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Overcoming survival bias in targeting mineral deposits of the future: Towards null and negative tests of the exploration search space, accounting for lack of visibility

Mahyar Yousefi[a,b,*], Vesa Nykänen[c], Jeff Harris[d], Jon M.A. Hronsky[e,f], Oliver P. Kreuzer[g,h], Guillaume Bertrand[i,j,k], Mark Lindsay[f,l,m]

[a] Faculty of Engineering, Malayer University, Malayer, Iran
[b] Centre for Exploration Data Mining, National Iranian Copper Industries Company, Tehran, Iran
[c] Information Solutions, Geological Survey of Finland, Rovaniemi, Finland
[d] HARRIS GEOSCIENCE, 6 Sixth St, Fenelon Falls, Ontario, Canada
[e] Western Mining Services PL, Suite 26, 17 Prowse St, West Perth, WA 6005, Australia
[f] Centre for Exploration Targeting, School of Earth Science, University of Western Australia, Crawley, WA 6009, Australia
[g] Corporate Geoscience Group, PO Box 5128, Rockingham Beach, WA 6969, Australia
[h] Economic Geology Research Centre (EGRU), School of Earth & Environmental Science, James Cook University, Townsville, QLD 4811, Australia
[i] Geology of Mineral Resources Unit, Georesources Division, BRGM – Geological Survey of France, Orléans, France
[j] Mineral Resources Expert Group, EuroGeoSurveys, Brussels, Belgium
[k] ISTO UMR7327 – Institute of Earth Sciences of Orléans, University of Orléans, Orléans, France
[l] CSIRO Mineral Resources, Kensington, WA 6151, Australia
[m] ARC Centre for Data Analytics for Resources and Environments (DARE), Perth and Sydney, Australia

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ABSTRACT

Broad consensus exists amongst mineral explorers that most outcropping mineral deposits have been found. The next generation of discoveries will rely on our ability to recognize the subtle or cryptic signals of deep-seated deposits. Exploration targeting under such conditions requires greater knowledge of the processes that formed the targeted mineral deposit types and new or improved exploration methods designed to effectively test for buried mineralization. Survival bias is a form of selection bias that is defined as the logical error resulting from neglecting data or information because of their "lack of visibility". In this study, "lack of visibility" refers to situations where (i) mineral explorers ignore or overlook particular terrain because it lacks or contains only weak signals of a mineralizing system, and (ii) such areas are excluded from further exploration as the existing data or information neither confirm nor support the targeting model. Therefore, it is critical to more comprehensively analyze a search space to more confidentially determine whether a terrain without the desired targeting signals satisfies the criteria of a null or negative test. The idea for this study is based on the notion that if a buried mineral deposit was present in an overlooked terrain it would nevertheless comprise distinctive geological features and targeting signals to guide the explorer, although, more likely than not, these signals would be very weak. Here we used a porphyry copper (Cu) district in Iran to explain and illustrate the adaptation of the survival bias concept. More specifically, in this study we tested the usefulness of a recently proposed targeting criterion, namely sites of potential focused fluid flux, as an input to mineral prospectivity analysis and exploration targeting. The findings of our study have implications for the future development of regional- to global-scale exploration information systems (EIS), designed to improve the performance of mineral exploration targeting.

1. Introduction

Data analysis methods for exploration targeting of mineral deposits have been progressively developed mainly by the analysis of geospatial data (e.g., Carranza, 2008, 2017; Carranza and Sadeghi, 2010; McCuaig and Hronsky, 2000, 2014; Yousefi et al., 2021; Yousefi et al., 2024).

* Corresponding author.
E-mail address: m.yousefi.eng@gmail.com (M. Yousefi).

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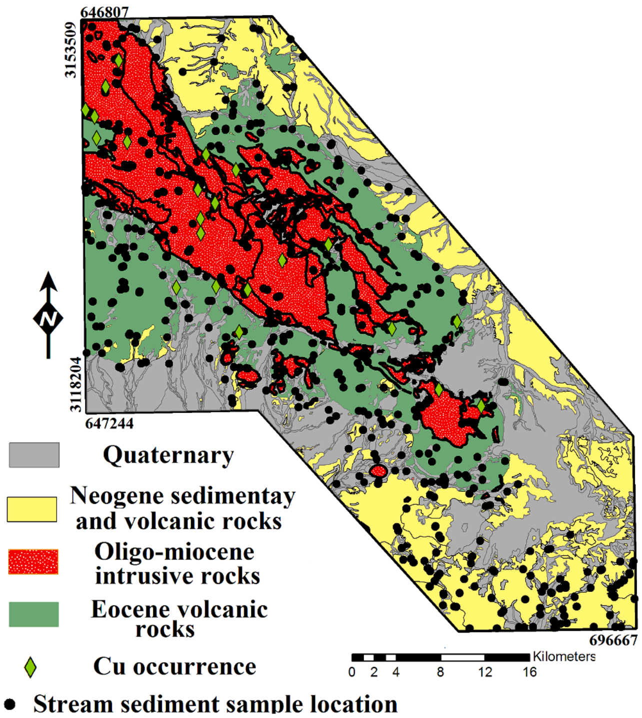

Fig. 1. Simplified geological map of the study.

Exploration geologists have attempted to introduce more robust data analysis methods to identify mineralization signals and to expand more-efficient weighting and integration approaches for prospectivity analysis of mineral deposits (e.g., Goodchild, 2009; Ford and McCuaig, 2010; Porwal et al., 2010, 2015; Hagemann et al., 2016; Zhang et al., 2016; Yousefi et al., 2019, 2021; Zuo et al., 2021). The foremost attention has been inclined toward working on the well-known geological features (e.g., fault, dyke, host lithology, alteration, etc.) and spatial proxies (e.g., geochemical and geophysical signals). However, given that exploration for mineral deposits is beginning to move from surface (or near surface) to greater depths, understanding the complicated geological processes and tracing the hints relevant to the processes become more difficult. Recent discoveries tend to be from deeper sources and thus require more capital to develop into a mine than the shallower mineral discoveries of the past (Wood, 2018). With respect to higher exploration and mining costs for deeper deposits, they need to be of high concentrations or volumes – compared to shallow deposits – to be economically viable.

