ION4RAW

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Mapping of by-product potential in mineral deposits

Authors : Dr. Blandine GOURCEROL (BRGM), Bertrand Guillaume (BRGM), Bailly Laurent (BRGM), Moreau Pauline (BRGM), Duhamel-Achin Isabelle (BRGM), Négrel Philippe (BRGM), Werner Warscheid (CUMBREX)

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Author(s)	Dr. Blandine GOURCEROL, Bertrand Guillaume (BRGM), Bailly Laurent (BRGM), Moreau Pauline (BRGM), Duhamel-Achin Isabelle (BRGM), Négrel Philippe (BRGM), Werner Warscheid (CUMBREX)
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Summary

The European-Peruvian ION4RAW project (H2020 program) is an ambitious initiative, which aims to develop a new energy-, material- and cost-efficient mineral processing technology to recover by-products from primary sources by means of innovative Deep Eutectic Solvent (DES) ionic liquids and an advanced electrochemical process for metal recovery as an only step. Targeted by-products elements of the ION4RAW project are tellurium (Te), bismuth (Bi), cobalt (Co), rhenium (Re), Molybdenum (Mo), platinum (Pt), antimony (Sb), germanium (Ge), selenium (Se), and indium (In); most of them being Critical Raw Materials. In the frame of this European initiative, one of the first step is to produce a geographically-based compilation of the by-product occurrences and potential in Europe. This inventory allows economical assessment of potential resources as well as assessment of metallogenic processes related to these critical raw material endowments. However due to heterogeneity of the existing databases and available knowledge, one of the key aspect was to perform a predictive assessment of these elements as they are not usually and/or automatically identified and/or assessed. Thus, the DataBase Querying DBQ approach has been applied on the European dataset and allowed determination of several areas of great interest for prospection of the targeted by-products of the project. It allows potential identification of commodities, which are either rarely reported in analyses or through divers permit/deposit reports by mining companies. These areas can be also studied to identify major mine sites which might be interested to apply the mineral process, which would be developed through the study. For Peru, a compilation has been initiated with partners and offers a great dataset of the sites, which might be of great interested for application of the process developed through ION4RAW.

Approval

Date	By
2021-03-22 19:53:51	Dr. Isabelle DUHAMEL ACHIN (BRGM)
2021-03-23 09:57:07	Mrs. Maria TRIPIANA (IDENER)

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Responsible Author(s)	Gourcerol Blandine
Contributor(s)	Bertrand Guillaume, Bailly Laurent, Moreau Pauline, Duhamel-Achin Isabelle, Négrel Philippe (BRGM), Werner Warscheid (CUMBREX)
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EXECUTIVE SUMMARY

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However due to heterogeneity of the existing databases and available knowledge, one of the key aspect was to perform a predictive assessment of these elements as they are not usually and/or automatically identified and/or assessed. Thus, the DataBase Querying DBQ approach has been applied on the European dataset and allowed determination of several areas of great interest for prospection of the targeted by-products of the project. It allows potential identification of commodities, which are either rarely reported in analyses or through divers permit/deposit reports by mining companies.

These areas can be also studied to identify major mine sites which might be interested to apply the mineral process, which would be developed through the study.

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KEYWORDS

Raw materials, critical raw materials, geology, statistic

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1 INTRODUCTION

In a context of climate change and global renewable energy policy, rapid growth of emerging economies as well as fast development of modern technologies have led to drastic upsurge in demand for a number of metals. Reliability of supply in critical raw materials is one of the major challenges facing Europe. Indeed, the availability of mineral resources is crucial in deployment of low-carbon technologies and economic activities. However, distribution of these critical raw materials is fairly restricted related to economical and technology limitations. For most of them, recovery is limited to a few deposit types during processes of the main ore (e.g., gold, silver, copper).

Thus, the European-Peruvian ION4RAW project (H2020 program) is an ambitious initiative, which aims to develop a new energy-, material- and cost-efficient mineral processing technology to recover by-products from primary sources by means of innovative Deep Eutectic Solvent (DES) ionic liquids and an advanced electrochemical process for metal recovery as an only step. A joint recovery of by-products from primary sources, which belong to the Cu-Ag-Au group, is considered for this project. Targeted by-products elements of the ION4RAW project are tellurium (Te), bismuth (Bi), cobalt (Co), rhenium (Re), molybdenum (Mo), platinum (Pt), antimony (Sb), germanium (Ge), selenium (Se), and indium (In); most of them being Critical Raw Materials.

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2 European Database

2.1 DATA SOURCES AND THE DBQ METHOD

In order to provide a reliable inventory of targeted by-product distribution in existing and currently unexploited resources from Europe, data from the ProMine Mineral Deposit (Cassard et al., 2015) database were considered (Figure 1). This database was developed through a European co-funded project (2009-2013), which aimed to stimulate the extractive industry by identification of potential areas of interest in Europe.

After removal of database duplicates (e.g., same sites with several names), the final dataset includes

8364 occurrences and deposits (see

Figure 1), classified into 17 metallogenic families and described with several related information such as location, status, deposit information (e.g., deposit type, morphology), description of mineralogy (gangue versus ore), host-rocks and economic information, commodities, etc.

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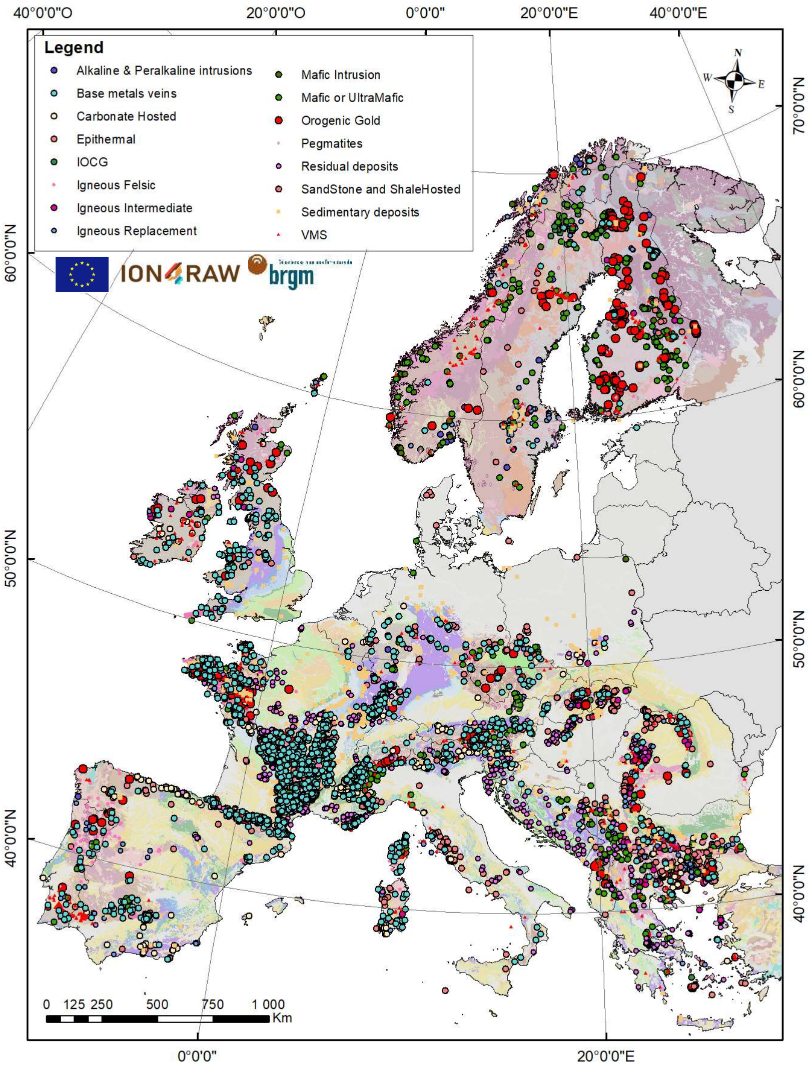

Figure 1: Distribution of all the EU occurrences (n = 8364) and deposits classified according to their metallogenic family.

However, the studied ION4RAW targeted by-products (i.e., Te, Bi, Co, Re, Mo, Pt, Sb, Ge, Se, In) have been rarely identified, assessed and/or calculated in the European occurrences. Indeed, these metals were not of significant interest in the last decades. As they represent, for most of them, by-products of "world first interest" metals such as gold and copper, they were not economically studied or assessed. Thus, according to the database, 1400 occurrences and deposits record the presence of the studied by-products (Figure 2).

