Journal of Geochemical Exploration 236 (2022) 106966

Contents lists available at ScienceDirect

Journal of Geochemical Exploration

journal homepage: www.elsevier.com/locate/gexplo

# Predictive assessment of metallogenic signatures using the DataBase Querying (DBQ) method: A European application

Blandine Gourcerol *, Guillaume Bertrand, Laurent Bailly, Pauline Moreau, Isabelle Duhamel-Achin, Maxime Picault, Philippe Négrel

*BRGM, F-45060 Orléans, France*

ARTICLE INFO

*Keywords:*
Prospectivity mapping
Mineral resources
By-products
Database querying
Europe

ABSTRACT

As part of the European-Peruvian ION4RAW project (Horizon 2020 framework programme of the European Commission), which aims at developing mineral-processing technology to recover selected by-products (e.g., Te, Bi, Co, Re, Mo, Pt, Sb, Ge, Se, In) from primary Cu-Ag-Au deposits, we assessed a geographical inventory of selected elements. However, not all elements of economic interest today have been systematically assayed and/or studied in the past, and the existing European databases commonly are incomplete from a 2022 viewpoint. The DataBase Querying (DBQ) geostatistical mineral prospectivity method helps address this gap between potential mineral occurrences and 'piecemeal' historical inventories. In addition to a 'classical' application of the DBQ method, we developed a new approach. This is based on the assessment of more global predictive metallogenic-signature aspects (e.g., VMS, orogenic, epithermal), by clustering studied elements known to occur in various metallogenic families, using ArcGIS software. Development of this method at a continental scale allowed identifying several areas of great interest in Europe for exploration of the targeted by-products. It also helps in assessing the favourability for the occurrence of commodities that are 'by-products' in their parageneses and that were, until recently, rarely reported in geochemical studies.

## 1. Introduction

In the context of climate change and related international renewable-energy policy, the fast growth of emerging economies and the rapid development of new technologies have caused a drastic increase in the demand for several metals and other elements. A reliable supply of critical raw materials is one of the major challenges now facing Europe (European Commission, 2020). The identification of accessible mineral resources is a critical step in the deployment of low-carbon technologies and securing strategic sectors of European industries. Among recently identified critical raw materials, several elements were, or are, not systematically identified and/or assessed in European databases, as their high economic importance and supply risk have only recently become apparent. Thus, a gap may exist between historical databases and current metal needs.

Geographic Information Systems (GIS) combined with geological and metallogenetic data are key tools for delineating prospective areas of selected metals and deposit types in a given geographical area (e.g., McCuaig and Hronsky, 2014; Carranza and Laborte, 2015; Yousefi and Carranza, 2015; Sadr and Nazeri, 2018; Parsa et al., 2021; Parsa and Maghsoudi, 2021; Parsa and Pour, 2021; Parsa, 2021). They are key inputs in mineral prospectivity mapping (MPM), offering a great opportunity to explore for undiscovered mineral deposits (Bonham-Carter et al., 1989; Carranza et al., 2008a, 2008b; Carranza, 2017). MPM translates field observations of ore-forming processes and significant features of mineral systems into predictive maps. This uses proxies and discrimination criteria derived from geostatistical or machine-learning algorithms in GIS-based models (Sun et al., 2019). Such models are conventionally classified into three categories: 1) Knowledge-driven, where maps and models are based on historical data and expert assessments (e.g., Porwal et al., 2003); 2) Data-driven, where identified mineral deposits drive the predictive modelling (e.g., Carranza, 2004, 2011; Sun et al., 2017); or 3) Hybrid models that combine the aforementioned types.

The DataBase Querying (DBQ) geostatistical method (Billa et al., 2016; Bertrand et al., 2017) is one of these methods, which can identify potential occurrences of elements in new areas. This method was initially developed for assessing the potential occurrence of by-product

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* Corresponding author.
*E-mail address:* b.gourcerol@brgm.fr (B. Gourcerol).

https://doi.org/10.1016/j.gexplo.2022.106966
Received 1 August 2021; Received in revised form 10 February 2022; Accepted 11 February 2022
Available online 16 February 2022
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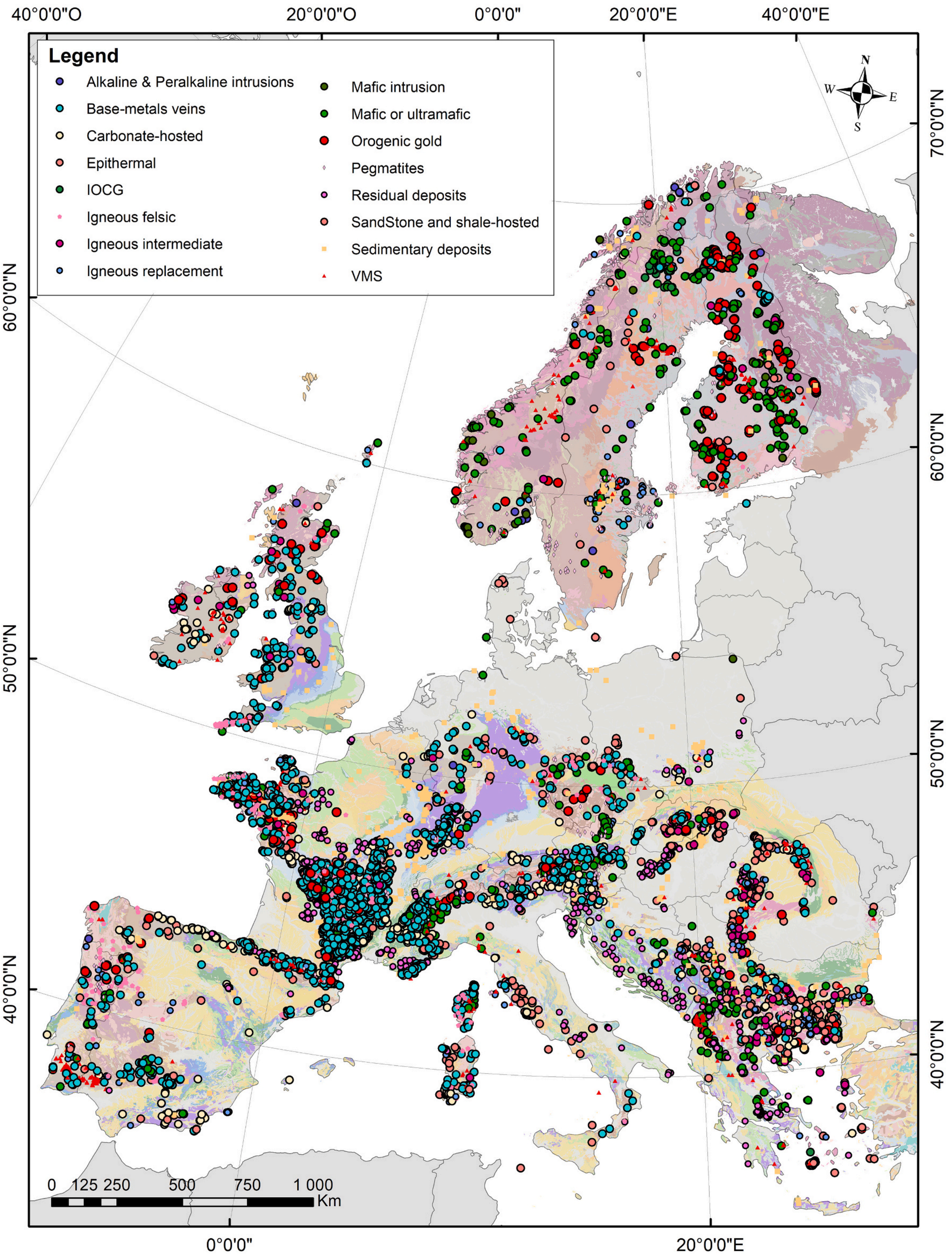

**Fig. 1.** Distribution of all European Union occurrences ($n = 8643$) and deposits classified according to their metallogenic family.