The next generation of mineral deposits mainly occur at greater depths and may be different from the surface expression of known deposits (Wood, 2018; Yousefi, 2022; Yousefi and Kreuzer, 2024). There are situations where although mineralization occurs at- or close to- the surface, less exhumation processes makes the deposits hard-to-discover. The next generation of mineral deposits may comprise undefined types (Davies et al., 2021) as well. Accordingly, future mineral deposits, due to their lack of visibility, may display poorer mineralization signals at the earth's surface. Exploring for new mineral deposits is faced with challenges and problems including a lack of exploration data, unknown or incompletely-known complex ore forming processes, and lack of visible features at the surface (Yousefi, 2022). Thus, exploration geologists attempt to develop methods and tools, for instance exploration information system (EIS), to improve the performance of mineral exploration targeting approaches (Yousefi et al., 2019, 2021), and it is a progressive field in outlook in terms of searching for new deposits (Yousefi and Hronsky, 2023). Such a lack of visibility at the surface and the characteristics above define the next generation of mineral deposits as blurred, which hereafter denoted as buried mineral deposits. Therefore, the regions, which have undiscovered buried mineral deposits, may be excluded from exploration programs. These regions may also suffer from lack of sufficient data that has been affected by survival bias concept. That is because, with the present state of geological knowledge, there is a lack of- well-known geological features and vectors to mineralization to highlight the buried deposits at the surface. Therefore, specific evolutions of exploration programs and technologies are needed to target such type of mineral deposits of the future. Consequently, analysis of the exploration search spaces in terms of Null (i.e., the available data cannot exclude the presence of mineralization at depth) or Negative (i.e., there is enough information indicating with confidence that a mineralized system is absent, even at depth) tests is a supportive practice.

Typically, prospectivity analysis for mineral exploration targeting has been conducted on regional to district scales (Partington, 2010; Partington and Sale, 2004; Nykänen, 2008; Nykänen et al., 2008; Nykänen and Salmirinne, 2007; Lisitsin et al., 2013; Harris and Grunsky, 2015; Harris et al., 2015; Joly et al., 2015; Yousefi and Carranza, 2015a; Yousefi et al., 2024) rather than on target scales (e.g., Abedi et al., 2017) and this is due to the general availability of only regional scale data which makes it a challenge to predict buried deposits. The modern data gathering and storage technologies have seen a huge increase in data volumes allowing mineral prospectivity modelling to be conducted successfully at various stages of exploration (Niiranen et al., 2019). Manipulating the data into geologically meaningful information about ore-forming processes is a challenge especially when applied to target buried mineralization. As pointed out by Yousefi et al., (2019, 2021) advanced technologies are required to address the issue of targeting buried mineralization. This problem raises the questions of 1) how can we improve regional to district scale exploration targeting in terms of identifying buried mineralization? and 2) is there any geological/geochemical signal that can be ascertained from buried deposits?

This paper aims to use exploration data for determining whether any signal or new geological feature representing undiscovered and buried mineral deposits could be identified. To face this challenge, we employed an adapted "survival bias" concept, a type of sampling error that results in neglecting possible events because of their "lack of visibility" or being less obvious. In the context of mineral exploration, especially in the field of prospectivity analysis as applied to exploration targeting, a "lack of visibility" may refer to situations where a target area lacks mappable spatial proxies or "mineralization signals". Thus, we have adapted the survival bias concept for mineral exploration, and demonstrate its relevance to porphyry Cu deposits in the Urumieh-Dokhtar Volcanic Belt in Iran.

2. Study area and datasets

The study area (Fig. 1) covers a small part of the southern Urumieh–Dokhtar Volcanic Belt, Iran, and is the same studied by Yousefi et al. (2024). The belt was formed as a result of the subduction of the Arabian Plate beneath central Iran during the Alpine orogeny (Berberian and King, 1981; Hezarkhani, 2006a). Exploration practices over the belt demonstrate its great potential for hosting porphyry-Cu deposits (e.g., Hezarkhani, 2006a, 2006b; Ranjbar et al., 2004). In the study area (Fig. 1), Oligo-Miocene intrusive rocks and their surrounding volcanic rocks are genetically and spatially associated with porphyry Cu deposits. Geological details of the Urumieh–Dokhtar Volcanic Belt, the characteristics of the study area and the applied datasets are found, respectively, in Berberian et al. (1982) and Yousefi et al. (2024). Following Yousefi et al. (2024), we used 22 known porphyry Cu deposits as a set of test sites to evaluate the performance of the models generated. In addition, we used the same geochemical data of porphyry Cu deposits (collected and analyzed by Geological Survey of Iran) that were utilized by Yousefi et al. (2024).

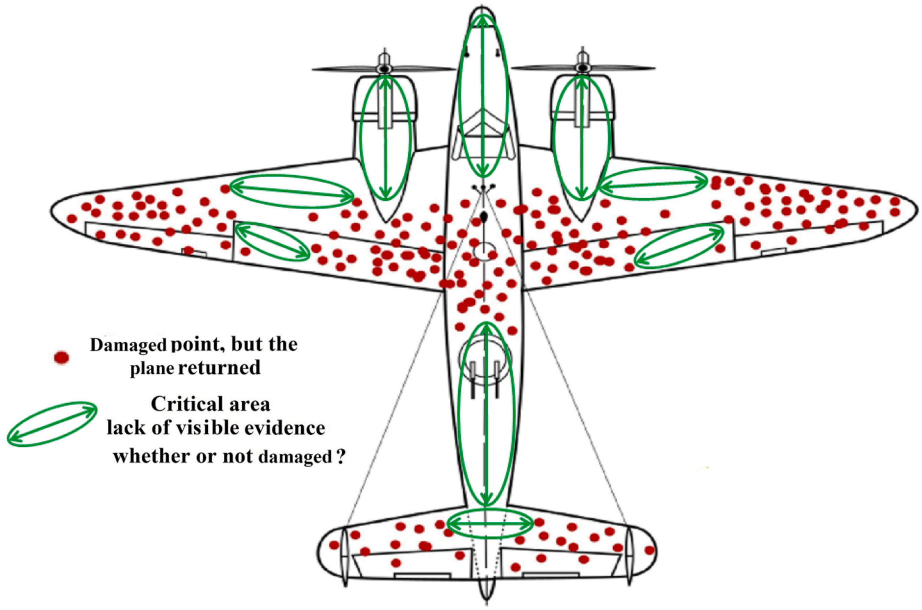

Fig. 2. Hypothetical data illustrating the survival bias concept taken from World War II combat aircraft and lack of visible evidence (modified after Wikipedia, 2021).

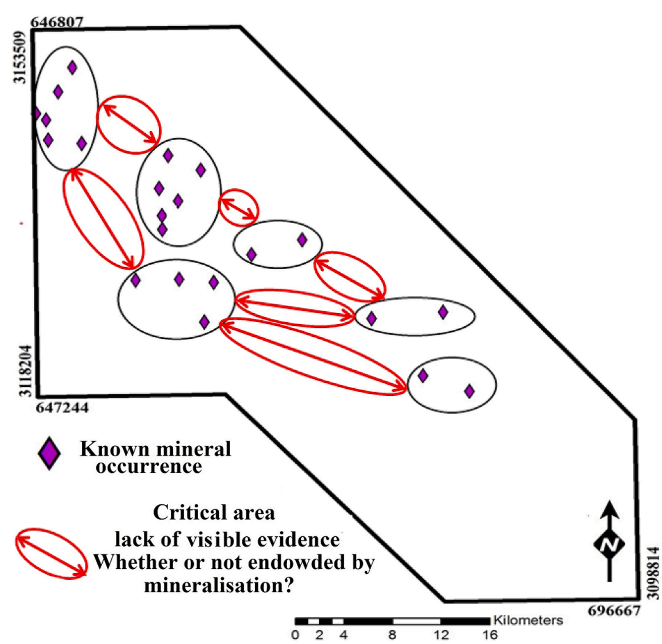

Fig. 3. Known mineral deposit locations/clusters and critical areas based on the survival bias concept. The arrow symbol represents the mineralization within critical areas that may show special patterns or trends.