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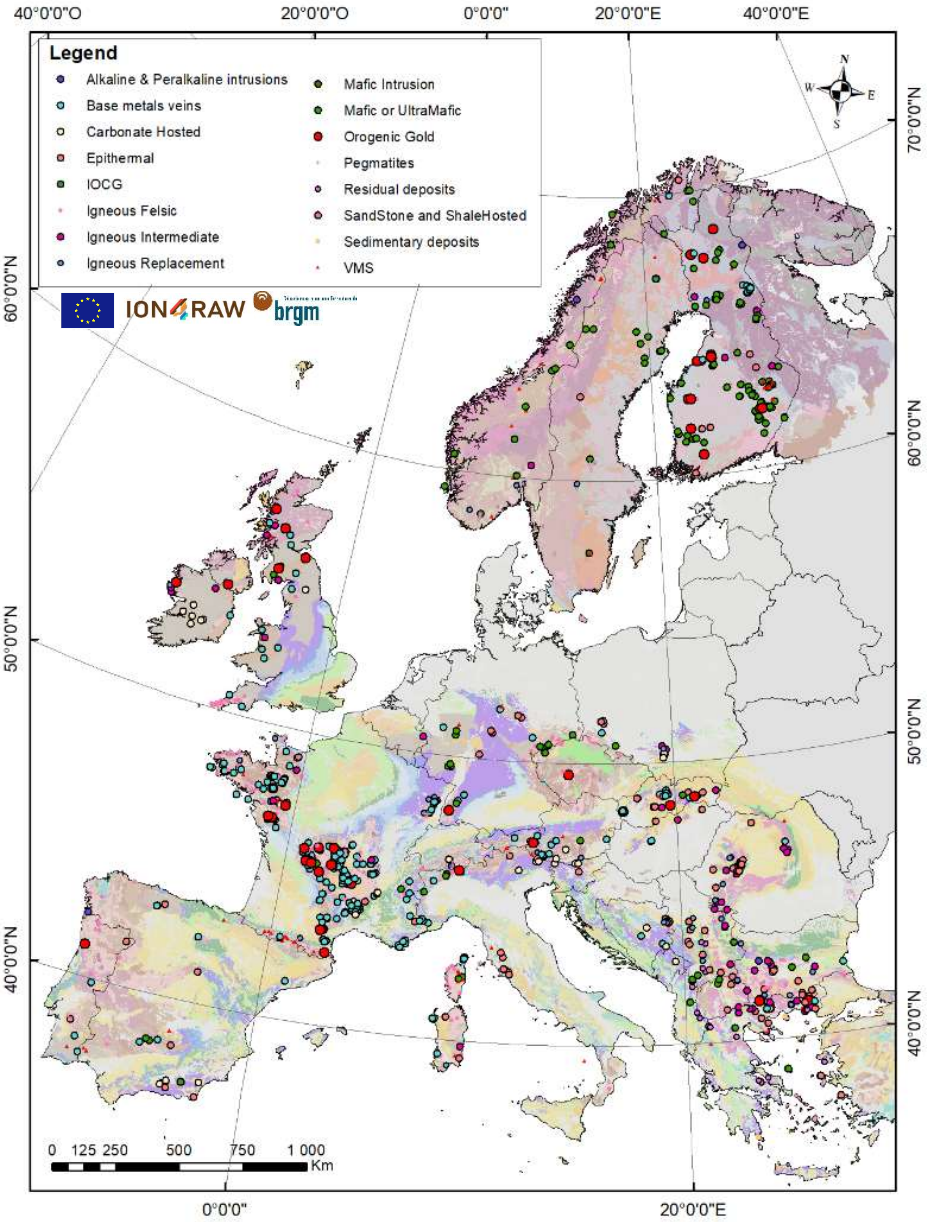

Figure 2: Distribution of the identified EU occurrences (n = 1400) showing identified ION4RAW targeted by-products classified according to their metallogenic family.

Because of a strong heterogeneity of the database, either due to lack of identification (explained above) or variable level of description according to the considered countries, authors have chosen to apply the DataBase Querying (or DBQ) geostatistical method (Billa et al., 2016; Bertrand et al., 2017). This method allows identification of potential occurrences of targeted by-product elements where they have not been searched or described. Moreover, this method presents the advantage to be usable with relatively small (hundreds of data) datasets.

2.2 Predictive assessment

The base principle of the DBQ method is first to identify metallogenic families that favour the targeted commodity. It is then to identify elements that are usually associated with the targeted commodity (i.e. its "characteristic signature"), then to score all deposits on their level of similarity to this characteristic signature. To do so, a prerequisite is to have a deposit database describing main and by-

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product commodities, not necessarily systematically (otherwise the targeted commodity would be described and there would be no need to search for it) but often enough to allow statistical calculation. From this database, a matrix is built listing for all deposits the presence (coded 1) of each element. An element that is not known as "present" in a deposit is coded zero, which either means that it is 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). The ER indicates the frequency of occurrence of the targeted element [e] in a given metallogenic family versus the whole dataset.

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

ER > 1 indicates a metallogenic family enriched in the selected element, while ER < 1 indicates a depleted one. To illustrate the work done with an example, the case of Co will be used in this paragraph. As presented 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). These four metallogenic families may represent almost 82% of the co-occurrences in Europe (177 occurrences for these 4 metallogenic families out of 216 occurrences in total).

Metallogenic family	Total number of occurrences	Number of occurrences containing Co	Enrichement 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 ShaleHosted	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	***8364***	***216***	

Table 1 : Example of ER calculation on Co occurrences applied on the ProMine database.

Thus, for each targeted by-product, similar calculations were performed and a distribution plot of the element-bearing deposits classified by the main metallogenic family can be obtained (Figure 3). Note that the not represented family (ER = 0) are not shown in this plot.

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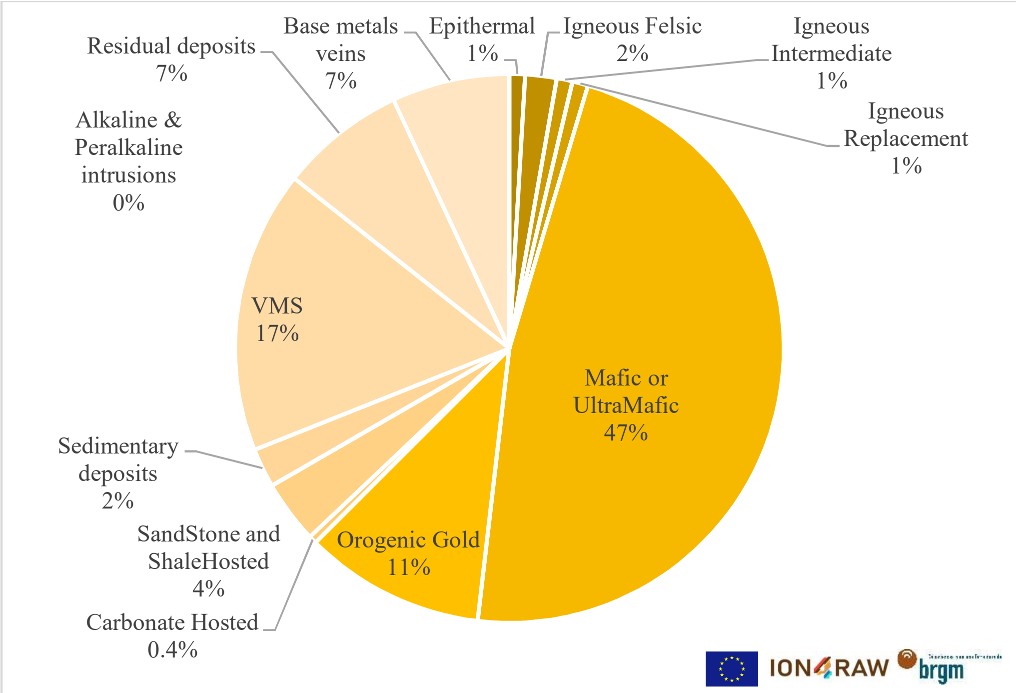

Figure 3 : Distribution of the Co-bearing deposits classified by metallogenic types.

The second step of the method is the identification of the multi-element – or "characteristic" - signatures. Indeed, for each enriched and selected metallogenic family, a frequency of occurrence in all deposits containing the selected element was calculated, per commodity. This leads to identification of a multi-element signature for each metallogenic family. Importantly, some metallogenic families may not show enough number of occurrences/deposits to be statistically representative of the database (which is not illustrated by the cobalt example herein). Therefore, the statistical value has to be considered carefully.

Regarding the Co example (Table 2), it appears that Cu shows 88.24% to be found in "Mafic or Ultramafic" deposit type where Co is reported. In Residual deposits, there is 100% of chance to meet Ni when Co is also reported etc.

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	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

Table 2 : Multi-element signatures of the selected Co-rich metallogenic families.

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Finally, all the occurrences/deposits in the database were scored according to their similarity to the multi-element signature of the metallogenic family they belong to using the following formula:

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

where ”binary presence value” takes the value of 1 if the scored deposit contains the commodity or zero if it does not contain it.

In order to compare scores of all deposits, they were weighted by their ER of the metallogenic family they belong to. Thus, for the cobalt, a weighted score for each of the 2299 occurrences/deposits related to the four selected metallogenic families (i.e., “Mafic-Ultramafic”, “VMS”, “Orogenic” and “residual” deposit types) were calculated.

The DBQ method is not spatial as the geographic location of an occurrence has no influence on its score, but the results can be mapped, using geographic coordinates of ranked occurrences and deposits (Bertrand et al., 2017).

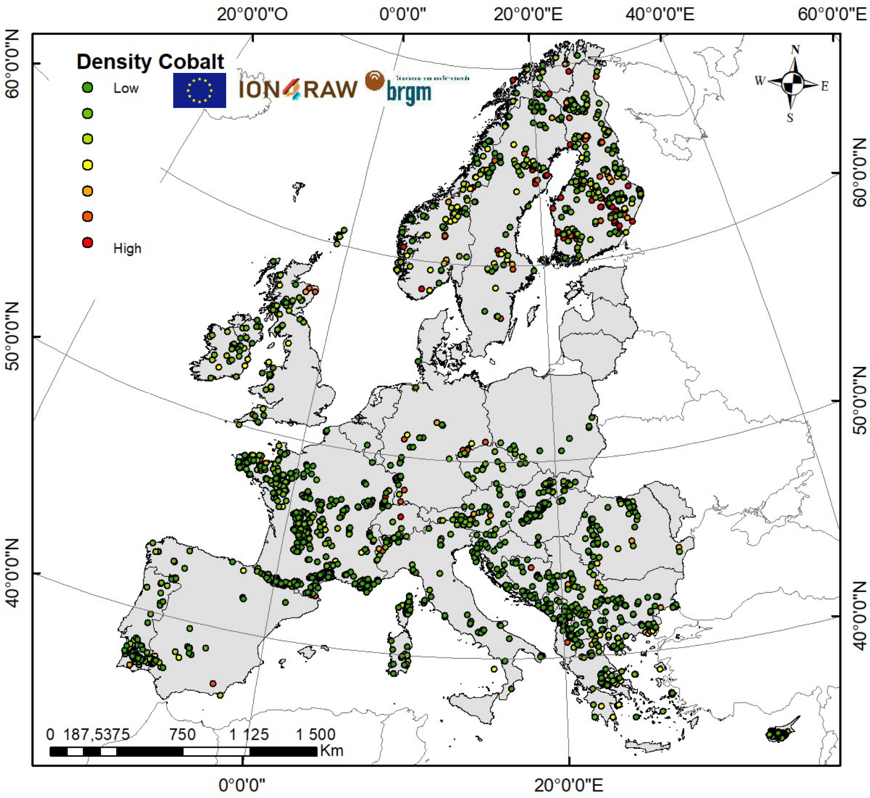

Figure 4 : Cobalt density distribution in Europe

Using the ArcGIS software, for each targeted element, a kernel density calculation was performed on the weighted scores in order to identify metal endowment neighbourhood (figure 4). The kernel density calculation is a statistical tool which estimates the probability density function of a random variable.