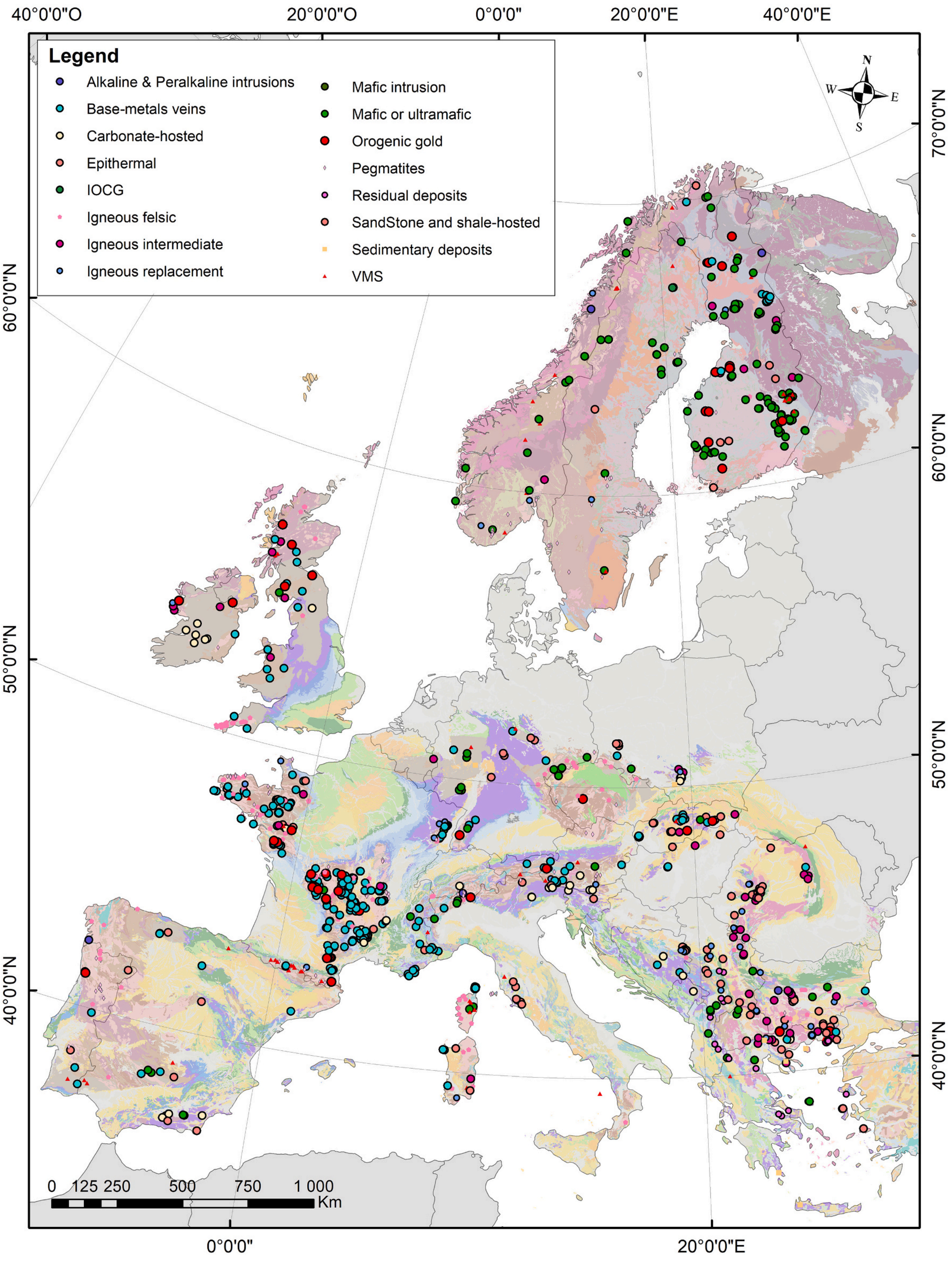

**Fig. 2.** Distribution of identified European Union occurrences ($n$ = 1400) showing identified ION4RAW targeted by-products classified according to their metallogenic family.

**Table 1**
Example of ER calculation of cobalt occurrences based on ProMine data. The bold text highlights the most relevant metallogenic families for Co occurrences.

| Metallogenic family | Total number of occurrences | Number of occurrences containing Co | Enrichment ratio |
|---|---|---|---|
| **Mafic or ultramafic** | **504** | **102** | **8.10** |
| **VMS** | **762** | **36** | **1.89** |
| **Orogenic gold** | **499** | **23** | **1.84** |
| **Residual deposits** | **533** | **16** | **1.20** |
| Sandstone and shale-hosted | 328 | 8 | 0.98 |
| Igneous Intermediate | 132 | 2 | 0.61 |
| Sedimentary deposits | 628 | 5 | 0.32 |
| Base-metals veins | 1902 | 15 | 0.32 |
| Igneous replacement | 359 | 2 | 0.22 |
| Epithermal | 415 | 2 | 0.19 |
| Igneous felsic | 861 | 4 | 0.19 |
| Carbonate-hosted | 588 | 1 | 0.07 |
| Alkaline & Peralkaline intrusions | 38 | 0 | 0.00 |
| IOCG | 68 | 0 | 0.00 |
| Mafic intrusion | 44 | 0 | 0.00 |
| Pegmatites | 703 | 0 | 0.00 |
| Placers | 278 | 0 | 0.00 |
| ***TOTAL*** | ***8642*** | ***216*** | |

elements that were commonly not assayed for in past geochemical exploration surveys, and for which information is often scarce in databases. DBQ identifies a “characteristic multi-element signature” associated with the targeted commodity, based on geochemical association and related deposit-type(s). It then statistically re-applies this signature to the historical deposit database in order to calculate a potential for finding the targeted element in a given occurrence. This is done by comparing the characteristic multi-element signature to the commodity association in a deposit, in order to score their similarity.

A major objective of the innovative European ION4Raw project was the identification of Te, Bi, Co, Re, Mo, Pt, Sb, Ge, Se and In potential in Europe. However, such elements are usually by-products in their parageneses, illustrating the gap described above between their recent criticality and their often-incomplete description in databases. The DBQ method may represent an answer for assessing the occurrence of such elements within the historically incomplete inventories.

We present a prospective assessment for the occurrence of these elements using the DataBase Querying DBQ approach (Billa et al., 2016; Bertrand et al., 2017). Beyond a ‘classical’ application of the DBQ method, we suggest extending its application through a more global predictive metallogenic-signature aspect, such as VMS or orogenic, by clustering selected elements illustrated in specific metallogenic families. This new development of the DBQ method may help better identify potential target areas for mineral exploration.

## 2. The DBQ method

### 2.1. The historical ProMine Mineral Deposit database and its structure

In order to provide a consistent inventory of targeted by-product-element distribution in existing or currently unexploited mineral deposits and occurrences in Europe, the European ProMine Mineral Deposit database (PMD), developed by Cassard et al. (2015), is considered a reliable and exhaustive inventory of mineral resources in Europe (Fig. 1). It was developed by the European co-funded ProMine project (2009–2013) and aimed at providing a homogeneous vocabulary, level of knowledge and representation throughout Europe of primary mineral resources. Its ultimate aim was to focus exploration work and foster the extractive industry, by identifying potential areas of interest in Europe. The DBQ method was developed during the ProMine project to reach this aim, and thus is particularly suited to the PMD database, another reason why we have used this data source. In details, each occurrence or deposit identified in the database is descripted through 40 features such as general information (e.g., location and status), deposit information (e.g., deposit type and morphology), information on mineralogy, host-rock, gangue and lithology, economic information such as exploration and production information per identified commodity etc. For more details, please refer to Cassard et al., 2015.

Most records in the PMD database were classified into 17 main metallogenic families (Bertrand et al., 2017) and described with related

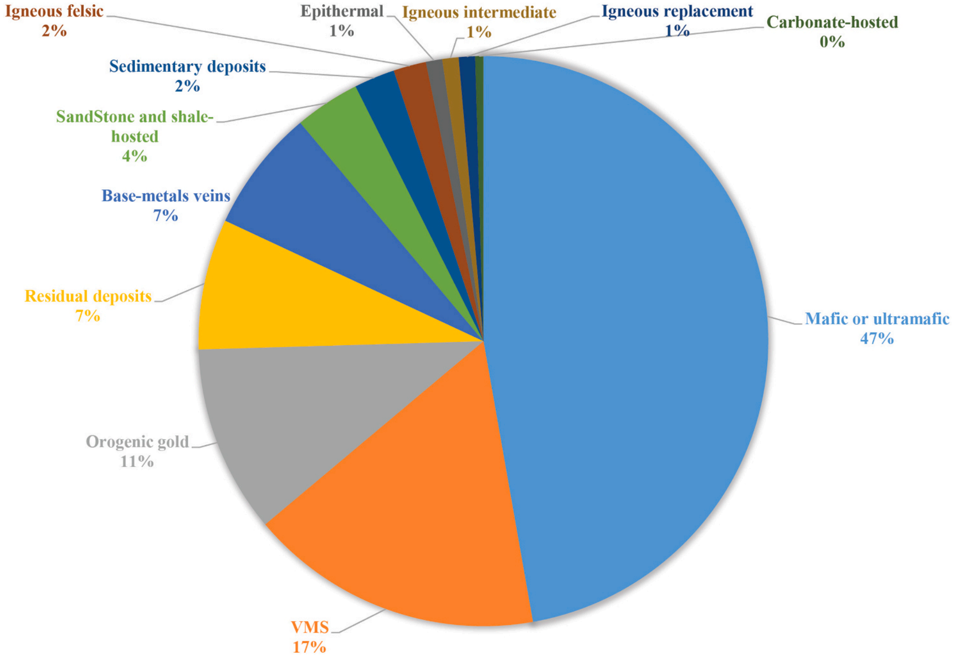

**Fig. 3.** Distribution of Co-bearing deposits classified by metallogenic family.

**Table 2**
Multi-element signatures of the selected cobalt-rich metallogenic families. The bold text highlights the most relevant metal occurrences for the selected metallogenic families.