3. Method and results

3.1. Survival bias concept

Survival bias is defined as the logical error that results in neglecting people or things, typically because of their lack of visibility (e.g., Wald, 1943). It is a form of selection bias that can lead to overly optimistic beliefs because failures are ignored. For instance, failed companies that no longer exist are excluded from analyses of financial performance. It can also lead to the false belief that the successes in a group have some special property, rather than just coincidence (correlation "proves" causality). For example, if three of the five students with the best college grades went to the same high school, that can lead one to believe that the high school must offer an excellent education when, in fact, it may be just a much larger school. This can be better understood by looking at the grades of all the other students from that high school, not just the ones who made the top-five selection process. Another example of a distinct mode of survivorship bias would be thinking that an incident was not as dangerous as it was because everyone communicated with afterwards survived. Even if one knew that some people are dead, they would not have their voice to add to the conversation, leading to bias in the conversation.

A better example of survival bias that can be adapted for mineral exploration is the way damaged points on the aircrafts in World War II were analyzed (Wald, 1943; Januszczak, 2021). The returning planes, even though they were partially damaged, were still able to return home. However, only the aircrafts that had survived their missions were available for investigation and all planes that had been lost were unavailable for assessment. This means the recorded damaged points of returning aircrafts were not critical. Conversely, other parts of the planes, between the recorded damaged points (e.g., engines, oil tank, nose, etc) should have been presumed as (if not more) significant and critical parts of the planes (Fig. 2).

3.2. From survival bias concept to undiscovered mineral deposit sites

Areas where there is a lack of or less mineralization evidence are commonly ignored and excluded from exploration. According to the survival bias concept, we believe such areas may show special patterns or trends and could be further investigated for finding possible mineralization (or exploration features representing the mineralization). This helps us to define a strategy of how to minimize ignorance of ore forming events in exploration programs. Similar to the Fig. 2, we prepared Fig. 3 to illustrate and adapt the survival bias concepts to exploration for the next generation of mineral deposits that lack visible evidence at the earth's surface and may be ignored during exploration. In Fig. 3, clusters of known mineral deposit locations and the areas between them correspond to the damaged points and the critical portions, respectively, in Fig. 2.

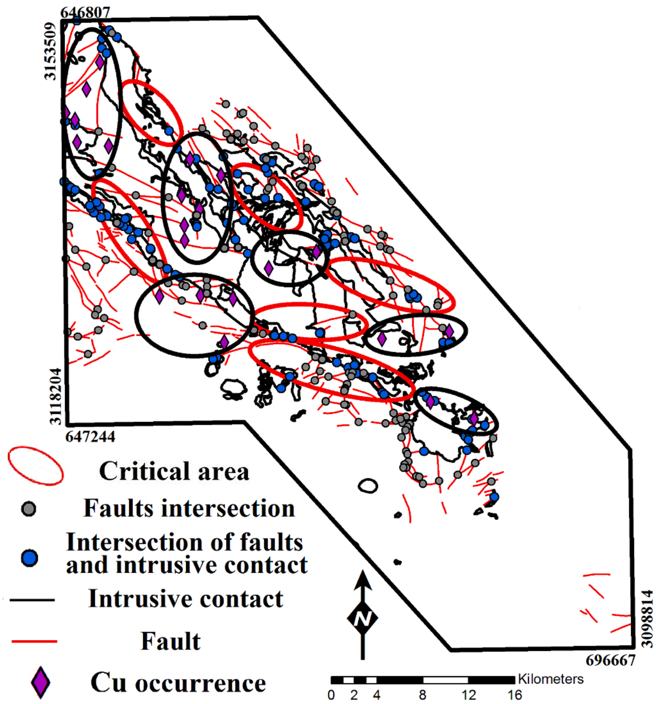

Fig. 4. Exploration features in the study area.

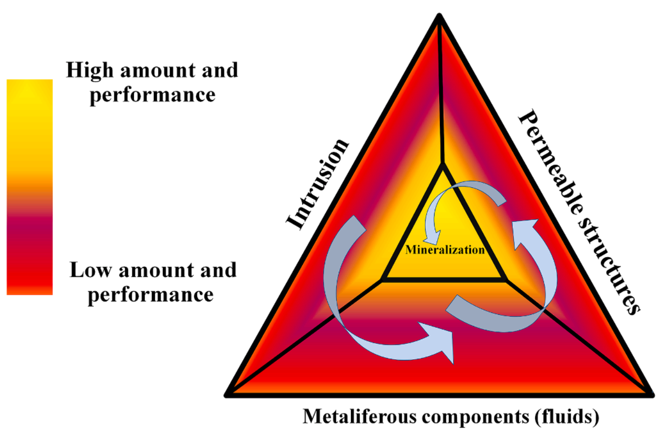

Fig. 5. A possible P-T window comprising three subsystems crucial to the ore-forming processes in hydrothermal mineral systems. Centre of the triangle can represent the areas around faults intersection with intrusions.

3.3. *Critical areas defined according to the survival bias concept*

Adaptation of the survival bias for mineral exploration focuses on the critical areas in Fig. 3. These areas can be investigated for evidence of mineralization, through weak signals from buried ore bodies. This could be called "negative control" meaning cross-examination of the areas that have been excluded from the search spaces. Subsequently, for this study we focused on the critical areas indicated in Fig. 3, and inspected them to determine whether geologic features of interest exist for exploration purposes (Fig. 4). According to the concept of survival bias, certain critical areas may not be recognized as prospective in a prospectivity analysis due to their lack of mineralization signals, especially areas that show lack of simultaneous presence of exploration features. Thus, whilst certain critical areas may have subtle expressions in various exploration datasets they may be excluded in prospectivity analyses.

Inspection of the features in Fig. 4 illustrates that there are faults, intrusive contacts, and fault intersections which exist in the study area.