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The map obtained in the case of Co is presented in Figure 5. This map indicates few areas of potential interest for Co: 1) mafic or ultramafic occurrences (e.g., 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 (i.e., ophiolites) in Cyprus.

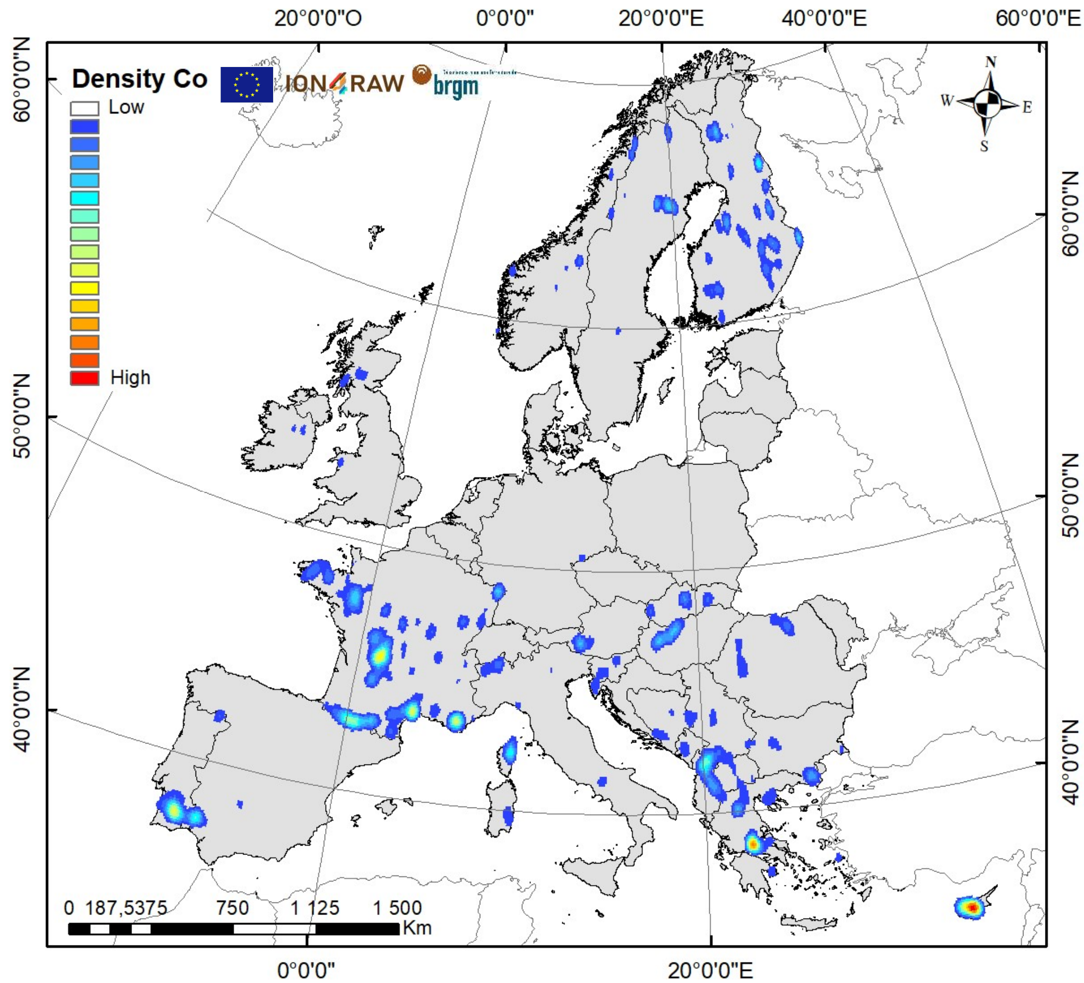

Figure 5 : Map of kernel density of weighted Co scores in Europe by DBQ geostatistical method.

This process was applied to all the targeted by-products of the ION4RAW project. The kernel density maps are presented in Appendices.

2.3 METALLOGENIC FAMILY SIGNATURE

After applying the DBQ method to each targeted by-products in the scope of the project, it appeared that most of them showed high ER values for similar metallogenic families. Thus, authors have chosen to classify the metallogenic families in function of the number of targeted by-products in which they are represented and in function of their ER values (Table 3). This is represented in the "TOTAL" column of the Table 3.

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	Sb	Bi	Te	Pt	Co	Mo	Ge	Se	Re	In	TOTAL
Epithermal	3,37	1,03	8,68				1,39	5,21		1,82	6,00
Igneous Intermediate			2,73			22,35		16,37	50,92	2,46	5,00
Igneous Replacement		2,67	1			1,85		4,01		2,71	5,00
Orogenic Gold	2,9	3,42	3,61		1,84			1,44			5,00
Mafic or UltraMafic		1,69	2,86	12,16	8,1						4,00
SandStone and ShaleHosted				1,44		1,01		2,2	5,86		4,00
Igneous Felsic		2,97				3,47				4,14	3,00
VMS					1,89		2,02			1,13	3,00
Residual deposits					1,2			1,35			2,00
Base metals veins	2,34						1,36				2,00
Mafic Intrusion				3,57							1,00
Carbonate Hosted							4,41				1,00
Placers				5,09							1,00
Alkaline & Peralkaline intrusions											0,00
IOCG											0,00
Pegmatites											0,00
Sedimentary deposits											0,00

Table 3 : ER values of the targeted by-product as a function of their metallogenic families.

For instance, "Epithermal" deposit type shows high ER values for six target by-products metals (Sb, Bi, Te, Ge, Se and In) whereas "Sedimentary" deposit does not represent a targeted deposit type for these metals (i.e., no targeted metal was identified in this deposit type).

In that respect, "Epithermal", "Igneous intermediate", "Igneous replacement", "Orogenic gold", "Mafic to ultramafic" and "Sandstone" deposits represent favorable deposit types for prospection of the ION4RAW targeted by-products as they contains at least 4 out of the 10 targeted elements of the project.

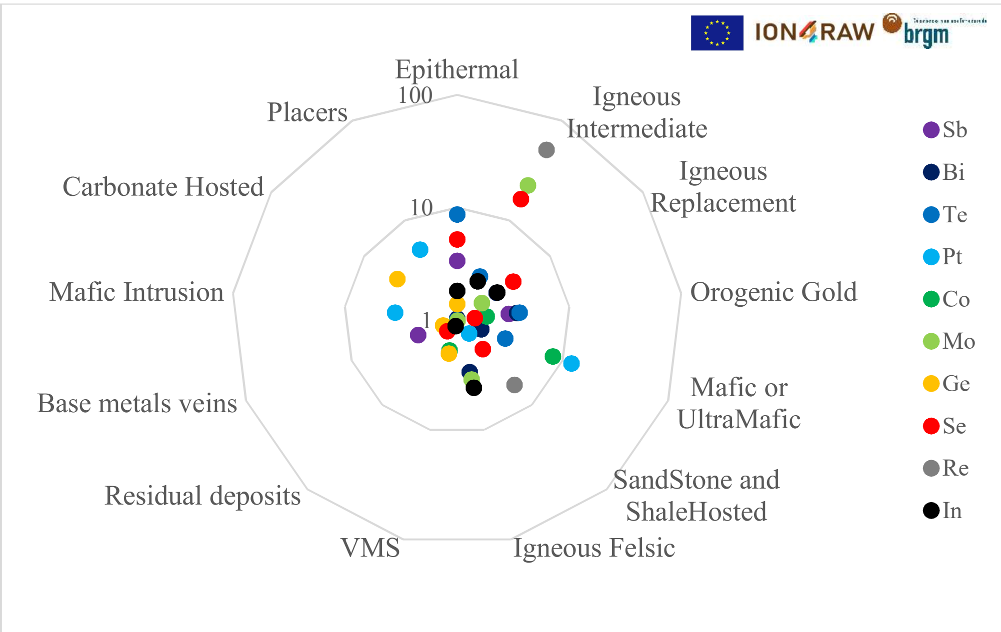

Figure 6 : Spider plot of number of by-products favorable occurrences in function of their metallogenic family.

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For this purpose, database of each element score where merged in ArcGis. Thus, a database of only occurrences in common of each element score considered (e.g., VMS: Co, Ge, In) is obtained. Kernel density maps were then drawn on ArcGis regarding these metallogenic families. Note that the "Sandstone and shale-hosted" deposit type was not considered in this study as it represents erosion product of the other deposit types and instead, "Igneous felsic" deposit type was included in the calculation.

2.3.1 Epithermal sites

As depicted in Figure 7, the epithermal favorable sites regarding the combination of the weighted Sb, Bi, Te, Ge, Se and In scores are located mainly in the Carpathian area, in Italy, in Corsica and in Cyprus (indicated by red dashed lines in Figure 7). Few small and isolated spots in France, Spain, Portugal and Finland may not be representative of typical epithermal areas and may be related to an artefact of the database.

