomalies, and geological features (Wang et al.
Yousefi et al. (2014), Yousefi and Nykänen (2016) and Yousefi and Carranza (2015a, 2016) have demonstrated that a combination of a set of effective layers of evidence of a certain type of ore deposit sought from different types of mineral exploration data (e.g., geochemical, geophysical, and geological) can be more reliable in targeting areas for more detailed exploration.

The spatial distribution of geochemical anomalies for a specific type of mineral deposit may differ from one area to another. Several geologically-based parameters that are related to the characteristics of a specific study area can be determined and may affect the spatial dispersion of certain geochemical elements (Spadoni 2006; Cheng 2007). For this reason, it is necessary to recognize that multi-elemental geochemical signatures may allow the delineation of anomalous zones. In this work, the multi-elemental Cu-Pb association has been found to have a good spatial relationship for the detection and predictor of the type of copper deposits found in the Tagmout basin. To generate an improved geochemical evidence map for MPM, the GMPI method was applied for the discrimination of anomalous copper zones, as it is a more powerful tool than an ordinary factor analysis for weighting and fuzzification of stream sediment geochemical data. As Yousefi et al. (2012, 2014) demonstrated, the transformation of geochemical signatures using a logistic function of FS increases the prediction rate of MPM and allows for better discrimination of geochemical populations compared to a factor score alone. The GMPI results based on an indicator component can then be considered as values of significant geochemical anomalous for the enhancement of exploration success. As can be seen in Figure 5, the area with known copper occurrences within the Tagmout basin has a high intensity of GMPI, but in the northeast portions of the basin without any known copper deposits also have a high intensity of GMPI. This portion of the basin should be considered a potential area for further mineral exploration, as it indicates promising new regions, which have not been previously determined by individual indicator components. Based on the geological map (Figure 2b), the GMPI and the Cu-Pb anomalies occurring in the western portions of the Tagmout basin are lithology related, as they correlate with the Basic series and the contact zones between the limestone and basement. The majority of the copper deposits in the Tagmout basin and surrounding area are located in these geological units.

Figure 8. Delimited potential areas for further exploration of minerals.
(Bouabdellah and Slack 2016) and whose origin was controlled by the NE-SW trending faults (Ouchchen et al. 2021). GMPI and Cu-Pb anomalies were also determined within the northeastern portion of the Tagmout basin and can be correlated with the E-W and NE-SW trending lineaments determined by magnetic tilt angle analysis (Figure 3c).

Fuzzy operators were applied to weight effective geochemical evidence layers and FD data (Figures 5b and 6). The spatial evidence values that come from different datasets are converted to the same data space from 0 to 1 which facilitates their integration for further analysis. Each of the maps generated in this work can be used in the mineral prospectivity modeling of copper deposits through the application of the geometric average model, which permits the delimitation of reliable target areas for mineral exploration. To estimate the ability of the generated mineral prospecting model to discriminate copper mineralization zones, the normalized density index (Nd) and the P-A were used to detect threshold values (Figure 7d). Our analysis indicated that the value of 0.31 was determined as the threshold for the validation of the prospectivity map (Figure 8). Thus, the determined Nd value shows that the applied prospectivity model is also efficient because Nd is >1 and the corresponding We values are positive. These results show that areas with high prospectivity values can be used as targets for further exploration within the Tagmout basin. Figure 8 shows that the target areas produced by using the geometric average function represent an area of 8.22% of the Tagmout basin that may contain significant copper occurrences with 30% of these being concentrated in the western part of the basin. These values indicate that the integrated layers have a strong spatial correlation with the known copper occurrences locations. These potential copper mineralization areas trend E-W and NE-SW near similarly trending known faults and magnetically determined lineaments. These potential copper mineralization areas are mostly located in the western, northeast, and southwest portions of the Tagmout basin.

The results of the current study can be used to define future exploration programs in the western, southwestern, and northeastern portions of the Tagmout basin which give a sustainable perspective of copper exploration and mining activities in Morocco. The data needed to run similar sustainability evaluations are stream sediment geochemical data, whole-rock geochemical data, detailed geological mapping including lithological mapping, fault analysis, and hydrothermal alteration mapping, and detailed geophysical exploration. The geophysical methods may include magnetic, airborne electromagnetic surveys, electrical resistivity, and ground electromagnetics.

Conclusions

Stream sediment geochemical, aeromagnetic, and geological data were analyzed in the Tagmout basin within the Anti-Atlas region of western Morocco to determine favorable locations for more detailed exploration for copper exploration. The datasets were analyzed using mineral prospectivity mapping based on the principle of the geometric mean. The input data to MPM was processed using fuzzy operators within a factor analysis on the stream sediment geochemical data and fault density data. The fault density data were determined from geological mapping and magnetic lineaments derived from a tilt angle analysis of the reduction to the pole aeromagnetic data. The MPM function using the fuzzy analysis results determined the most favorable regions of potential copper mineralization for future exploration activities. These potential copper mineralization regions were further analyzed to determine the accuracy of the MPM model. The accuracy as indicated by the normalized density index was 1.22. This value suggests that the suggested copper mineralization areas are statistically reliable.
The MPM model suggests that 8.22% of the Tagmout basin contains significant concentrations of copper mineralization. Out of this percentage, 30% occurs in the western Tagmout basin. The northeastern and southwestern portions of the basin also contain significant amounts of copper mineralization. These mineralization zones lie along east- and northeast-trending regions and are parallel to known faults and magnetic lineaments in the region. Faults are important for copper mineralization in the western Anti-Atlas since they facilitate the circulation of copper-bearing fluid from deeper crustal levels upward to the favorable lithology for precipitation. The MPM modeling succeeded to predict the locations of well-known copper deposits in the western part of the Tagmout basin and suggests other potential regions in the northeastern and southwestern of the basin for further exploration activities which indicate that the MPM is a potential technique for sustainable mineral exploration and mining activities.

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Ethical statement

The authors declare that all ethical practices have been followed in relation to the development, writing, and publication of the article.

Disclosure statement

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Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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