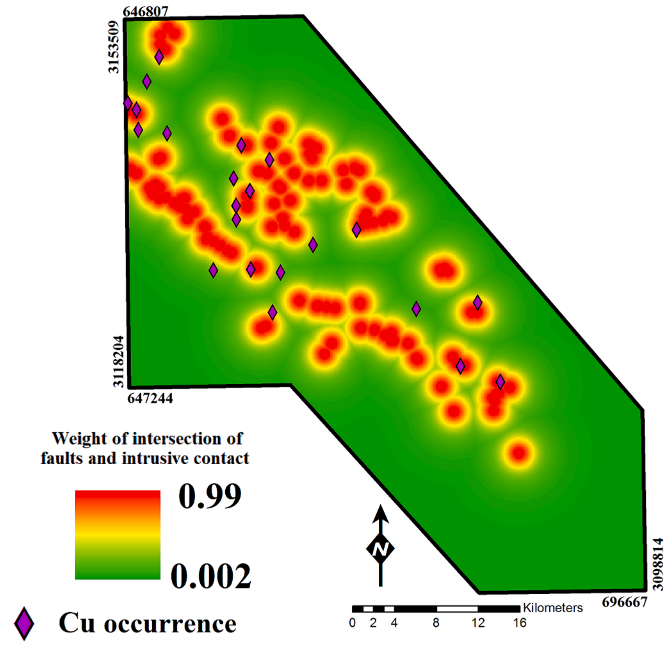

Fig. 6. Weighted map of intersection of faults and intrusive, the point feature explored in this study.

All these features are well-known and widely-used in prospectivity analysis for mineral exploration. These features can be seen in the critical areas that exist between the known deposits. There are many examples of exploration activities in which faults, intrusive contacts, and fault intersections have been used as predictors of mineralization and to delimit areas into smaller regions for further exploration (e.g., Austin and Blenkinsop, 2009; Micklethwaite et al., 2010; MamiKhalifani et al., 2019; Ghasemzadeh et al., 2022). We have noticed the same point feature, derived from the intersection of faults and intrusive contacts that has been recently reported by Yousefi and Hronsky, (2023) and represents a critical mineral system parameter. Thus, we further investigate how important this newly-explored point feature is with respect to mineral system concepts in ore-forming processes. Furthermore, according to the survival bias concept we determine if there is a link between the point and other mineralization evidence.

3.4. *Intersection of faults and intrusive contacts*

The zones around the intersection of faults and intrusions within the critical areas in Fig. 4, would provide the proper conditions for the simultaneous existence and operation of spaces and metalliferous fluids flux, providing a suitable environment for ore formation (Yousefi and Hronsky, 2023). Hydrothermal mineral systems involve the mobilisation of metals from a source by fluids and concentration of these metalliferous fluids in suitable geological trap sites. Therefore, if the fluids contain metal ions, the areas around the point feature are endowed with three physico-chemical subsystems crucial to the ore formation process including a) function of intrusions, b) spaces provided by faults and fractures, and c) chemical scrubbers (Yousefi and Hronsky, 2023). Such areas can be a favourable pressure–temperature (P-T) window for ore deposition. Fig. 5 illustrates a possible P-T window providing conditions suitable for ore formation around the intersection between faults and intrusions explored in the critical areas identified in this study, according to the adaptation of survival bias concept.

Fluid flux requires an effective thermal engine and permeable structures for circulation (e.g., Sillitoe, 2000, 2010; Loucks, 2022). For our case study, porphyry Cu ore bodies are developed in the endo- and *exo*-contacts of the ore bearing intrusions and are controlled by fractures, constituting mineralization. Thus, there are clear close spatial and

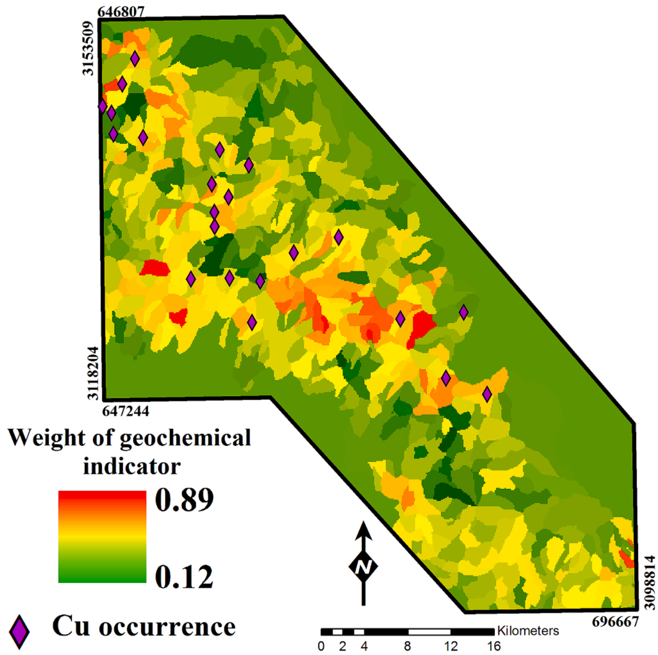

Fig. 7. Geochemical evidence layer, weighted Cu contents.

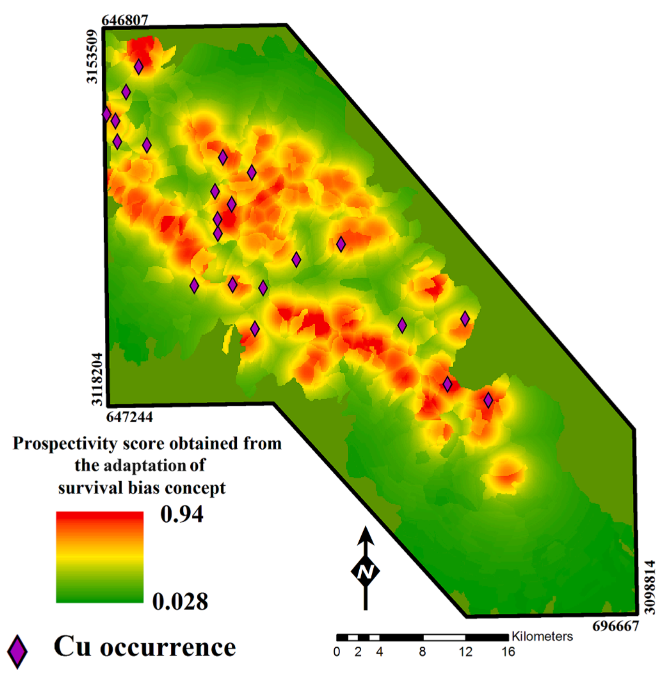

Fig. 8. Exploration targeting model generated through adaptation of survival bias concept and including the intersection of faults with intrusions.