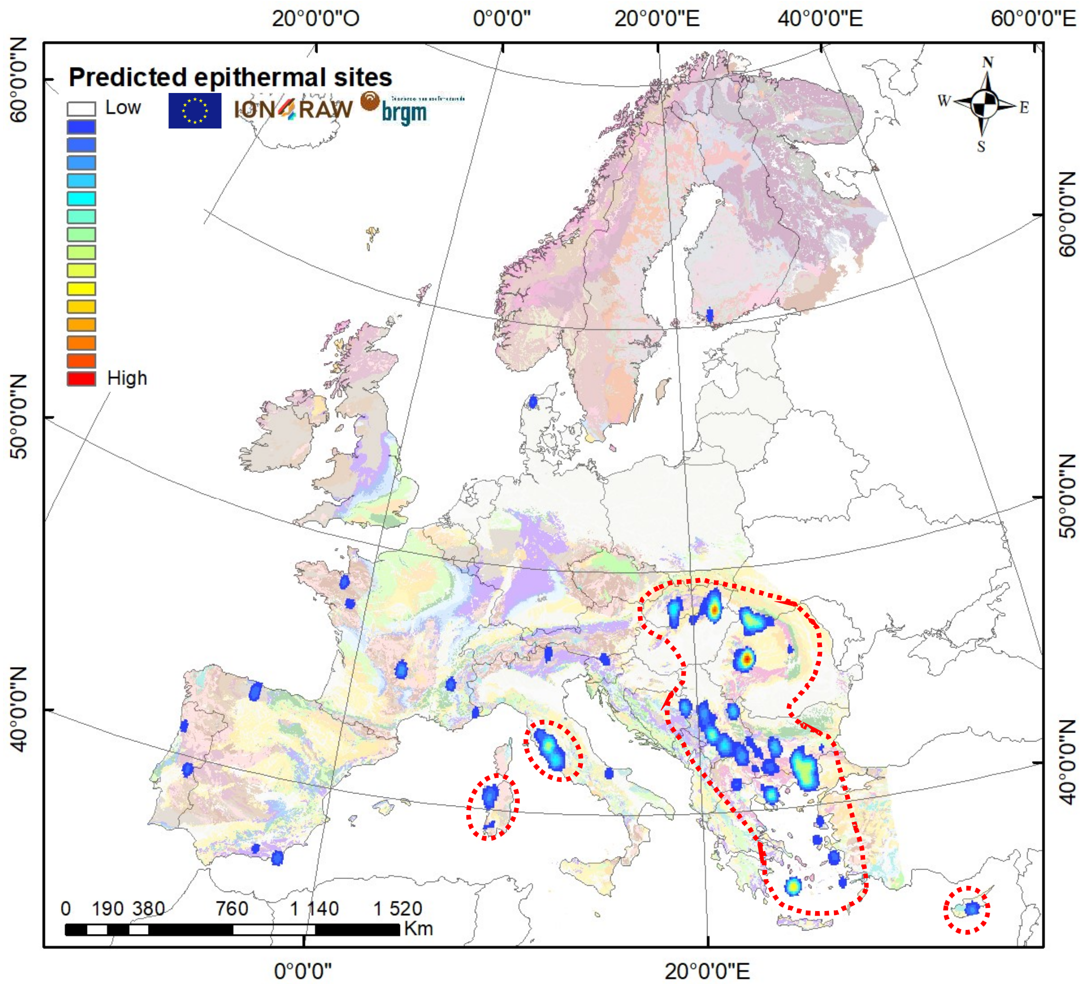

Figure 7 : Kernel density of the predicted epithermal sites in Europe based on combination of weighted Sb, Bi, Te, Ge, Se and In scores.

2.3.2 Igneous intermediate sites

The intermediate igneous favorable sites regarding the combination of the weighted Te, Mo, Se, Re and In scores are mainly located in the Carpathian area and Corsica (red dashed lines, see Figure 8).

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Similar regions are highlighted with the epithermal favorable study. This metallogenic family might represent rocks such as diorite and may be related to porphyry deposits.

Few spots are observed in the northern part of UK, which may be related to diorite emplacement during the Caledonian.

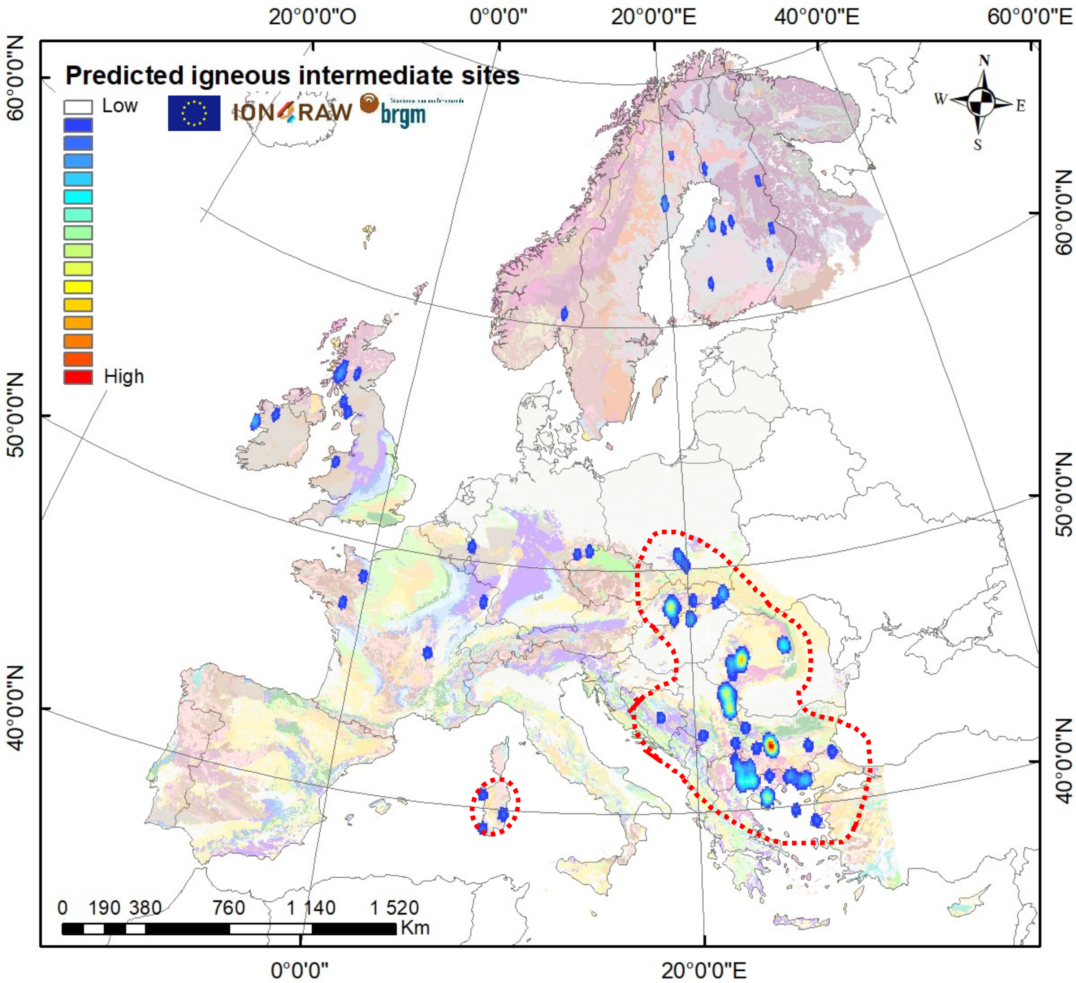

Figure 8 : Kernel density of the predicted igneous intermediate sites in Europe based on combination of the weighted Te, Mo, Se, Re and In scores.

2.3.3 Igneous replacement sites

Only a few areas are highlighted through the combination of the Bi, Te, Mo, Se and In scores (see Figure 9) and this metallogenic family includes skarn deposit types (circulation of magmatic fluids in carbonate host-rocks). This type of deposit can be illustrated in the southern part of France, in Spain, in Italy and in the Carpathian area.

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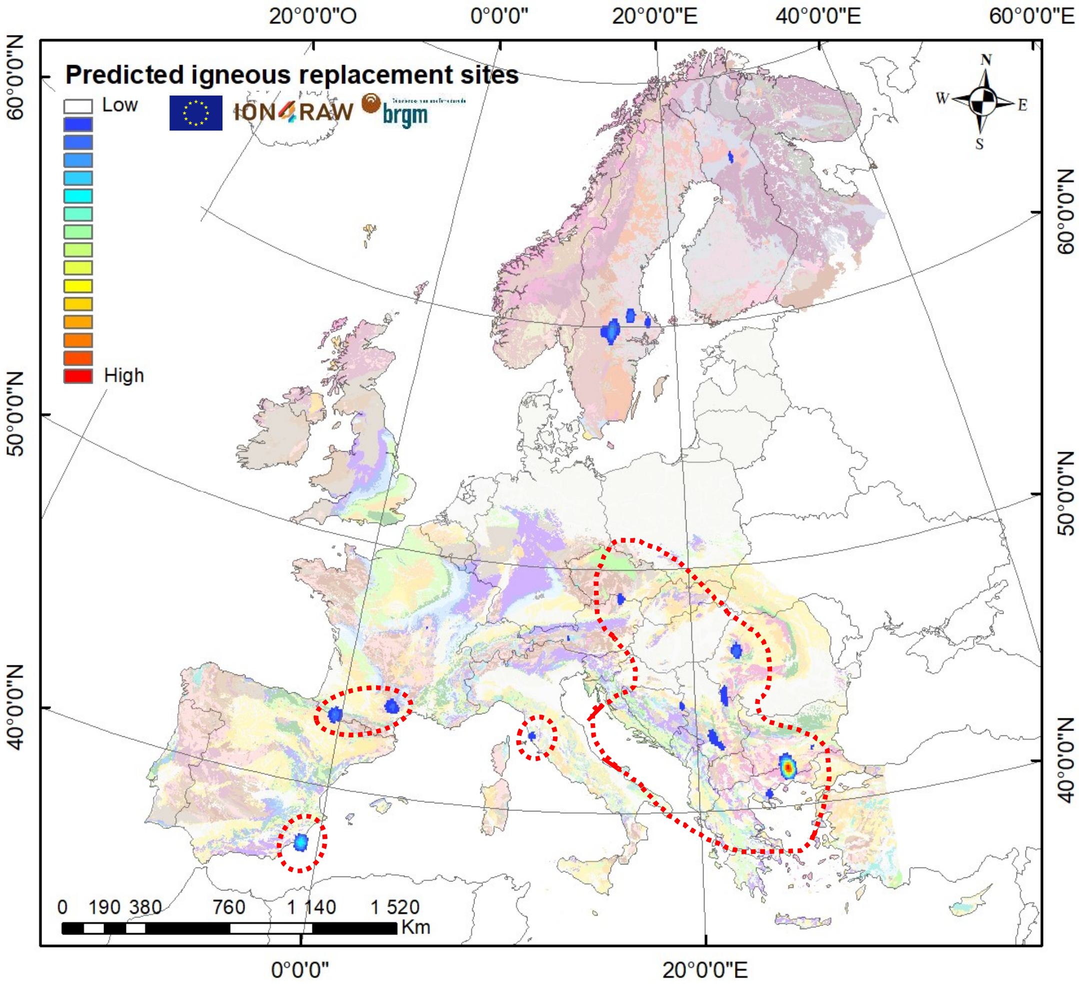

Figure 9 : Kernel density of the predicted igneous replacement sites in Europe based on weighted Bi, Te, Mo, Se and In scores.