| | All metallogenic families | Mafic or Ultramafic | Orogenic Gold | VMS | Residual deposits |
|---|---|---|---|---|---|
| **Co** | **100.00** | **100.00** | **100.00** | **100.00** | **100.00** |
| Cu | **80.09** | **88.24** | **100.00** | **86.11** | 6.25 |
| Ni | **73.61** | **96.08** | **21.74** | **50.00** | **100.00** |
| Au | **27.78** | 7.84 | **100.00** | **50.00** | **12.50** |
| Ag | **23.61** | 7.84 | **30.43** | **44.44** | 6.25 |
| Zn | **21.76** | 6.86 | **13.04** | **63.89** | 6.25 |
| Pb | **14.35** | 0.98 | **13.04** | **27.78** | 6.25 |
| Fe | **12.50** | 3.92 | 4.35 | **11.11** | **68.75** |
| Cr | 8.80 | 3.92 | 4.35 | 0.00 | **56.25** |
| Pd | 8.33 | 14.71 | 0.00 | 2.78 | 6.25 |
| Pt | 8.33 | 15.69 | 0.00 | 0.00 | 6.25 |
| As | 7.41 | 2.94 | 0.00 | **11.11** | **31.25** |
| U | 6.48 | 4.90 | **17.39** | 0.00 | 0.00 |
| Mn | 6.02 | 0.00 | 0.00 | 2.78 | **43.75** |
| Mo | 5.09 | 0.00 | **17.39** | 0.00 | 6.25 |
| Bi | 4.17 | 3.92 | 0.00 | 5.56 | 0.00 |
| V | 4.17 | 2.94 | 4.35 | 0.00 | 6.25 |
| Mg | 3.24 | 0.00 | 0.00 | 0.00 | **43.75** |
| Cd | 2.31 | 0.00 | 0.00 | 5.56 | 6.25 |
| REE | 2.31 | 0.00 | **17.39** | 0.00 | 6.25 |
| Sb | 2.31 | 0.00 | 0.00 | 2.78 | 6.25 |
| Ba | 1.85 | 0.00 | 0.00 | 2.78 | 0.00 |
| Ge | 1.85 | 0.00 | 0.00 | 5.56 | 0.00 |
| Sn | 1.85 | 0.98 | 0.00 | 2.78 | 6.25 |
| Al | 1.39 | 0.00 | 0.00 | 0.00 | **18.75** |
| In | 1.39 | 1.96 | 0.00 | 2.78 | 0.00 |
| Ti | 1.39 | 1.96 | 0.00 | 0.00 | 6.25 |
| W | 1.39 | 0.98 | 0.00 | 0.00 | 6.25 |
| Ga | 0.93 | 0.00 | 0.00 | 2.78 | 0.00 |
| Gr | 0.93 | 1.96 | 0.00 | 0.00 | 0.00 |
| Hg | 0.93 | 0.00 | 0.00 | 2.78 | 0.00 |
| Rb | 0.46 | 0.00 | 4.35 | 0.00 | 0.00 |
| Re | 0.46 | 0.00 | 0.00 | 0.00 | 0.00 |
| S | 0.46 | 0.00 | 0.00 | 0.00 | 0.00 |
| Sc | 0.46 | 0.00 | 0.00 | 0.00 | 6.25 |
| Se | 0.46 | 0.00 | 0.00 | 0.00 | 6.25 |
| Sr | 0.46 | 0.00 | 4.35 | 0.00 | 0.00 |
| Y | 0.46 | 0.00 | 0.00 | 0.00 | 6.25 |
| Zr | 0.46 | 0.00 | 0.00 | 0.00 | 6.25 |
| Be | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ce | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Cs | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fl | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Hf | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Li | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Nb | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Ta | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Te | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Th | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Tl | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

information, such as location, current status, deposit information (type, morphology), identified commodities, mineralogy (ore versus gangue), host rock (age, geology), economic information, etc. Deposits not belonging to one of the 17 families—either poorly described in terms of deposit type, or belonging to more 'exotic' metallogenic families—were discarded. The resulting dataset contained 8364 deposits and occurrences in 34 European countries.

As mentioned above, the targeted 'by-products' (Te, Bi, Co, Re, Mo, Pt, Sb, Ge, Se and In) were historically rarely reported, estimated and/or assessed in European databases. Such metals were considered not of significant economic interest in the past as most of them are by-products of "primary interest" metals, such as gold and base metals. According to the database, only 1400 occurrences and deposits record the presence of such targeted by-products (Fig. 2).

## 2.2. *The DBQ method*

Despite the efforts of the ProMine project to construct a homogeneous pan-European database of primary mineral resources, heterogeneities remained either due to the lack of identification (as explained above), or to the variable level of descriptions in the various countries. For that reason, the statistical DBQ method was developed and applied (Billa et al., 2016; Bertrand et al., 2017). As mentioned above, this method allows the assessment of the potential occurrence of targeted by-product elements where they have not been described. It also has the advantage of providing reliable rules governing the presence or absence of selected commodities in relatively small (hundreds of data) datasets compared to (in terms of data) probability-based methods such as the Weight of Evidence (Bonham-Carter et al., 1988, 1989; Agterberg et al., 1990). Cassard et al. (2015) explained that the Weight of Evidence approach is easier to apply to major commodities (e.g., Zn) than to critical ones (e.g., Ge) as they are not systematically reported in databases. Moreover, the commodity may or may not be related to a given metallogenic family (e.g., Zn deposits), and may or may not be associated to its occurrences. DBQ is more appropriate for exploring deposits, as it compares identified deposits for which the targeted commodity has never been investigated, with those where it has been identified.

The core philosophy of the DBQ method is three-fold. 1) Identify metallogenic families that are enriched in the targeted commodity; 2) Identify 'characteristic signature' elements that are usually associated with the targeted commodity; 3) Score all deposits on their level of similarity to this characteristic signature. A prerequisite is to have a deposit database describing main and by-product commodities, not necessarily systematically, but enough for statistical calculation, otherwise the targeted commodity would have been reported and there would be no need to search for it. A matrix is built from this database, listing for all deposits the presence of each element, coded one (1). An element that is "not present" in a deposit is coded zero (0), which means that it is either absent, or not observed.

The first step of the method is to calculate, for each of the 17 metallogenic families of the dataset listed in Table 1, an enrichment ratio (ER) according to Eq. (1). ER is the frequency of occurrence of the targeted element [e] in a given metallogenic family versus the whole dataset.

$$\mathrm{ER} = \frac{frequency\ of\ occurrence\ of\ [e] in\ a\ given\ metallogenic\ family}{frequency\ of\ occurrence\ of\ [e] in\ the\ whole\ dataset} \tag{1}$$

where ER >1 indicates a metallogenic family enriched in the selected element, while ER <1 indicates a depleted one. This step can be illustrated as follows for cobalt. As shown in Table 1, cobalt appears enriched in the "Mafic or Ultramafic" (ER = 8.10), "VMS" (ER = 1.89), "Orogenic" gold deposits (ER = 1.84) and "Residual" deposits (ER = 1.20) metallogenic families. These four families contain almost 82% of the Co-bearing occurrences in Europe (177 occurrences for these four metallogenic families out of 216 in total).

Thus, for each studied targeted by-product (i.e., Te, Bi, Re, Mo, Pt, Sb, Ge, Se and In), similar calculations are performed. Fig. 3 shows a distribution plot of the element-bearing deposits classified by the main metallogenic family. Note that not-represented families (ER = 0) are not shown.

The second step of the method is the identification of multi-element 'characteristic' signatures. For each selected (or enriched, i.e. with ER >1) metallogenic family, a frequency of occurrence in all deposits

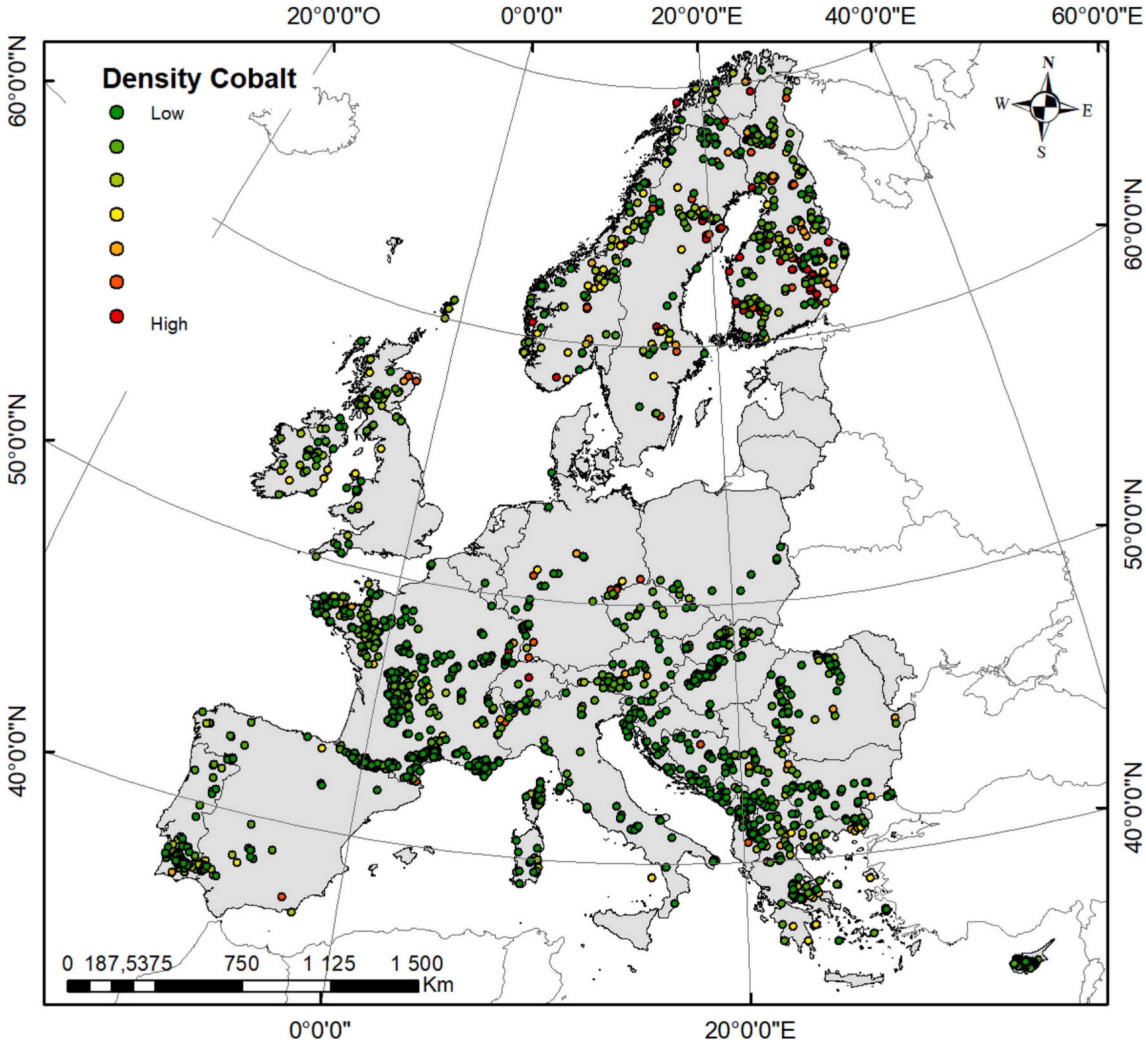

**Fig. 4.** Cobalt frequency distribution in Europe.

containing the targeted element is calculated, per commodity. This identifies a multi-element signature for each metallogenic family, giving the frequency of association of each commodity with the targeted element. Importantly, some metallogenic families may not contain a sufficient number of occurrences/deposits to provide statistically meaningful results (not affecting our cobalt example). Therefore, the statistical value has to be considered carefully, especially when the number of deposits containing the targeted element in a given family is small.