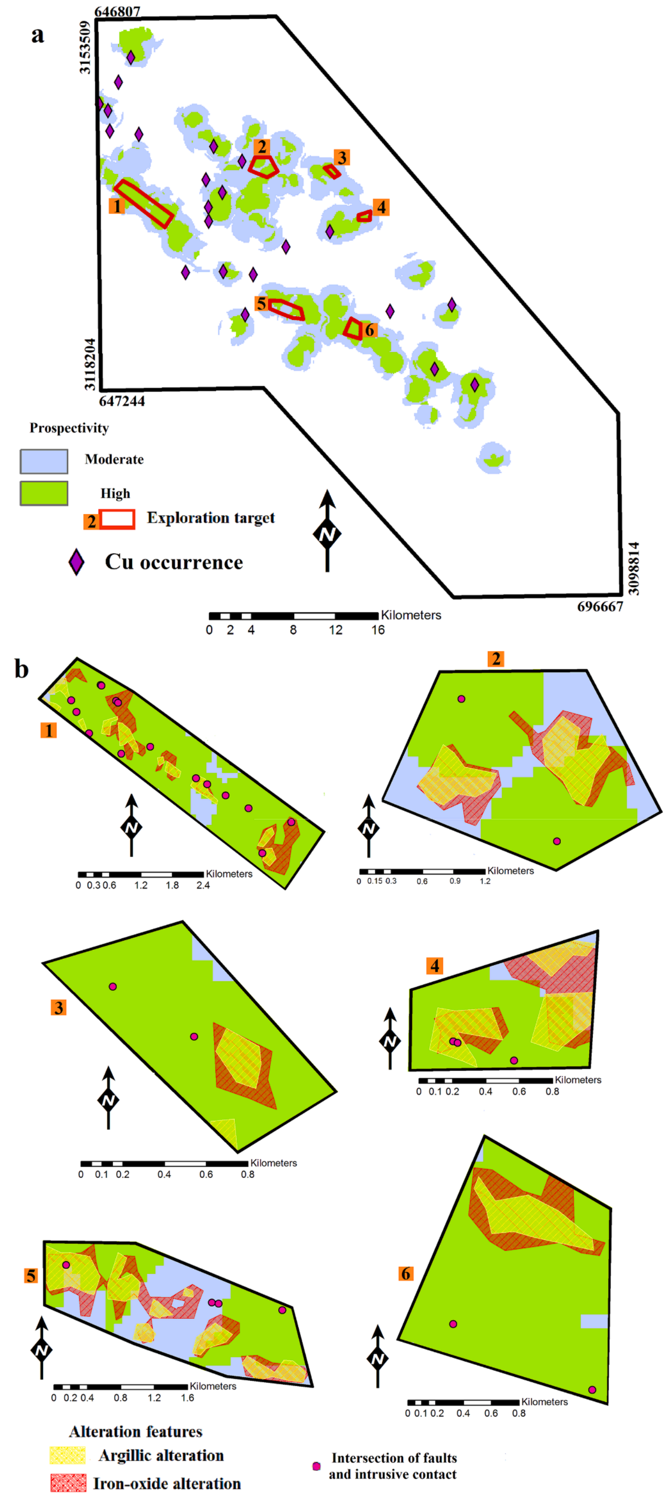

Fig. 9. Map of high and moderate prospectivity values (a) and inspection of the exploration targets therein (b).

temporal relations between intrusions and hydrothermal mineralization, here porphyry Cu deposits. Metal anomalies in different media are geological expressions for the result of geochemical dispersion (e.g., Ghasemzadeh et al., 2019; Grunsky and de Caritat, 2020), indicating the presence of metalliferous components and operation of a chemical scrubber as a subsystem of ore-forming critical processes. Therefore, many deposit types are associated with geochemical anomalies. Consequently, the higher the amount and performance of the three crucial subsystems are, the more the suitable conditions of ore formation would be (Fig. 5), and that the areas around the intersection of faults with intrusions would provide a possible ore deposition zone.

3.5. *Implementation of the adapted survival bias concept for target generation*

To examine and evaluate the performance of fault intersections with intrusions, we first created an intersection proximity map and transformed the map values into [0–1] range using a fuzzy membership function (e.g., Almasi et al., 2017) (Fig. 6). Accordingly, the areas close to the point were assigned a larger membership value compared to the

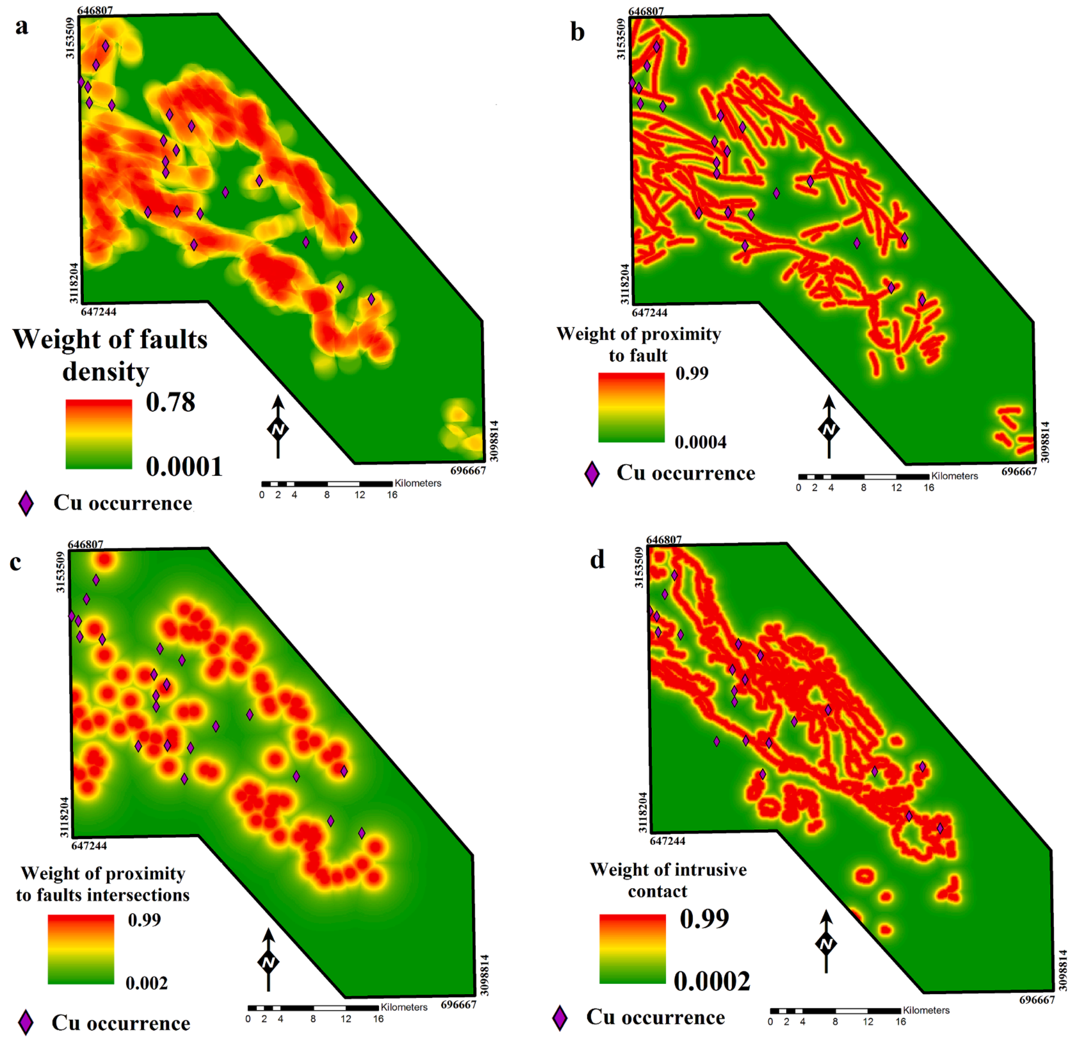

Fig. 10. Fuzzified evidence layer of a) fault density, b) proximity to faults, c) fault intersections, and d) intrusive contacts.

distal areas.