2.3.4 Orogenic sites

As depicted in Figure 10, the orogenic favorable sites regarding the combination of the weighted Sb, Bi, Te, Co and Se scores are mainly located in the Armorican Massif and in the western part of the Massif Central in France as well as along the eastern Variscan orogeny (e.g., Austria). Few areas are also pointed out in Finland within the Precambrian basement. Few small spots in UK and Greece are also indicated.

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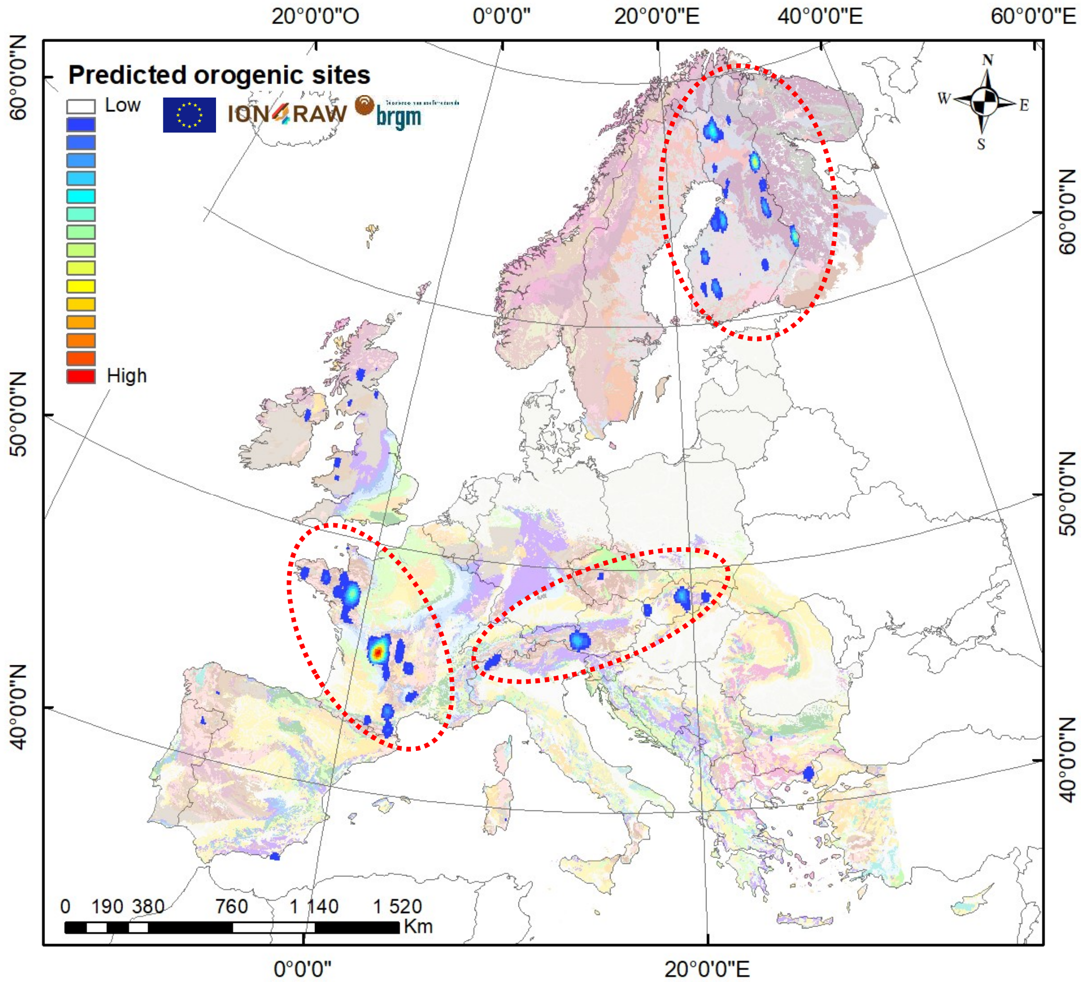

Figure 10 : Kernel density of the predicted orogenic gold sites in Europe based on weighted Sb, Bi, Te, Co and Se scores.

2.3.5 Mafic to ultramafic sites

The mafic to ultramafic favorable sites regarding the combination of the weighted Bi, Te, Pt and Co scores are well represented through all the European countries (see Figure 11). The areas of interest are mainly related to: 1) the Fennoscandian Shield; and 2) the ophiolites occurrences in the Greece, Serbia and Kosovo area.

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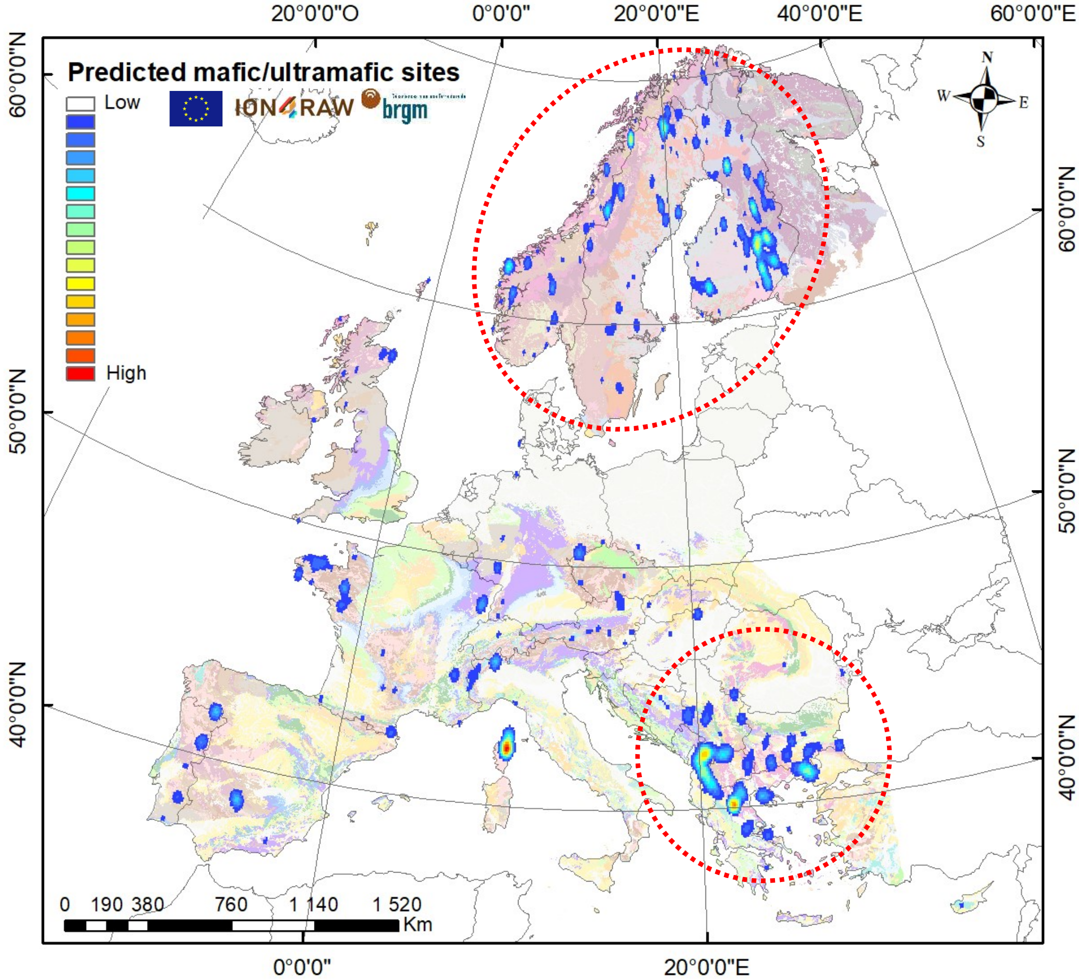

Figure 11 : Kernel density of the predicted mafic to ultramafic sites in Europe based on weighted Bi, Te, Pt and Co scores.

2.3.6 Igneous felsic sites

Finally, the igneous felsic favorable sites regarding the combination of the weighted Bi, Mo and In scores are mostly represented in Spain, in France and in UK within the St Austell area, both related to the Variscan Orogeny (see Figure 12). This metallogenic family reflects pegmatite and granite occurrences. Note that a great effort has been made recently on pegmatite identification through the Variscan Orogeny especially in France and in Spain (e.g., Gourcerol et al., 2019).