Regarding the cobalt example (Table 2) and considering copper, Cu is present in, or associated with, 88% of “Mafic or Ultramafic” deposits where Co is reported. However, lead in “Mafic or Ultramafic deposits” is associated with Co only in 0.98% of Co-bearing deposits. Consequently, it is much more probable to find Co in a Cu-bearing “Mafic or Ultramafic” deposit than a Pb-bearing one.

Based on this principle, all occurrences/deposits in the enriched metallogenic families are scored according to their similarity to the multi-element signature of their family, using Eq. (2):

$$\text{Rank} = \sum_{commodity\#1}^{commodity\#n} \left( \frac{commodity\ frequency\ x\ binary\ presence\ value}{100} \right) \tag{2}$$

where “binary presence value” takes the value of one (1) if the scored deposit contains the commodity, or zero (0) if it does not contain it.

In order to compare results from different metallogenic families, the score of each deposit is weighted with the ER of the family to which it belongs to. Thus, for cobalt, a weighted score for each of the 2299 occurrences/deposits belonging to the four selected (enriched) metallogenic families (“Mafic-Ultramafic”, “VMS”, “Orogenic” and “Residual”) was calculated.

It is important to note that the DBQ method is not spatial in its basic principle. The geographic location of an occurrence has no influence on its score. Nevertheless, the results can be mapped with the geographic coordinates of ranked occurrences and deposits, for a better

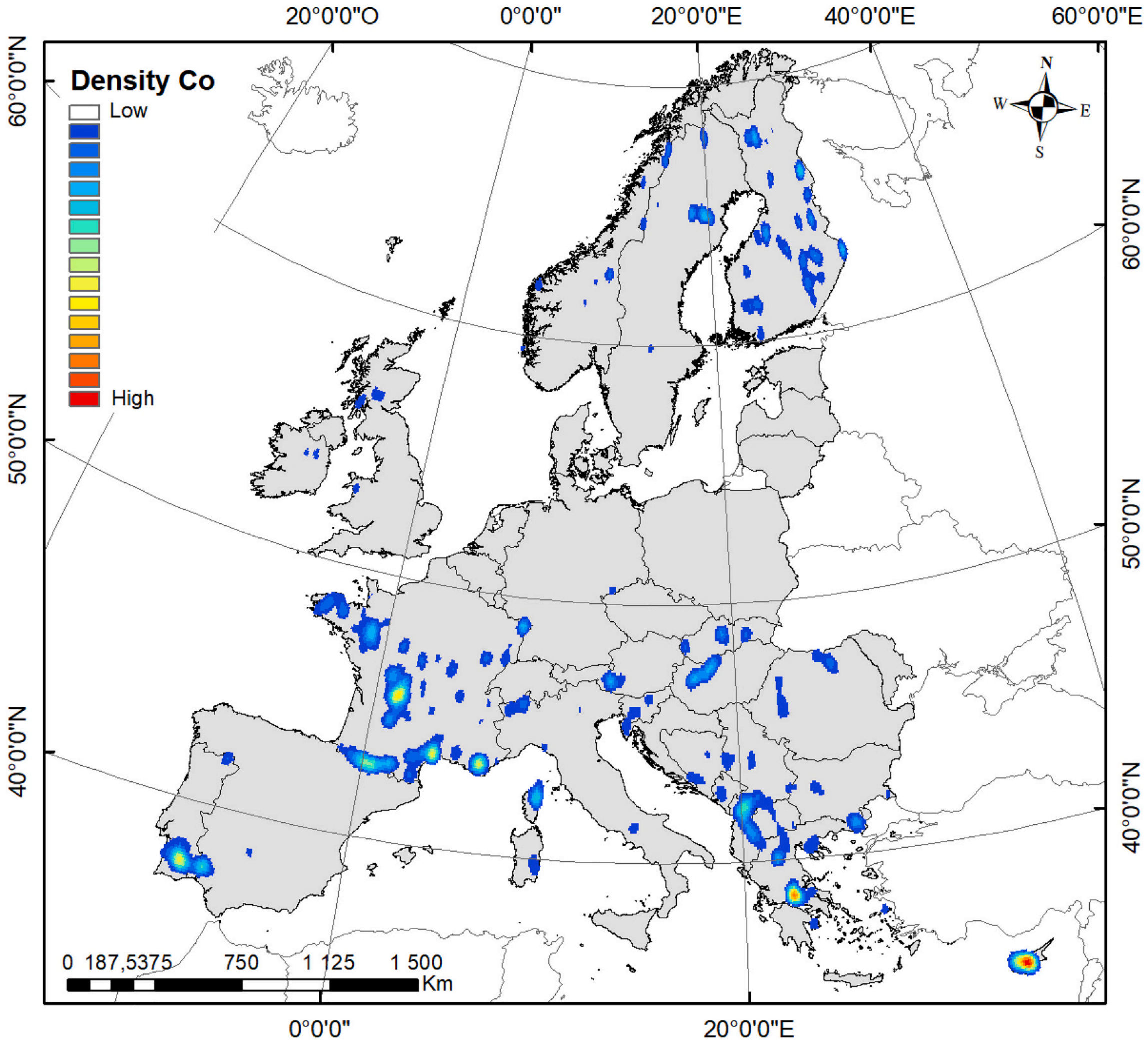

**Fig. 5.** Map of kernel density of weighted Co scores in Europe by DBQ geostatistical method.

**Table 3**
ER values of the targeted by-products as a function of their metallogenic family. The bold text highlights the most relevant metal association regarding the selected metallogenic families.

| | Sb | Bi | Te | Pt | Co | Mo | Ge | Se | Re | In | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Epithermal** | **3.37** | **1.03** | **8.68** | | | | **1.39** | **5.21** | | **1.82** | **6** |
| **Igneous intermediate** | | | **2.73** | | | **22.35** | | **16.37** | **50.92** | **2.46** | **5** |
| **Igneous replacement** | | **2.67** | **1** | | | **1.85** | | **4.01** | | **2.71** | **5** |
| **Orogenic gold** | **2.9** | **3.42** | **3.61** | | **1.84** | | | **1.44** | | | **5** |
| **Mafic or ultramafic** | | **1.69** | **2.86** | **12.16** | **8.1** | | | | | | **4** |
| Sandstone and shale-hosted | | | | 1.44 | | 1.01 | | 2.2 | 5.86 | | 4 |
| Igneous felsic | | 2.97 | | | | 3.47 | | | | 4.14 | 3 |
| VMS | | | | | 1.89 | | 2.02 | | | 1.13 | 3 |
| Residual deposits | | | | | 1.2 | | | 1.35 | | | 2 |
| Base-metals veins | 2.34 | | | | | | 1.36 | | | | 2 |
| Mafic intrusion | | | | 3.57 | | | | | | | 1 |
| Carbonate-hosted | | | | | | | 4.41 | | | | 1 |
| Placers | | | | 5.09 | | | | | | | 1 |
| Alkaline & Peralkaline intrusions | | | | | | | | | | | 0 |
| IOCG | | | | | | | | | | | 0 |
| Pegmatites | | | | | | | | | | | 0 |
| Sedimentary deposits | | | | | | | | | | | 0 |