The exploration evidence layer in Fig. 6 represents two of three of the conceptual subsystems (intrusion and permeable structures shown in Fig. 5). As illustrated in Fig. 5, presence of metal ions and metalliferous fluids are a cornerstone of the model representing the fertility of the intrusion and fluids. Models of geochemical anomalies act as chemical scrubbers depositing metals in trap sites. To incorporate this significant subsystem into the prospectivity modeling procedure, we used Cu content in stream sediments and transformed the concentrations into [0–1] range using a fuzzy membership function (e.g., Almasi et al., 2017), Through this we created a Cu evidence map (Fig. 7) whereby high and low values of element contents assigned by large and small fuzzy memberships close to 1 and 0, respectively. In this model, we have used catchment basins to display Cu concentrations (e.g., Bonham-Carter and Goodfellow, 1986).

After generation of the two fuzzified evidence layers, corresponding to the three subsystems of ore forming processes in Fig. 5, they were integrated using a geometric average function (Yousefi and Carranza, 2015a) as a multi-criteria decision-making approach to produce an exploration targeting model shown in Fig. 8. This function has the ability of combining fuzzified evidence layers and returns the n^{th} root of the product of n variables (here n fuzzy memberships) as their geometric average for multi-criteria decision making problems, e.g., prospectivity analysis for mineral exploration targeting (Yousefi and Carranza, 2015a, b).

The values in the exploration targeting model in Fig. 8 were then classified into three categories representing high, moderate, and low prospectivity (Fig. 9a) using a natural break classification method (Jenks, 1967). On the classified map, six prospective zones (marked as 1–6) were selected for further inspection (Fig. 9b). Given that the exploration targeting model in Fig. 8 was generated using the fault-intrusion intersections and Cu anomalies for further assessments of the prospective zones, we have evaluated the presence or absence of argillic and iron-oxide alteration as other evidence of mineralization. Interaction of metalliferous fluids in an intrusive contact zone and surrounding host rocks results in wall rock alteration and ore deposition. Therefore, syn- and post-mineralization alteration are evidence of prospective zones and are worthy of exploration follow-up.

3.6. Comparison of the proposed modeling approach and the existing prospectivity analysis methods

In mineral exploration targeting, it is common practice to apply fault density, proximity to faults, and fault intersections to model structural features as zones of fluid circulation and deposition. Similarly, proximity to intrusive contacts has been widely used as evidence layers in mineral prospectivty modeling (MPM) (e.g., Austin and Blenkinsop, 2009; Micklethwaite et al., 2010; Yousefi and Nykänen, 2016). In contrast, the new point feature explored in this research, simultaneously models the function of both structure and intrusion in the process of ore formation. Thus, if an evidence layer of intersections between faults and intrusions is integrated with a model of geochemical anomalies, an

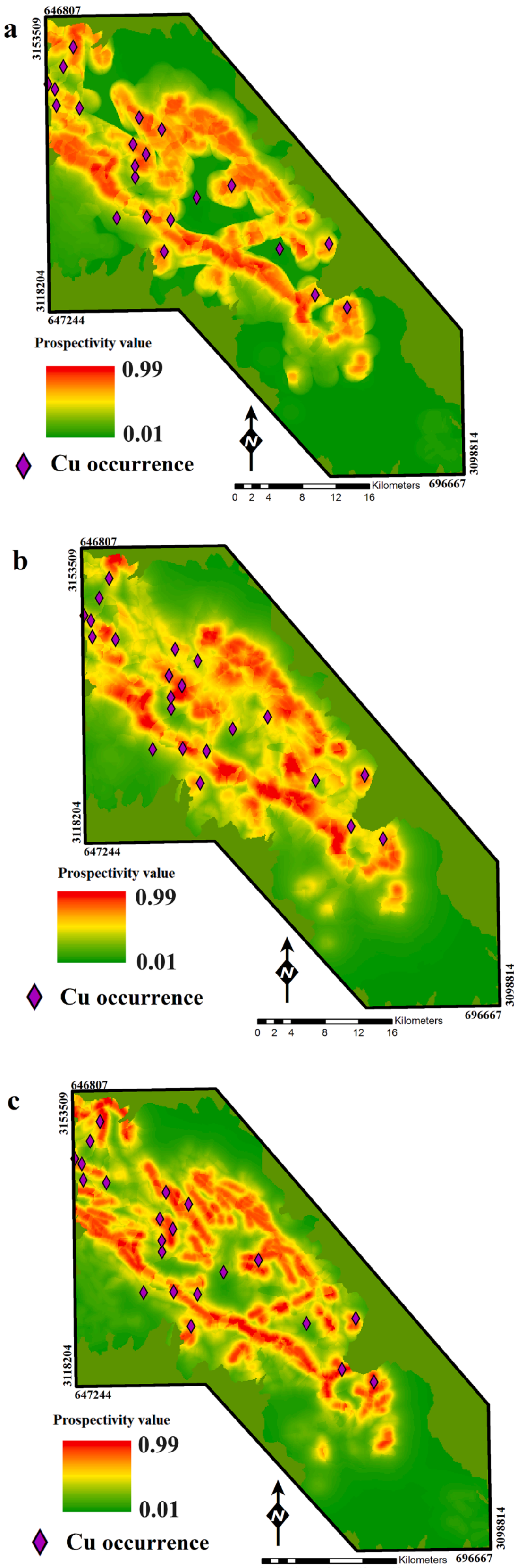

Fig. 11. Prospectivity model generated using well-known structural features of (a) faults density, (b) proximity to faults intersection, and (c) proximity to faults.

exploration targeting model is generated. Therefore, for making a comparison between our proposed approach in this study and existing MPM practices, we have generated three additional prospectivity models using three sorts of evidence maps comprising fuzzified layers of a) fault intersections, intrusive contacts, and geochemical anomalies, b) proximity to faults, intrusive contacts, and geochemical anomalies, and c) fault density, intrusive contacts, and geochemical anomalies using the same integration function (i.e., geometric average approach described above). The fuzzified evidence layers and the corresponding exploration targeting models are shown in Fig. 10 and Fig. 11.