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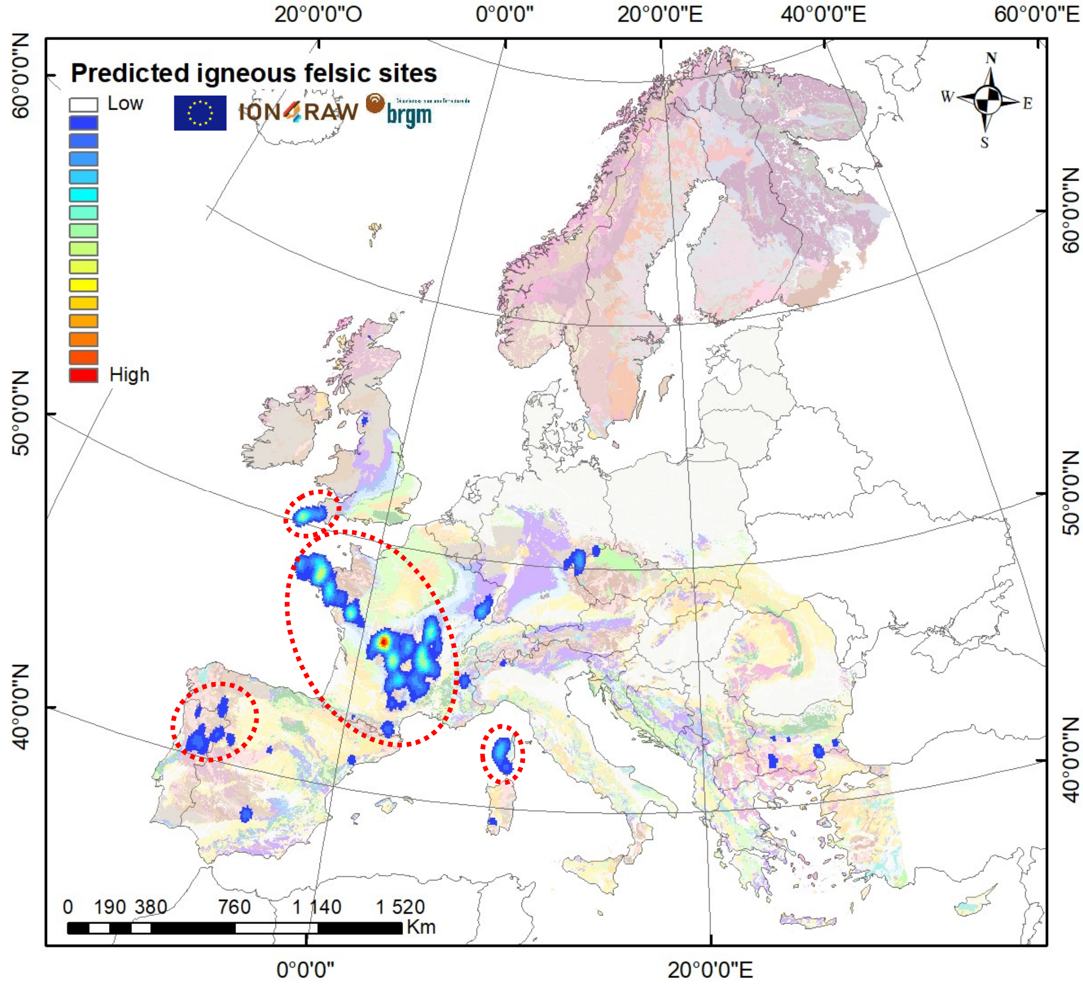

Figure 12 : Kernel density of the predicted igneous felsic sites in Europe based on weighted Bi, Mo and In scores.

2.4 LIMITATIONS OF THE DBQ METHOD

Despite that DBQ method highlights potential areas for prospection of selected elements or deposit types, it also shows few limitations which have to be known to correctly interpret the results.

The first point to care about is the possible impact of spatial heterogeneity of data that may overestimate some areas and underestimate others. For instance, the variscan segments in France appears highly favorable and it definitely is an interesting prospective area. One should keep in mind though that data coverage for France in the ProMine mineral deposit database is high and that may lead to slightly exaggerated highlight of the favorable areas on a kernel density map, compared to other countries where data is scarcer.

Another important point is, as for all mineral prospectivity approaches, the quality of input data. The reliability of the prospectivity assessment directly derives from the quality of the input dataset. In the case of the DBQ approach, 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, we believe that the ProMine database, even though it necessarily misses some information (either because it is not available or unknown), is the best available for DBQ assessment in Europe at continental scale.

The last important point is to keep in mind that the DBQ approach, as for any mineral prospectivity assessment, is an upstream phase of mineral exploration. It has been designed to assess geological

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favourability for undescribed by-products in known deposits of common metallogenic types. The results of DBQ assessments have to be confirmed by exploration work and they do not prejudge the economic viability of any discovery.

3 Peruvian dataset

Cumbres Exploraciones S.A.C and the BRGM have produced an update of the database for mainly Peruvian Au-Ag-Cu-Zn-Pb deposits/occurrences despite that few Fe-Li-U-P-W-Sb-Sn occurrences are reported. This update has led to an identification of 404 deposits/occurrences whereas 512 records were initially identified (Figure 13). The main reason for having less records is that the original database had 155 records that could not be verified through name, location with the current public and private information. Some others were repeated or are part of currently producing mining districts. This means that 317 original records were validated and 87 additional records were added mainly of newly producing mines and advanced stage projects

Authors have chosen not to apply a DBQ method on the dataset as only a few information were collected on the data. Indeed, the occasional metals such as Ge, In, Co etc. were not systematically reported and only a few element associations have been identified for each site. Thus, the DBQ approach was impossible to conduct compared to the European database.

Moreover, we can also mention an official map (INGEMMET, 2017) that presents most of the deposits considered for this project. It might be considered as a comparable contribution.

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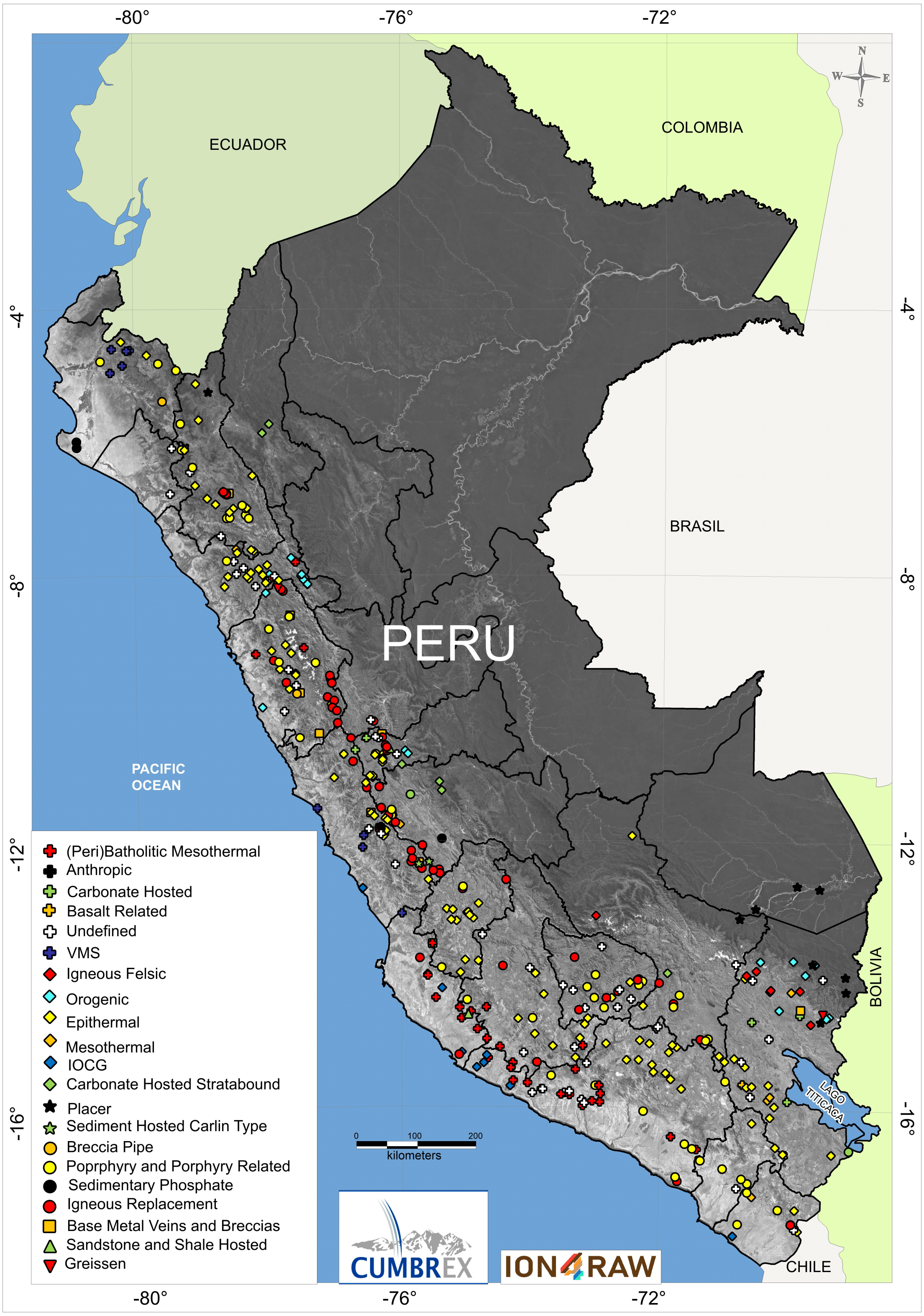

Figure 13 : Update of the Peruvian dataset after a review conducted through the ION4Raw project. This database included 404 records.

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4 CONCLUSIONS

The DBQ approach allows determination of several areas of great interest for prospection of the targeted by-products of the European-Peruvian ION4RAW project (H2020 program). It allows potential identification of commodities, which are either rarely reported in analyses or through divers permit/deposit reports by mining companies.

These areas can be also studied to identify major mine sites which might be interested to apply the process, which would be developed through the study.

For Peru, an updated database offers a great dataset of the sites, which might be interested by the process developed through ION4RAW.

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5 BIBLIOGRAPHY

Billa M., Bertrand G., Cassard D. 2016. Méthode de sélection par requête et notation d'indices à métaux critiques (Ge, Ga, In, Ta, Co) non identifiés à partir d'une base de données gîtologique (ProMine). BRGM report RP-65590-FR (in French).

Bertrand G., Cassard D., Billa M., Angel J.M., Tertre F., Tourlière B. 2017. Predictive assessment of rare earth occurrences in Europe using the Database querying method; ERES 2017, the 2nd conference on European rare earth resources, 28-31 May, Santorini, Greece.

Cassard D., Bertrand G., Billa M., Serrano J.J., Tourlière B., Angel J.M., Gaál G. 2015. ProMine Mineral Databases: New Tools to Assess Primary and Secondary Mineral Resources in Europe. In P. Weihed (ed.), 3D, 4D and Predictive Modelling of Major Mineral Belts in Europe, Mineral Resource Reviews, 9-58.