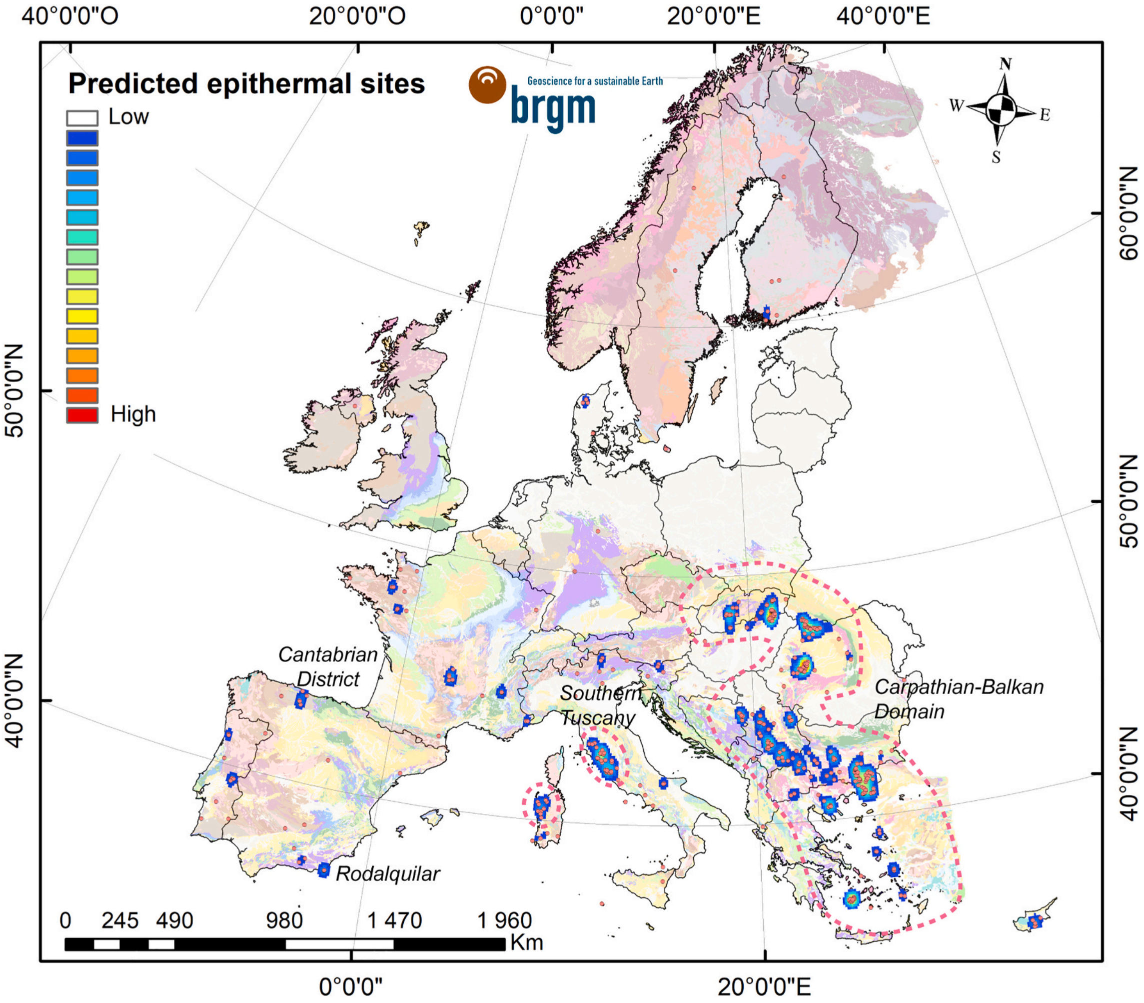

**Fig. 6.** Kernel density of predicted epithermal sites in Europe based on combined weighted Sb, Bi, Te, Ge, Se and In scores.

visualization and comparison with other geographic data, such as geological or structural maps. Bertrand et al. (2017), for instance, produced a kernel-density map of DBQ scores for rare-earth elements (REE) in Europe. The kernel-density calculation is a statistical tool that estimates the probability density function of a random variable.

Similarly, we calculated with ArcGIS software, for each targeted element, a kernel density of weighted scores to identify the metal-endowment neighbourhood (Figs. 4, 5). The corresponding favourability map obtained in the case of Co is shown on Fig. 5, indicating several areas of potential interest: 1) Mafic or ultramafic occurrences (komatiites/tholeiites) in the Precambrian Fennoscandian Shield (Norway, Sweden and Finland); 2) VMS occurrences in France, Spain and Portugal; 3) Residual deposits (related to primary ophiolite occurrences) in Greece, Serbia and Kosovo; and 4) Mafic to ultramafic occurrences (ophiolites) in Cyprus (Figs. 3, 5). This process was replicated for all targeted by-products (Te, Bi, Co, Re, Mo, Pt, Sb, Ge, Se and In) in the scope of the ION4RAW project. The resulting kernel-density maps are presented and discussed in the following sections.

### 2.3. Metallogenic family signature assessment

The DBQ method applied to each targeted by-product showed that most of them have high ER values for similar metallogenic families. We therefore opt to classify the metallogenic families as a function of the number of targeted by-products for which they are enriched (ER >1; see “TOTAL” column of Table 3). For instance, the “Epithermal” deposit type shows high ER values for six studied by-product elements (Sb, Bi, Te, Ge, Se and In), whereas “Sedimentary” deposits do not represent a targeted deposit type for these metals, as no targeted elements were identified in this deposit type.

We then merged the DBQ score datasets of all elements in ArcGIS to obtain a dataset of scored occurrences for selected elements, relevant to a metallogenic family (e.g., VMS: Co, Ge, In). Kernel-density maps were then drawn with ArcGIS software for all identified metallogenic families. Instead of focusing on a single commodity, this approach allows assessment of the favourability for a complete metallogenic family, gathering all commodities usually included in its paragenesis. Although this implies ‘globalizing’ the approach to a group of commodities rather than a single one, we consider that it facilitates the interpretation of the results and their connection with the geological and metallogenic setting. Note that the “Sandstone and shale-hosted” and “Placer” deposit types were not considered in this study as they represent erosion products of other deposit types, but that instead the “Igneous felsic” deposit type was included in the calculation.

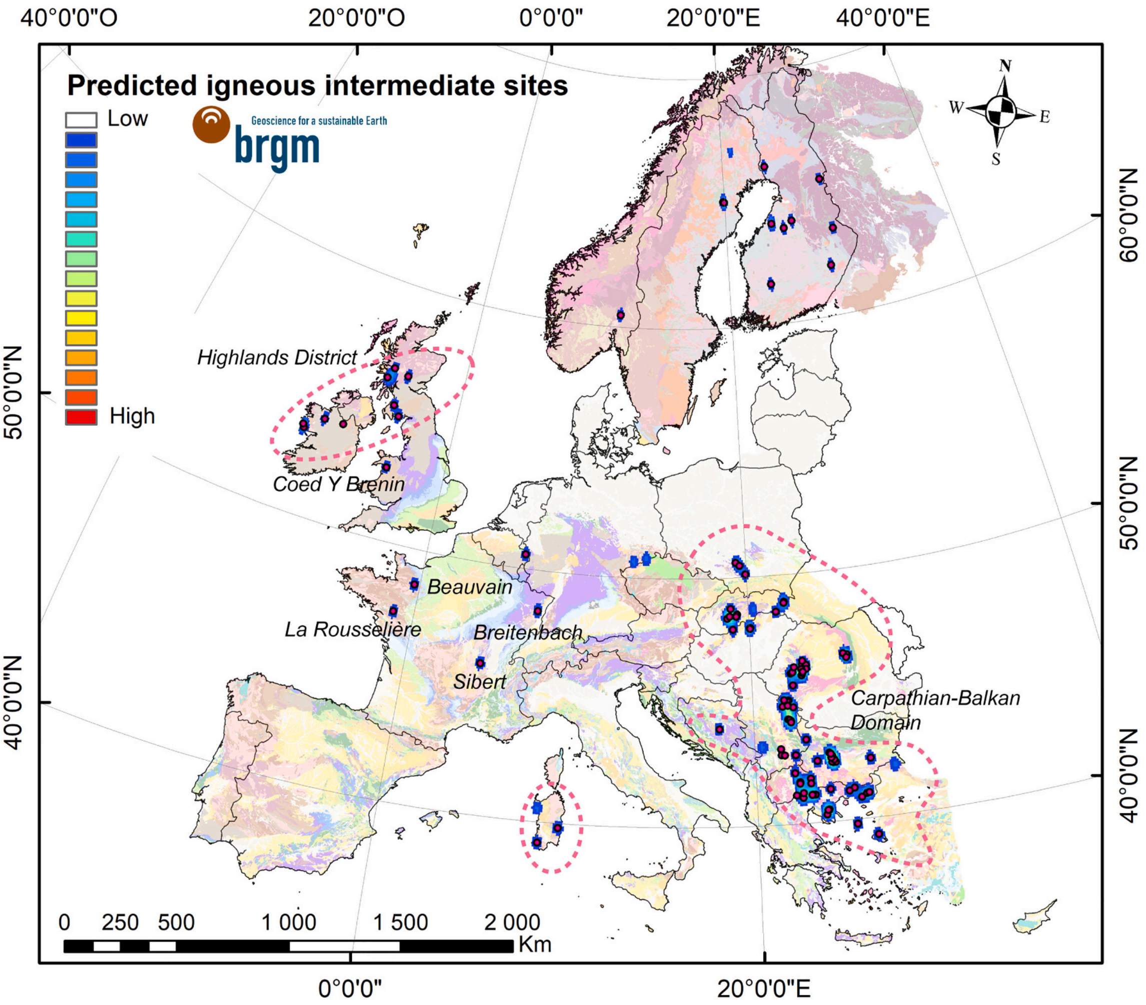

**Fig. 7.** Kernel density of predicted igneous intermediate sites in Europe based on combined weighted Te, Mo, Se, Re and In scores.

### 2.3.1. *Results*

*2.3.1.1. Epithermal sites.* It is generally agreed that high- and low-sulphidation epithermal deposits are significant for Au and Ag exploration, but also for Sb, Hg, Te, Cu and In. Epithermal mineralization in Europe occurs in Romania, Spain, Italy, the Balkan countries, Hungary, Bulgaria, Slovakia, Ukraine and Greece generally in subduction-related volcanic arcs, along with calc-alkaline volcanism and closely related to major strike-slip faults (Lattanzi, 1999; Hedenquist et al., 2000).

Using the DBQ method, combining weighted Sb, Bi, Te, Ge, Se and In scores, the most prospective areas are located in the Carpathian area, Italy, Corsica and Cyprus, shown by pinkish dashed lines on Fig. 6. The mineralization is mostly Miocene-age calc-alkaline magmatism related to the opening and evolution of the western Mediterranean Sea (Heinrich and Neubauer, 2002; Cassard et al., 2004).

*2.3.1.2. Igneous intermediate sites.* Cu, Mo, Au and Re associations in porphyry deposits illustrate intermediate igneous mineralization (Cooke et al., 2005; Singer et al., 2008). In Europe, they are mainly related to the Late Cretaceous and Cenozoic evolution of the western Tethyan suture, especially in eastern Europe (e.g., Lips et al., 2004; Cassard et al., 2015).