3.7. Model effectiveness

The four exploration targeting models generated using the intersection of faults with intrusive contacts proposed in this study (Fig. 8) and using existing modeling methods for the integration of faults and intrusions (Fig. 11a-c), were compared. We applied prediction-area plot (Yousefi and Carranza 2015b) of the models to calculate normalized density (Mihalasky and Bonham-Carter, 2001), through which, the ability of the models in terms of predicting mineral deposit locations is evaluated while occupied areas of the exploration targets contribute in the evaluation procedure. Normalized density for a certain prospectivity class or an exploration targeting model is the ratio of rate of mineral deposits predicted by the prospectivity class or by exploration targeting model to occupied area of the class or targets (Mihalasky and Bonham-Carter, 2001; Yousefi and Carranza 2015b). Higher normalized density indicates a smaller area containing large a number of mineral deposits, so the prospectivity class or exploration model is more relevant for searching for undiscovered mineral deposits (Yousefi and Carranza 2015b). Normalized density of the exploration targeting models have been given in Fig. 12 indicating that the exploration targeting model, generated using intersection of faults and intrusives, is stronger than other models.

Given that the prospectivity values in the exploration targeting models in Fig. 8 and Fig. 11 are continuous, to make the models usable in real-world exploration, the potential areas having high prospectivity values, should be highlighted for possible exploration follow-up. For this, all of the models were classified using the same geometrical interval method, and then, the highest prospectivity class for each of the four exploration targeting models were highlighted (Fig. 13). However, many classification methods can be used for categorization of prospectivity values, we applied the geometrical interval method (Frye, 2007) because it provides an alternative to the equal interval, natural breaks and quantiles, and really any variance minimized classification method. It is a classification scheme for categorizing a range of values based on a geometric progression. This method is suitable to visualize continuous data that is not normally distributed, e.g., here nonlinear exploration geological data. An important issue is that all of the models should be classified by the same method, for comparison purposes. The normalized density was then calculated for every single model (Fig. 14). The exploration targeting model generated using the intersection of faults and intrusive is superior to the others. The new targets in Fig. 13a are those that have been recognized based on the adaptation of survival bias concept.

4. Discussion

Typically, regional scale data are available in 2D making it challenging to predict those buried deposits that show less or a lack of mineralization signals at the surface. This is likely the reason that researchers have pointed out that there is a decline in mineral exploration success (Davies et al., 2021), especially when search spaces for finding mineralization are moving from the near-surface environments to greater depth. These issues flag the need of mineral exploration industries for novel exploration strategies (e.g., Knox-Robinson and Wyborn, 1997; Lindsay et al., 2020, 2022; Yousefi, 2022; Yousefi and

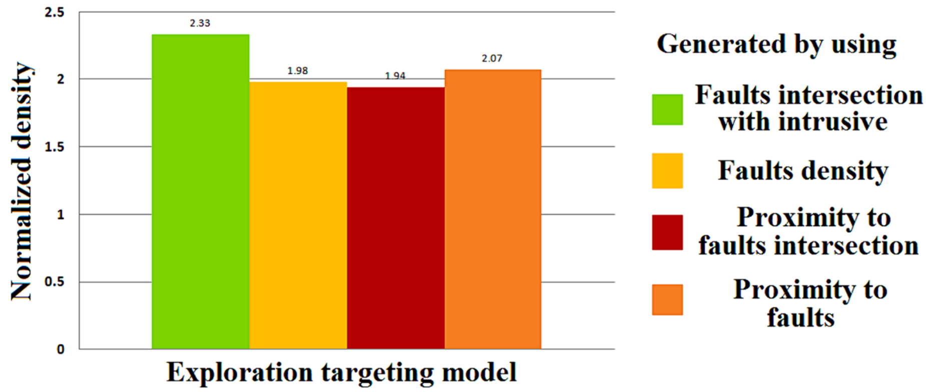

Fig. 12. Normalized density for exploration targeting models, which have been generated using four types of fuzzified exploration evidence layers.