Gourcerol B., Gloaguen E., Melleton J., Tuduri J., Galiegue X. 2019. A re-assessment of European lithium resource potential – A review of lithium resources and metallogeny. Ore Geology Reviews, v. 109, 494-519.

INGEMMET, 2017. Peruvian Map of the mines and mining projects.

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6 APPENDICES

6.1 Tellurium

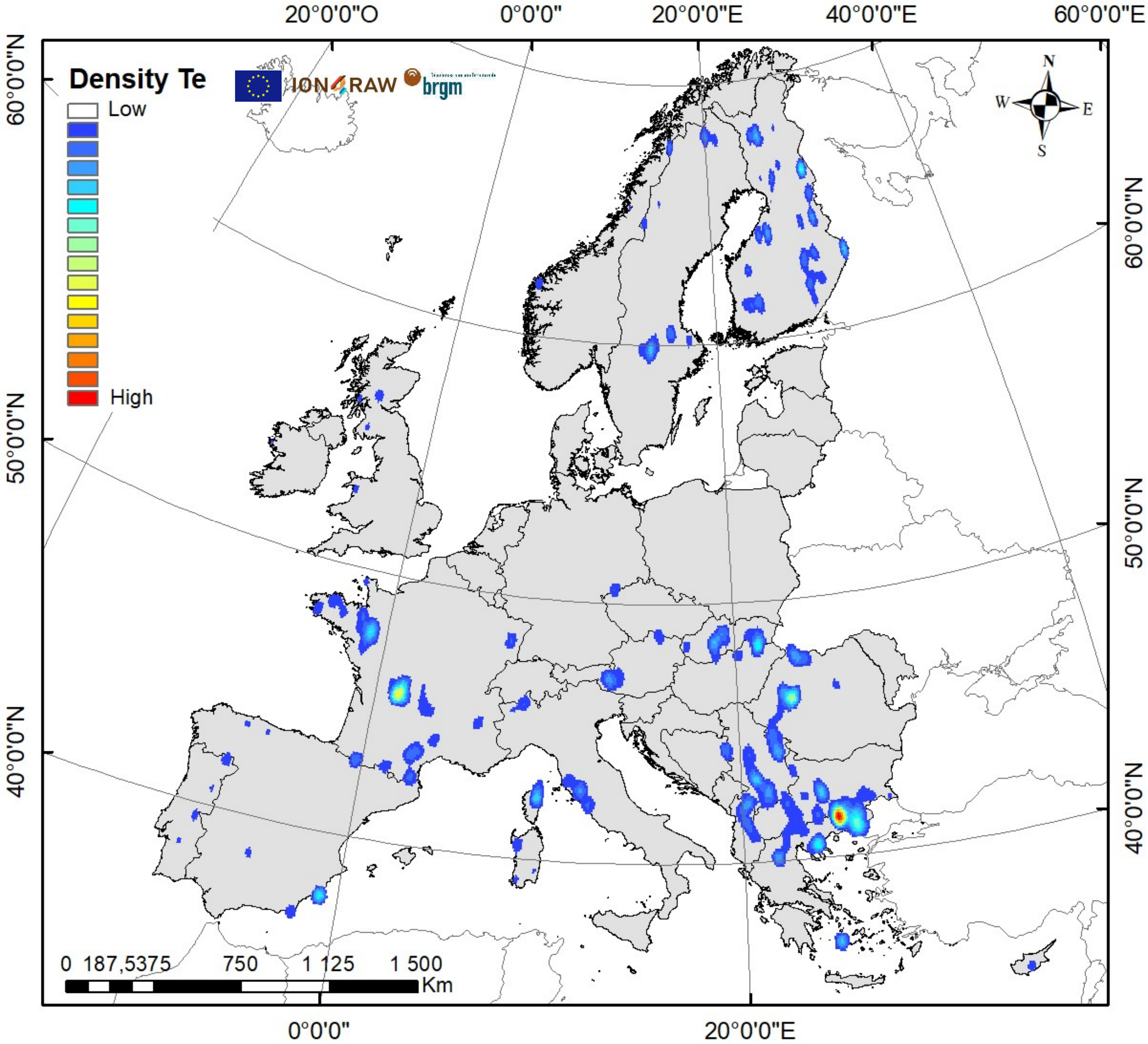

Figure 14 : Map of kernel density of weighted Te score in Europe by DBQ geostatistical method.

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6.2 Bismuth

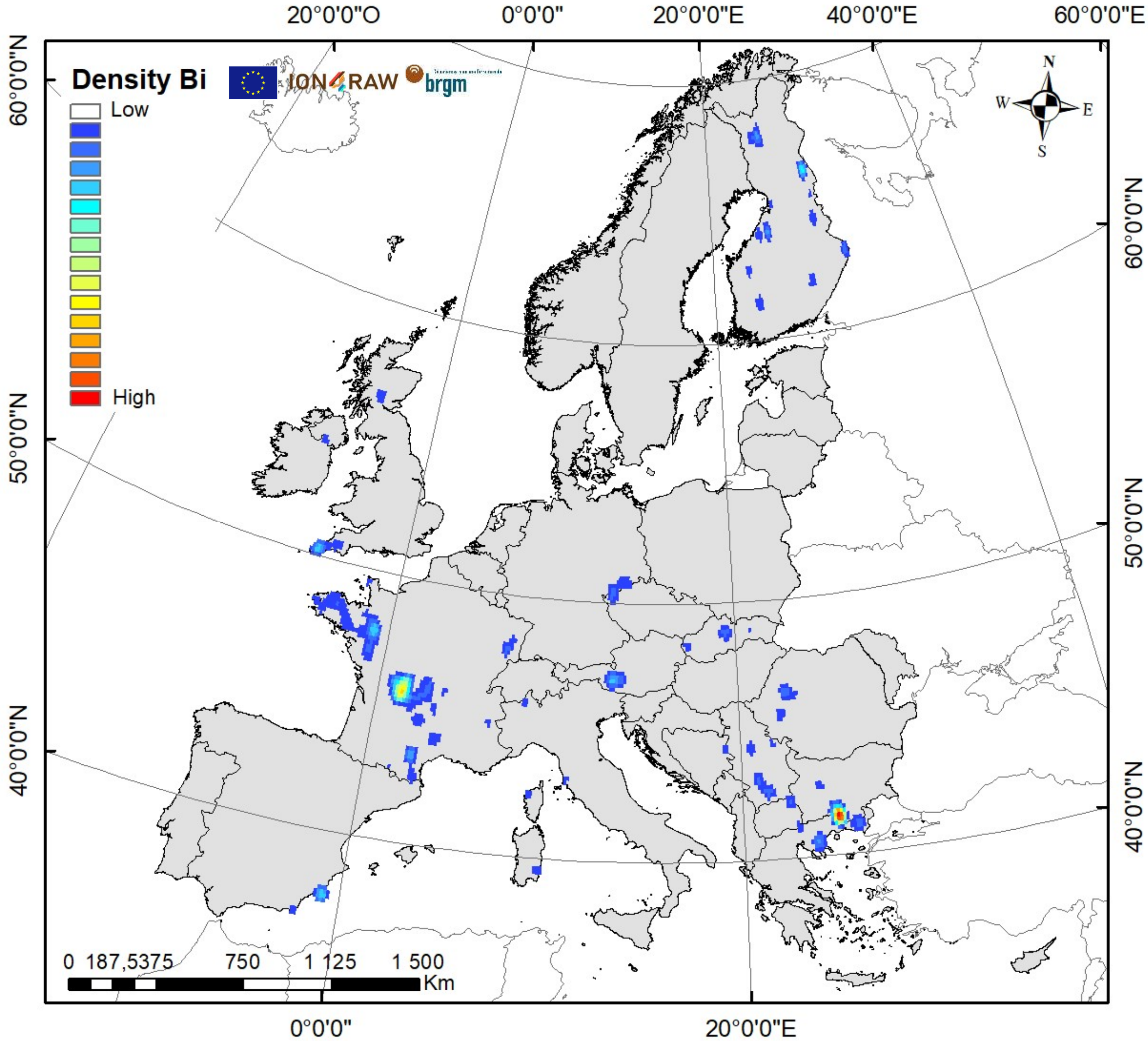

Figure 15 : Map of kernel density of weighted Bi score in Europe by DBQ geostatistical method.