According to the DBQ method, favourable intermediate igneous areas combining weighted Te, Mo, Se, Re and In scores mostly occur in the Carpathian-Balkan area and in Corsica (red dashed lines, Fig. 7), overlapping some of the favourable areas highlighted by the epithermal DBQ work. This is expected, as porphyry-epithermal mineral systems commonly show a spatial and temporal association with intermediate/felsic sub-aerial volcanic rocks and related sub-volcanic intrusions (e.g., Cardon, 2007). Note that a few spots also occur in the Scottish Highlands and Ireland, probably related to the Caledonian orogeny.

*2.3.1.3. Igneous replacement sites.* Igneous replacement skarn deposits (circulation of young magmatic fluids in carbonate hostrock) are illustrated by Fe, W, Pb, Zn, Cu and Au mineralization (Einaudi et al., 1981). The identified European deposits occur in the Fennoscandian Shield, the Hercynian domain of southern Europe and the Carpathian-Balkan domain (Cassard et al., 2015).

Only a few areas in southern France, Spain, Italy and the Carpathian area are highlighted through combination of the Bi, Te, Mo, Se and In DBQ scores (Fig. 8). In the Hercynian domain, this is related to Cambrian-Devonian carbonates affected by Variscan magmatism resulting in development of tungsten-bearing skarns in the Pyrenees and Alps. In the Carpathian-Balkan domain, many Mesozoic carbonate units near Cenozoic porphyry-epithermal mineral systems contain such deposits. In the Mediterranean area, minor skarn occurrences in Sardinia and Spain are related to Tertiary and Quaternary magmatism (Cassard

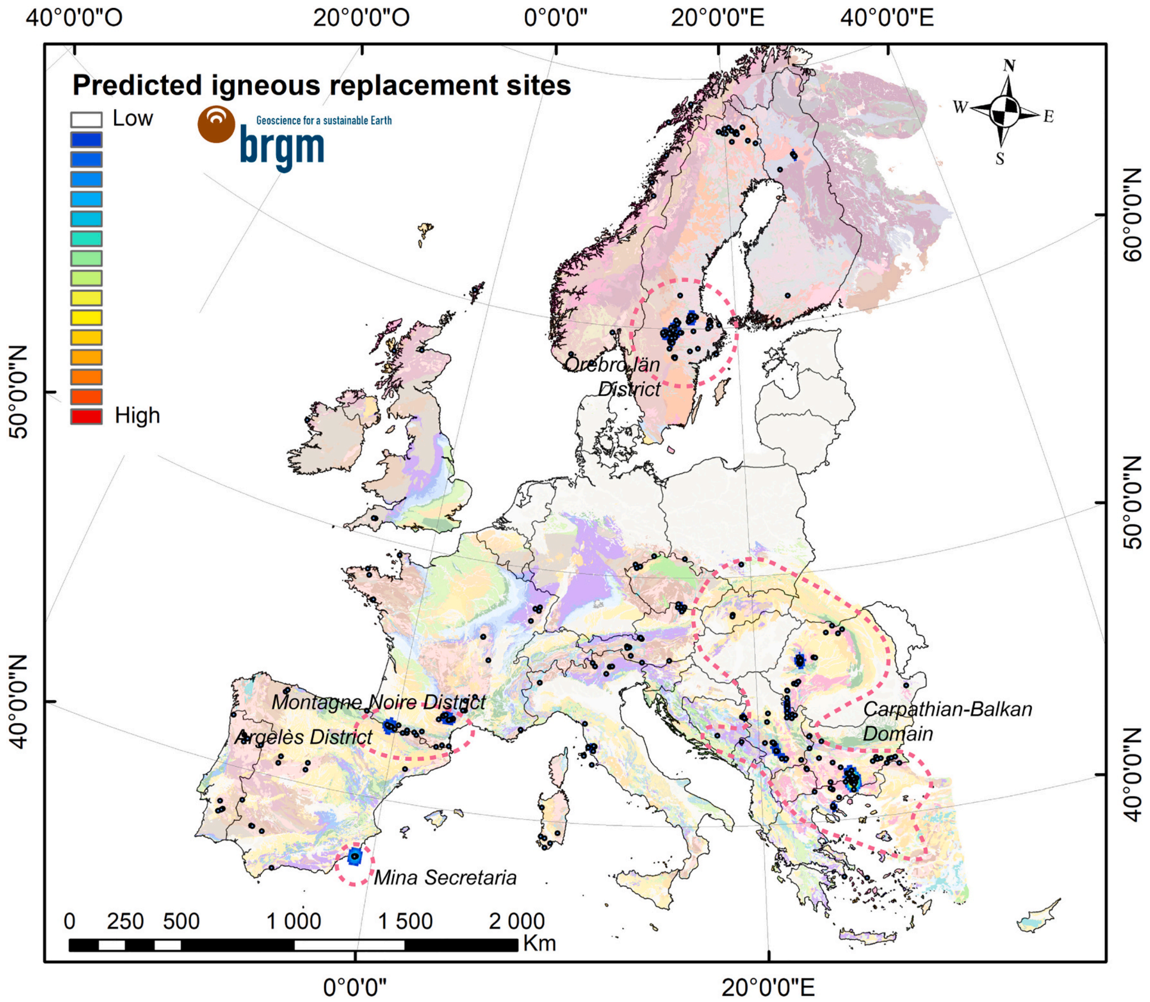

**Fig. 8.** Kernel density of predicted igneous replacement sites in Europe based on weighted Bi, Te, Mo, Se and In scores.

et al., 2015).

*2.3.1.4. Orogenic sites.* In Europe, the distribution of orogenic deposits is mainly related to either Paleoproterozoic (Fennoscandian Shield) or Hercynian (Iberian Peninsula, French Massif Central, Bohemian Massif) processes. A few deposits were also identified in the Caledonian and the Carpathian-Balkan domains (Cassard et al., 2015).

As shown on Fig. 9, the favourable orogenic areas when combining weighted Sb, Bi, Te, Co and Se DBQ scores are mainly located in the Armorican Massif and the western part of the Massif Central in France, as well as along the eastern Variscan orogeny (Austria). Some areas occur in Finland, in the Precambrian Fennoscandian Shield, and a few small spots in UK and Greece are also indicated.

*2.3.1.5. Mafic to ultramafic sites.* Mafic or ultramafic deposits are illustrated by Ni, Cr, Cu, PGE, Co, Bi, U and Ag mineralization. Known European deposits are mainly distributed in the Fennoscandian Shield and the Czech Republic, the Balkans, Greece, and local ophiolites occurrences (Cassard et al., 2015). Mafic to ultramafic favourable sites when combining weighted Bi, Te, Pt and Co DBQ scores are well represented in most European countries (Fig. 10). Areas of interest are mainly found in the Fennoscandian Shield and Mesozoic ophiolites in Greece, Serbia and Kosovo. In the Fennoscandian Shield, such deposits may be related to early rifting during the Sveconorwegian orogeny, or to mafic-ultramafic intrusions during the Scandinavian-Caledonian orogeny (e.g., Weihed et al., 2005).

*2.3.1.6. Igneous felsic sites.* In Europe, the distribution of igneous felsic mineralization is related to Sn, W, Ta, Nb, Mo, Li, Be, In, B and F occurrences, related to Hercynian granitic and pegmatite intrusions (Cassard et al., 2015). Regarding the combination of weighted Bi, Mo and In DBQ scores, the favourable sites are mostly located in Spain, France, and the UK (St Austell area), all related to the Variscan Orogeny (Fig. 11). This metallogenic family is consistent with pegmatite and granite occurrences related to late-Variscan magmatism. Note that significant progress has been made recently on pegmatite identification throughout the Variscan Orogeny, especially in France and in Spain (Gourcerol et al., 2018).

## 3. Discussion

### 3.1. Geological sustainability of the DBQ method

The DBQ method and the combination of weighted-element scores through metallogenic families' assessment can give reliable results on potential exploration areas. Our results show that DBQ study of by-