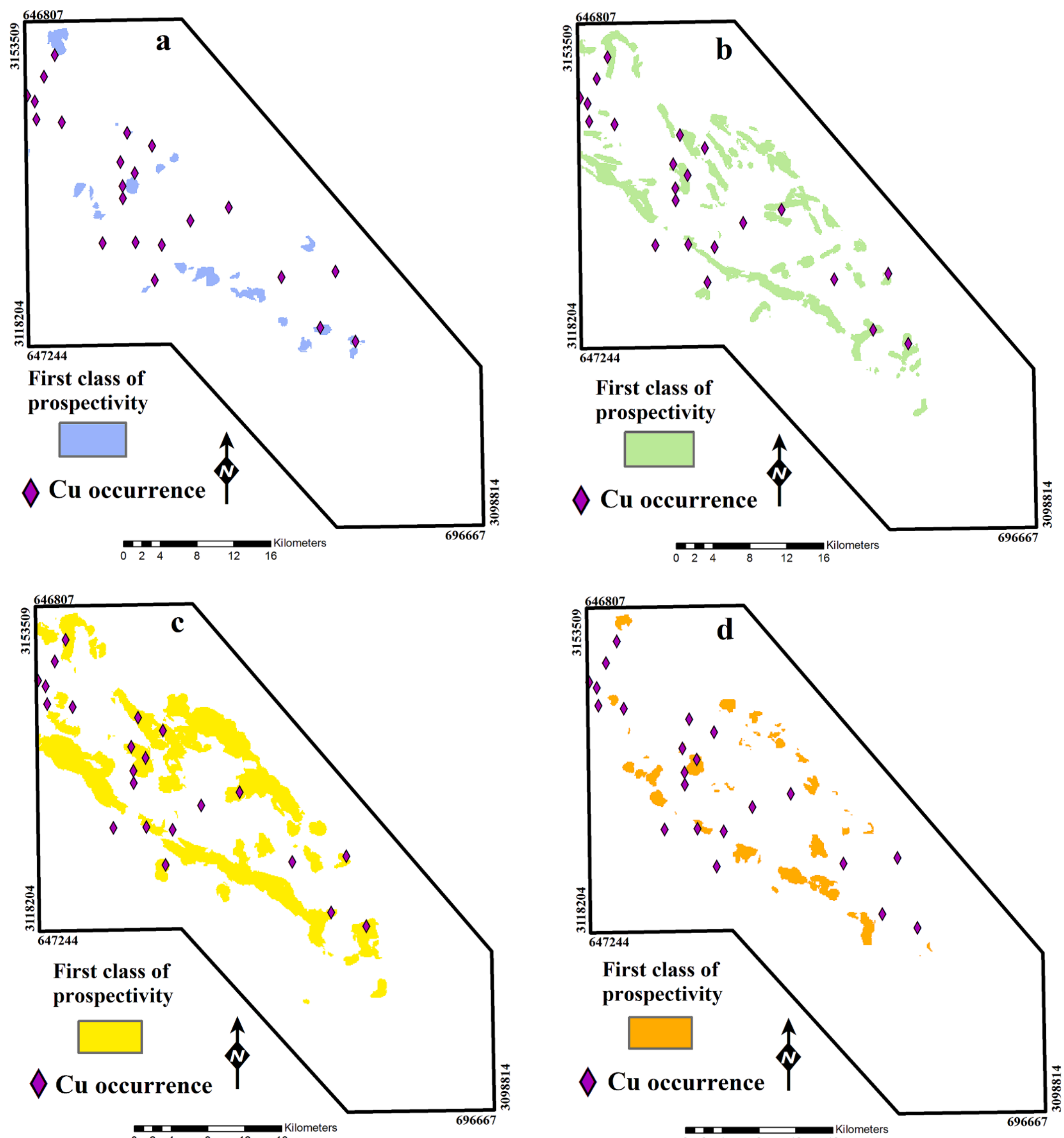

Fig. 13. First class of prospectivity for exploration targeting model generated using intersection of faults with intrusive contacts (a), proximity to faults intersections (b), proximity to faults (c), and fault density (d).

Hronsky, 2023; Yousefi et al., 2024).

Prediction of undiscovered mineral deposit locations depends on data resolution, quality, and quantity. In this paper, we have explored the existence of an exploration point feature, i.e., intersection of faults and intrusions (Yousefi and Hronsky, 2023) in the critical areas recognized by the adaptation of survival bias concept. The point is applied as a

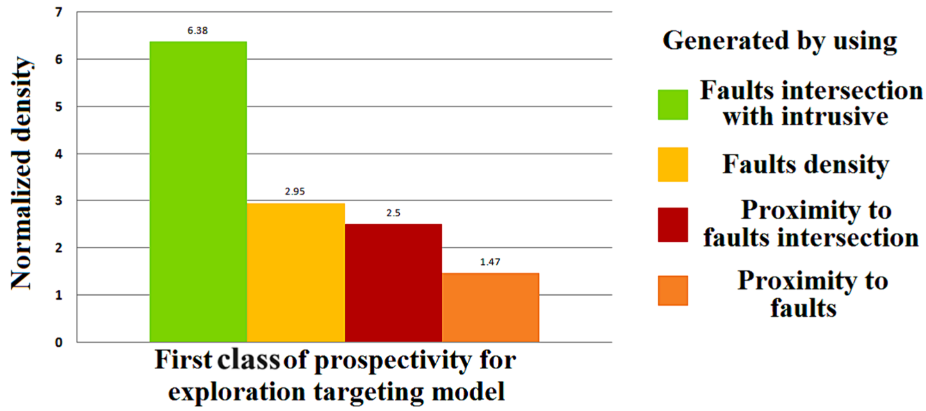

Fig. 14. Normalized density for the first class of prospectivity in the four exploration targeting models generated in Fig. 13.

criterion, exploration data, in prospectivity analysis for mineral exploration targeting. We have given an example how the point feature derived from the intersection of the faults and intrusive contacts works as a part of critical mineral systems and enhances delineation of new potential areas.

We should focus on new search spaces located away from the known deposit locations to discover deeper mineral deposits. MPM in new search spaces takes greater uncertainty, and in contrast, has greater opportunity to find new mineralization (Davies et al., 2021; Yousefi, 2022). The discussions provided in this study dealing with survival bias have highlighted that excluding critical areas from the exploration priorities should be done with caution. According to the adaptation of the survival bias concept, a negative control, i.e., controlling the areas that due to less or lack of mineralization evidence have been excluded from the exploration programs, should be conducted to verify the presence or absence of mineralization features. A way to control the negative areas is to apply the same procedure proposed in this study and that was presented by Yousefi and Hronsky (2023) dealing with the application of intersection of faults and intrusive in the prospectivity analysis.

Mineral exploration industry is now very much focusing on areas where there is no obvious near-surface evidence of the presence of mineralization. In terms of practical mineral exploration, there is a need for discussion on how to best deal with this problem. A good MPM will predict areas where known mineral deposits occur but also highlight prospective areas where no deposits are known to occur. In this paper, the exploration targeting model predicts known mineral deposits better than existing approaches, while it introduces new exploration targets, which is the focus of this paper. Given that in the new exploration targets recognized in this study, there are low and poor mineralization features, according to survival bias concept and its adaptation there may be mineral deposits at depth. Thus, further exploration programs (e.g., geophysical data acquisition) are recommended over the targets obtained.

According to the concept of exploration search space and following what have been discussed in this paper, it is necessary to do an analysis of the search space in order to determine if areas without significant mineralization represent Null or Negative tests. If they are Null tests – i.e., the available data cannot exclude the presence of mineralization at depth – then the concepts described in this paper can apply, for instance we look for evidence of a fluid upflow system (Yousefi and Hronsky, 2023) that hosts a blind deposit. This typically occurs in areas concealed by post-mineral cover. However, in many cases, areas without significant mineralization actually represent Negative tests. This means we have enough information to say with confidence that it is unlikely that a mineralized system is present, even at depth. This occurs when either the prospective geological units are not present (perhaps they have been eroded away) or they are present without any evidence of related exploration features (e.g., hydrothermal alteration, geochemical anomalies, etc). Therefore, we should exclude such areas from the application of prospectivity analysis at the target scale. We generally tend to assume that non-favorable pixels are Negative, but it would be a great progress to identify those that could be Null. Consequently, including the ability of Null and Negative tests in EIS could improve the system's ability in terms of targeting the next generation of mineral deposits, and help to more confidently discard any areas deemed non-prospective, which would be a very valuable information for exploration companies.

5. Concluding remarks

- The geological point feature, intersection of faults and intrusive bodies, was proposed as an ore-forming subsystem relating to the porphyry environment, which improves strategies in the search for the next generation of mineral deposits.
- These points are linked to mineralization in terms of spatial and genetic aspects rather than an alternative to the existing structural evidence criteria, i.e., fault density, proximity to faults, and faults intersection.
- Adaptation of survival bias may introduce exploration targets where there are less indicators of mineralization. However, the newly-introduced critical areas and exploration features in this paper lead to delimit search spaces.
- In the future, non-traditional features and proxies, similar to what have been given in this paper, may emerge to find signs of mineralization.
- The discussions given in this paper are seminal in the next-nascent strategies for searching for hard-to-explore mineral deposits those that show less or lack of evidence in the surface.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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