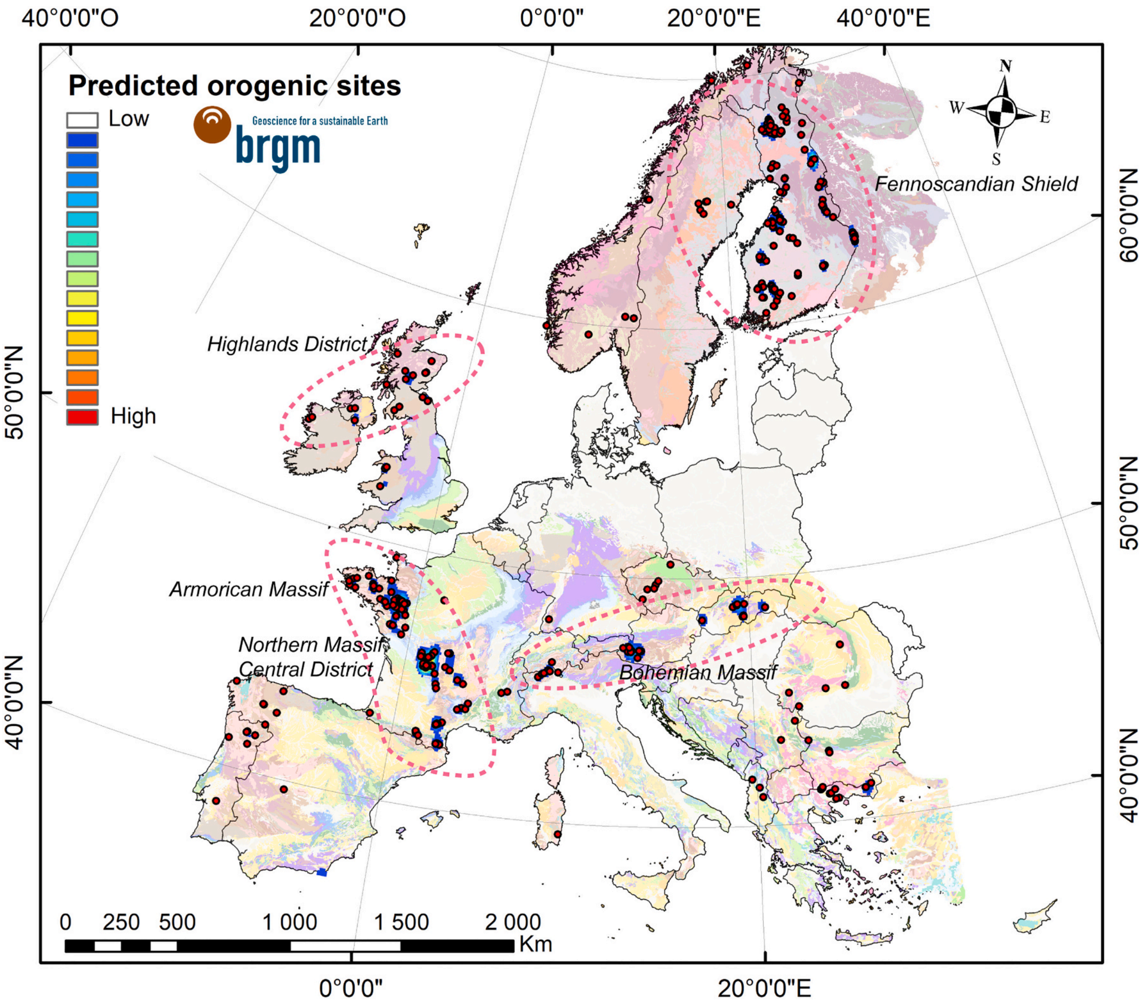

**Fig. 9.** Kernel density of predicted orogenic gold sites in Europe based on weighted Sb, Bi, Te, Co and Se scores.

product elements (e.g., Te, Bi, Co, Re, Mo, Pt, Sb, Ge, Se and In) can provide consistent positive results in the search for major commodities (Au, Ag, Sb, Cu, Fe) as obtained in Cassard et al., 2015. This suggests that the DBQ method is a reliable predictive method for mineral exploration of all types of commodities in hitherto incompletely studied areas.

Several areas were identified through the predicted epithermal sites. Minor epithermal and volcanic potential areas can be found in the Fennoscandian Shield and the Western Hercynian domain. However, the highest potential is related to the Tethyan suture in southeastern Europe as we will discuss below.

Among the highlighted areas in Italy, potential locations are in southern Tuscany and Sardinia, both corresponding to Neogene magmatic activity and being part of the peri-Tyrrhenian geological domain (Lattanzi, 1999). Both regions are well-known for their epithermal activity. In Sardinia, highlighted areas include the Nulvi, Osilo S. Marino, Bosano and Monti Ferru epithermal mineralization in the north, as well as the Furtei and Sarroch mineralization in the south (Ruggieri et al., 1997).

In Spain, the highlighted northern area corresponds to the Cantabrian Mountains, including the epithermal Cu-Co-Ni Aramo mine (Paniagua et al., 1988). In the south, the Rodalquilar epithermal district is also well identified (Sänger-von et al., 1990).

Not all known European deposits are identified through this method. For instance, the Freiberg epithermal district in Germany (Swinkels et al., 2021) was not identified on the kernel density map. Regarding the igneous intermediate example, Sardinia shows three potential sites, the north-western one of which is the Calabona intrusive complex (Frezzotti et al., 1992), whereas the eastern site refers to the Baccu Locci gold district. The southern site falls within the allochthonous complexes of the Iglesiente and is, so far, unknown, though several base-metal deposits are known from this region. The few favourable spots in the northern part of UK, may be related to diorite emplacement during the Caledonian orogeny.

The island of Corsica (France) is used as an example of the relevance of metallogenic signatures using the DBQ approach (Fig. 12). The method illustrates mafic to ultramafic (Bi-Te-Pt-Co assemblage) and igneous felsic (Bi-Mo-In assemblage) signatures in the north-eastern and western parts, respectively. These results were confirmed by mapping (Lin et al., 2018): the north-eastern part of the island is composed of Alpine ophiolite-bearing “schistes lustrés” nappes, whereas the western

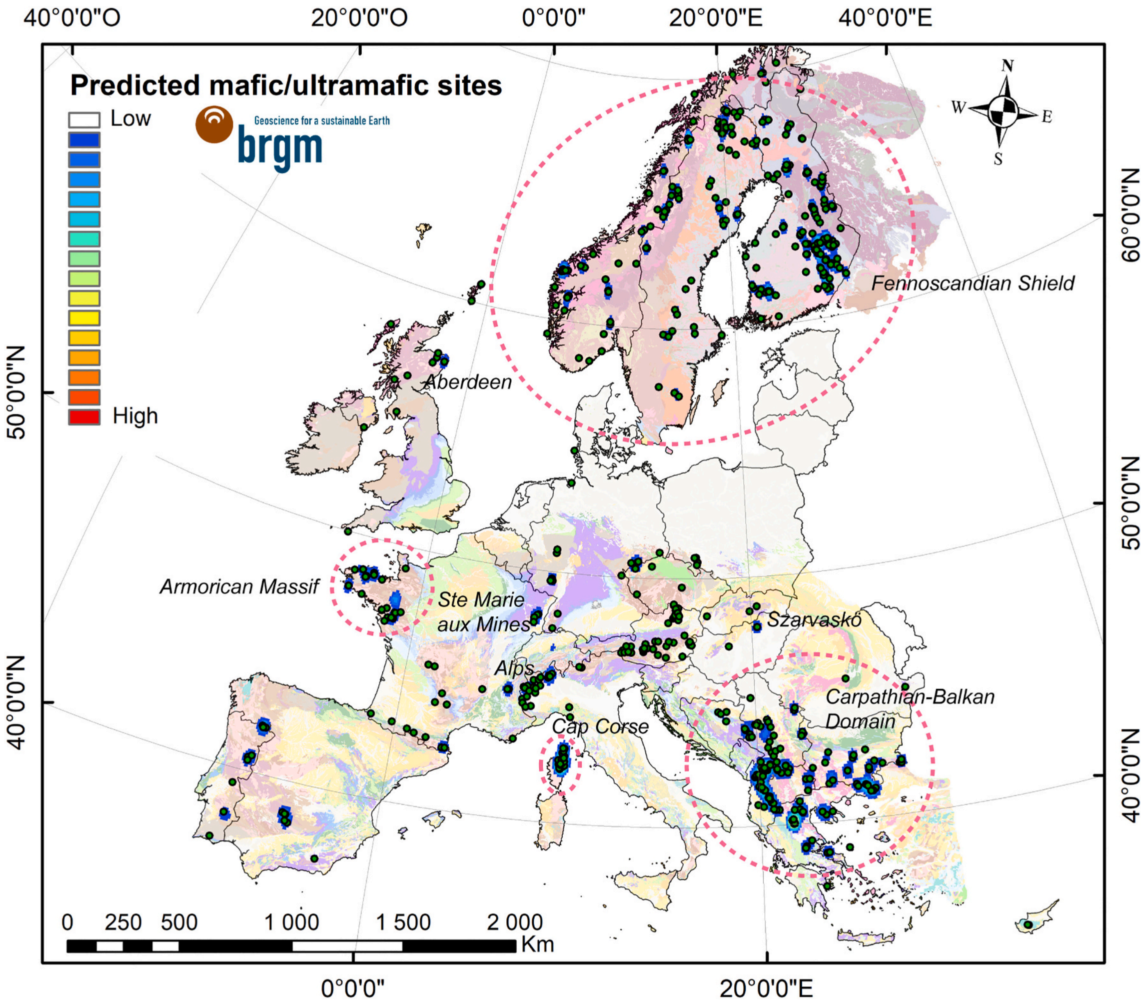

**Fig. 10.** Kernel density of the predicted mafic to ultramafic sites in Europe based on weighted Bi, Te, Pt and Co scores.

part consists of Variscan granodiorite/monzogranite intrusions and Permian volcanic rocks. This is further confirmed by known metal occurrences, as the northern Cap Corse peninsula contains antimony occurrences and cobalt is reported from volcanic rocks in the Finosa area (centre-east) (Fig. 12).

### 3.2. Discussion on the DBQ method: benefits and limitations

The DBQ method can highlight potential areas for exploration of selected deposit types and their by-product elements. It is a technically simple and relatively fast approach, easy to implement when suitable datasets are available, and allowing straightforward interpretation. However, it also has some limitations that have to be considered for a correct interpretation of the results and for further improvement of the method.

One of the main limitations is that the initial dataset for training purposes must include a significant amount of positive (commodity identified for a given deposit and coded by “1”) and negative data (commodity not identified for a given deposit and coded by “-1”). Only then can the dataset be used as a basis for reliable training of a model that will lead to an acceptable predictive accuracy.

A second limitation is that the spatial data heterogeneity may overestimate some areas and underestimate others. This point does not affect the individual scores of the deposits, but their aggregation as density maps as we presented above. For instance, the Variscan segments in France appear as highly favourable and interesting prospective areas; however, data coverage for France in the ProMine mineral deposit database is relatively dense, which may lead to a slightly overestimated favourability on the Kernel density map, compared to other countries where data is scarcer.

As for all mineral prospectivity approaches, the quality of input data is of paramount importance. The reliability of the assessment directly derives from the quality of the data. In the case of the DBQ method, an as thorough as possible description of by-products in occurrences and deposits is critical for the validity of the prospectivity assessment. Based on our experience, the ProMine database (Cassard et al., 2015)—even though it necessarily lacks some information (not accessible or unknown)—is the best available data source for DBQ assessment in Europe at continental scale.

A last major point is to keep in mind that the DBQ approach, like any mineral prospectivity assessment method, is an ‘upstream’ phase of mineral exploration. It has been designed for assessing the geological

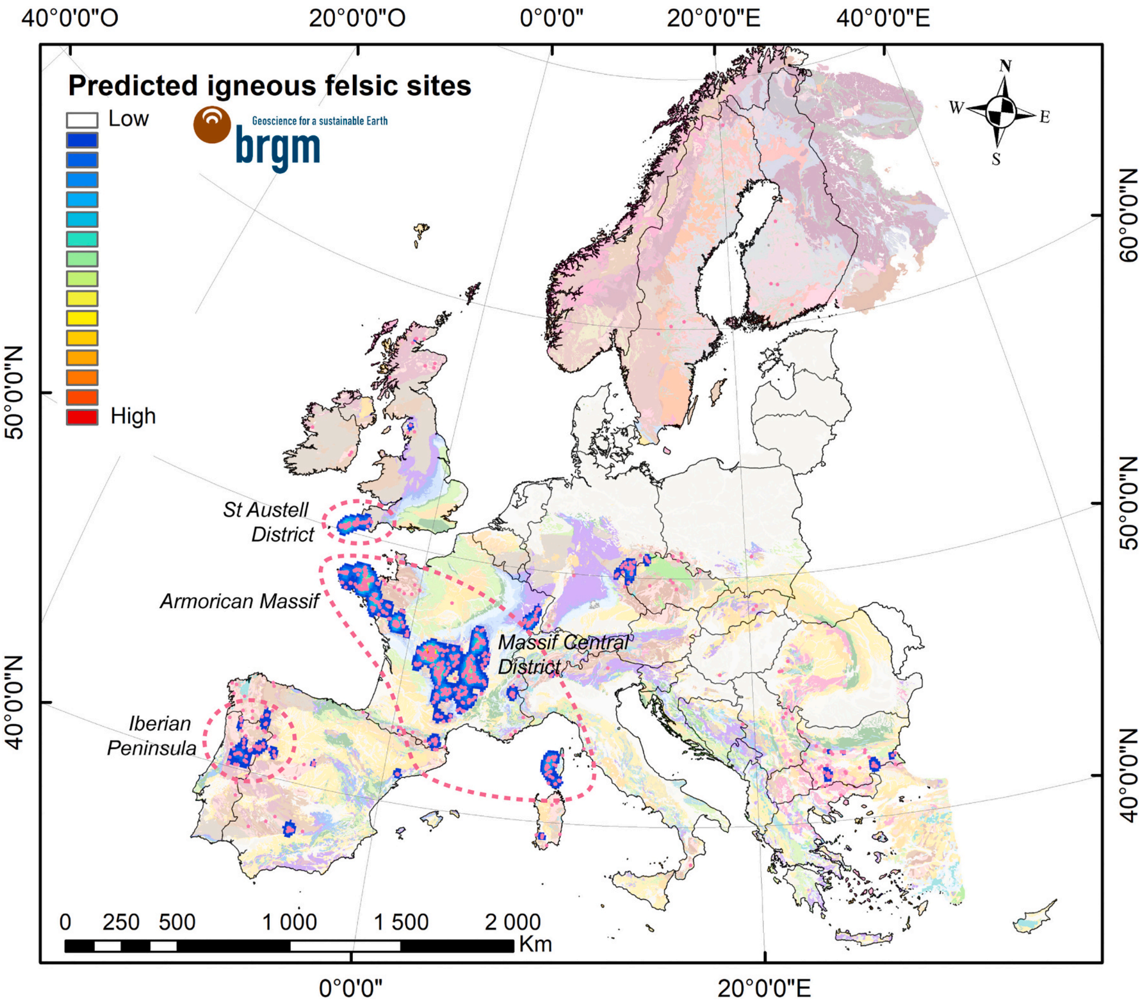

**Fig. 11.** Kernel density of predicted igneous felsic sites in Europe based on weighted Bi, Mo and In scores.

favourability for the existence of potential by-products in known deposits or occurrences of common metallogenic types. For that reason, it can only highlight areas that were previously explored and/or mapped, while unexplored areas cannot be identified as favourable.

Finally, as the results of DBQ assessments can only provide insight into the geological potential, they must be confirmed by exploration work and cannot be used for prejudging the economic viability of any discovery.

Thus, in view of these limitations, a careful review of the resulting maps is always required for evaluating their predictive accuracy and efficiency.

## 4. Conclusions

The DBQ approach allows assessing favourability of by-product commodities that were not systematically searched for or described in the mineralization. DBQ can be seen as a computational statistics approach, but differs from machine learning as the algorithm does not automatically improves from experience gained by processing the input data. In that sense, it is a technically simple, fast and easy to implement approach that requires no or little data sciences skills. Its main requirement remains in the input data that has to be exhaustive enough to be statistically relevant. DBQ was applied for prospectivity mapping of metallogenic families at a continental scale, as part of the European-Peruvian ION4RAW project (Horizon 2020 framework programme). It has determined several areas in Europe of great interest for the exploration of mineral by-products of major economic importance.

The method initially allows identifying the favourability for commodities that hitherto have been rarely reported, either in geochemical analyses, or through various permit and deposit reports by mining companies. The approach we present herein allows extending the application of the DBQ method from individual commodities to metallogenic families in order to assess their prospective areas and evaluate the pertinence of these in their geological context. These areas should be further studied to identify major mine sites, which might be of interest for the extraction of targeted commodities.

## Declaration of competing interest

We state that there is no conflict of interest and that all the funding sources have been cited in the manuscript. All the authors have read and approved the revision of this manuscript.

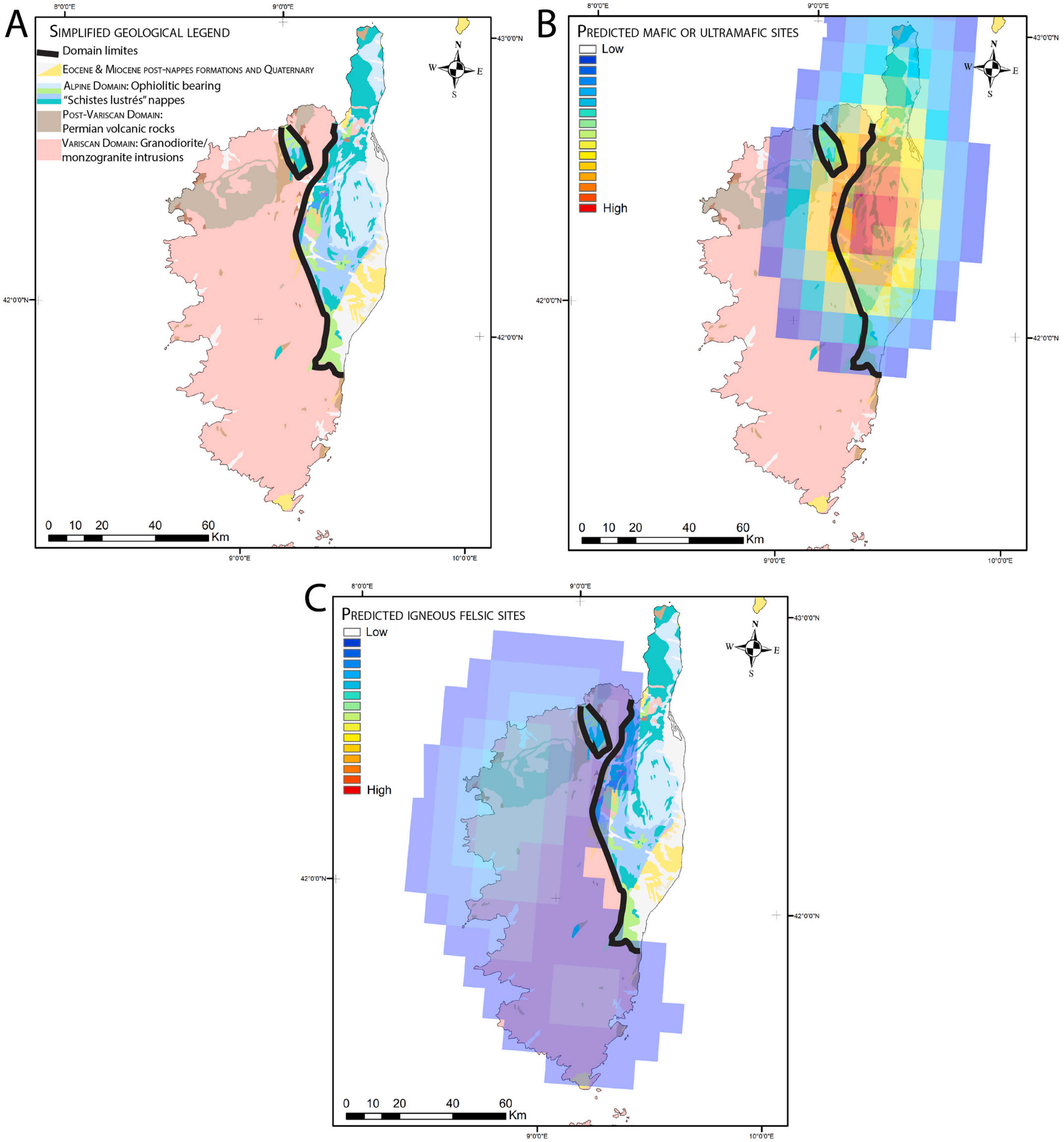

**Fig. 12.** Geological map of Corsica (A) and the respective predicted mafic/ultramafic (B) and the igneous felsic (C) metallogenic family maps.

## Acknowledgements

This study was part of the ION4RAW project that received funding from the European Union's Horizon 2020 research and innovation programme under Grant agreement number 815748. H.M. Kluijver, PhD, revised the original English-language MS.

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