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6.3 Rhenium

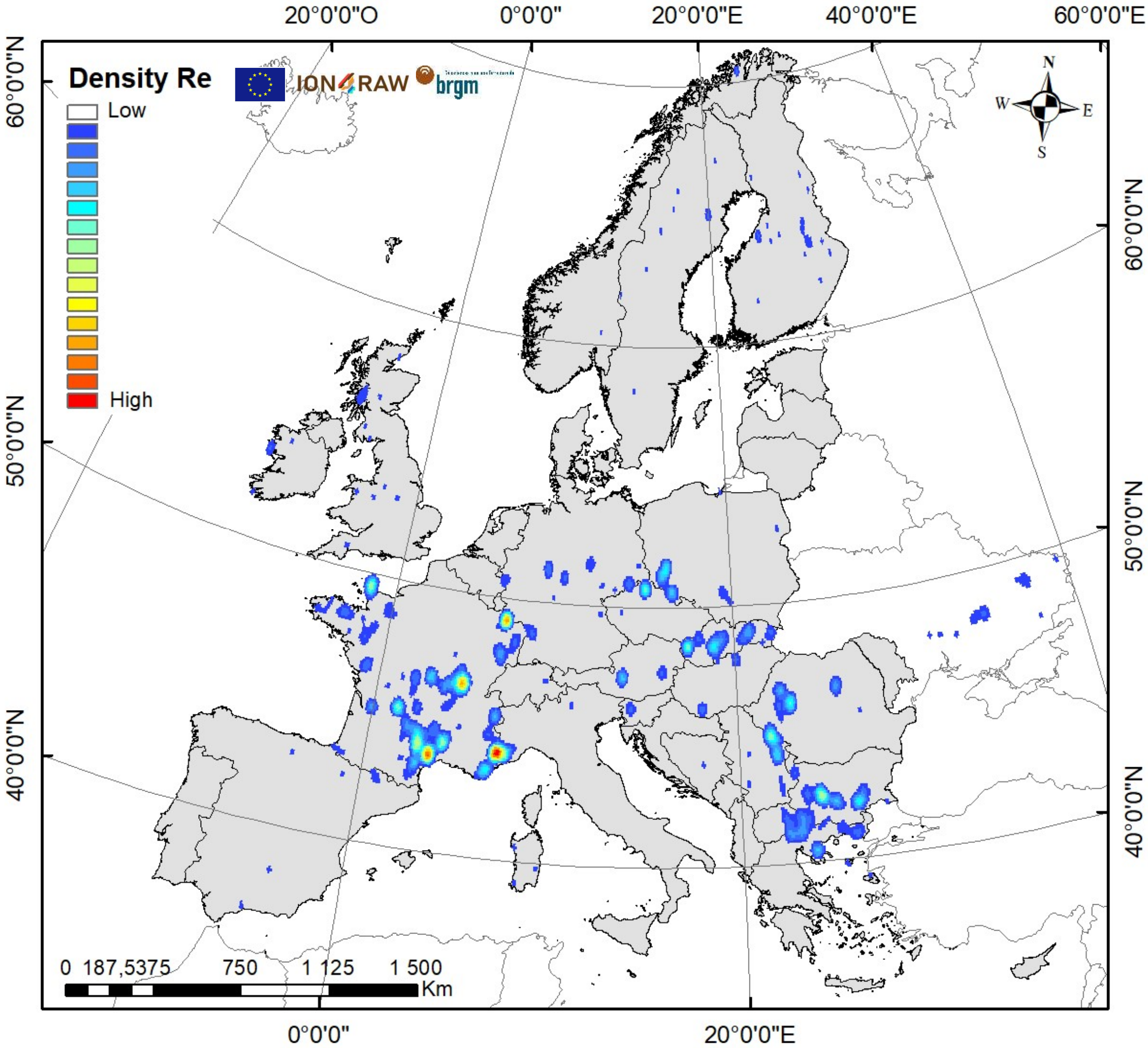

Figure 16: Map of kernel density of weighted Re score in Europe by DBQ geostatistical method.

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6.4 Molybdenum

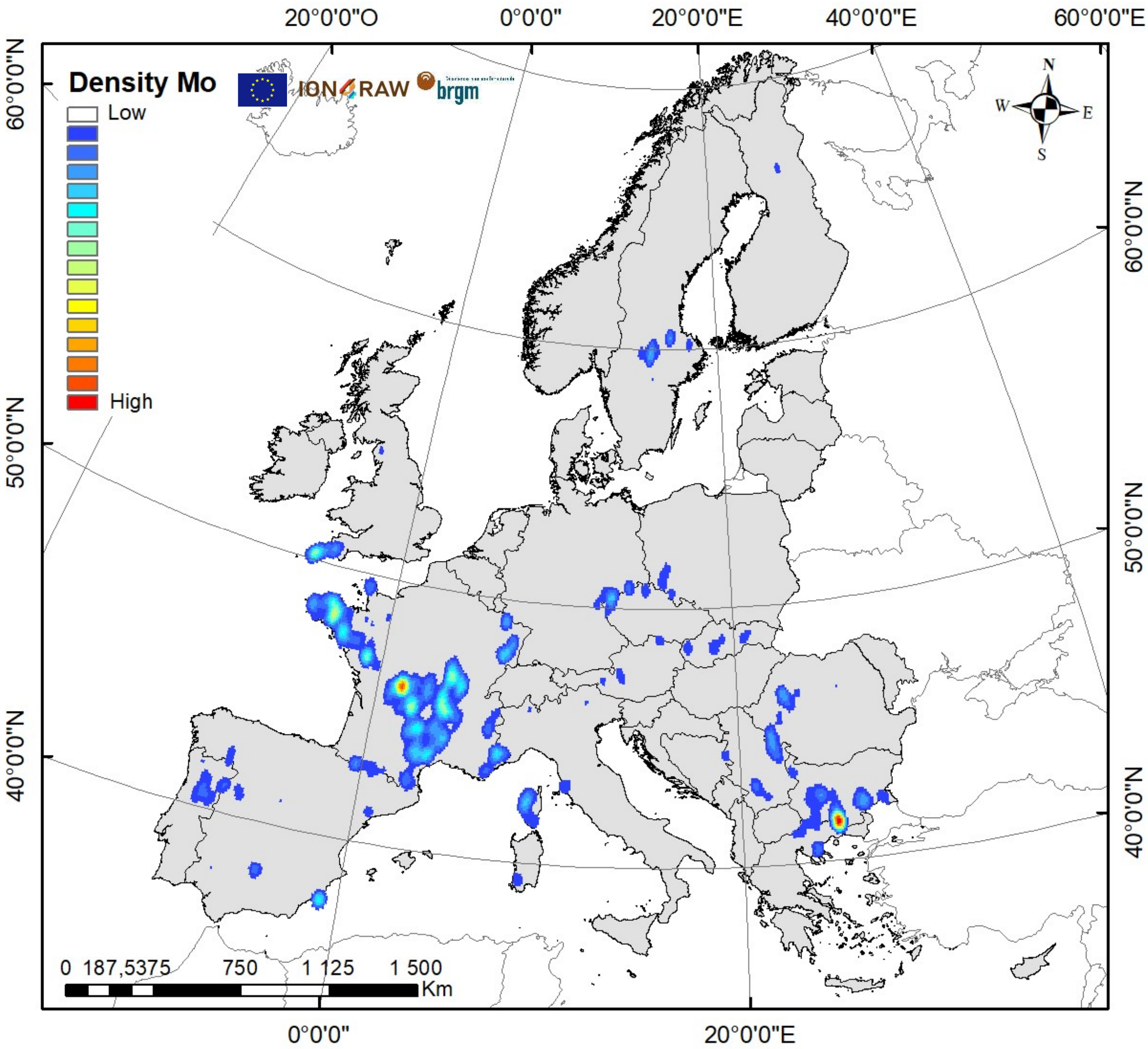

Figure 17 : Map of kernel density of weighted Mo score in Europe by DBQ geostatistical method.

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6.5 Platinum

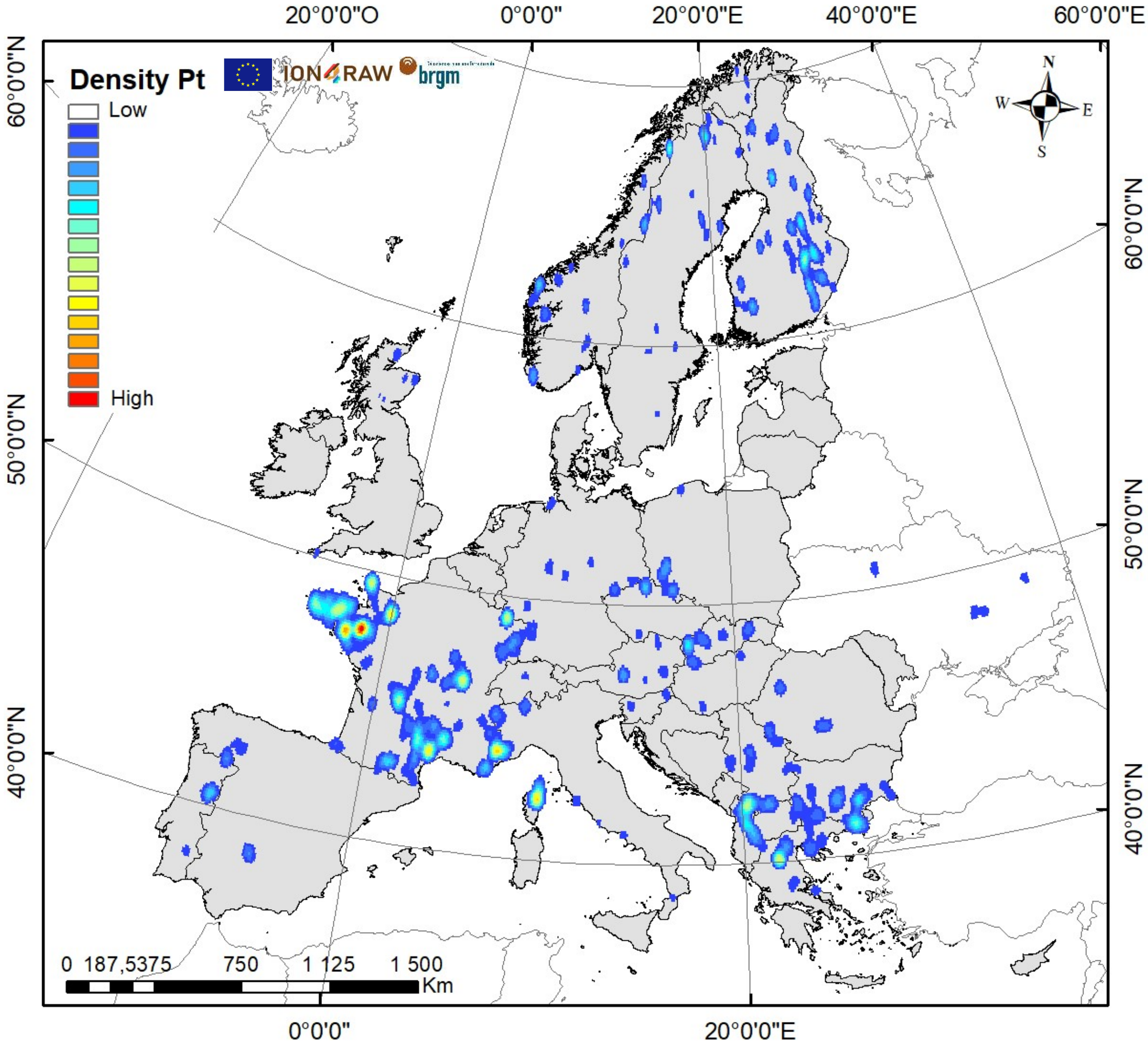

Figure 18 : Map of kernel density of weighted Pt score in Europe by DBQ geostatistical method.

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6.6 Antimony

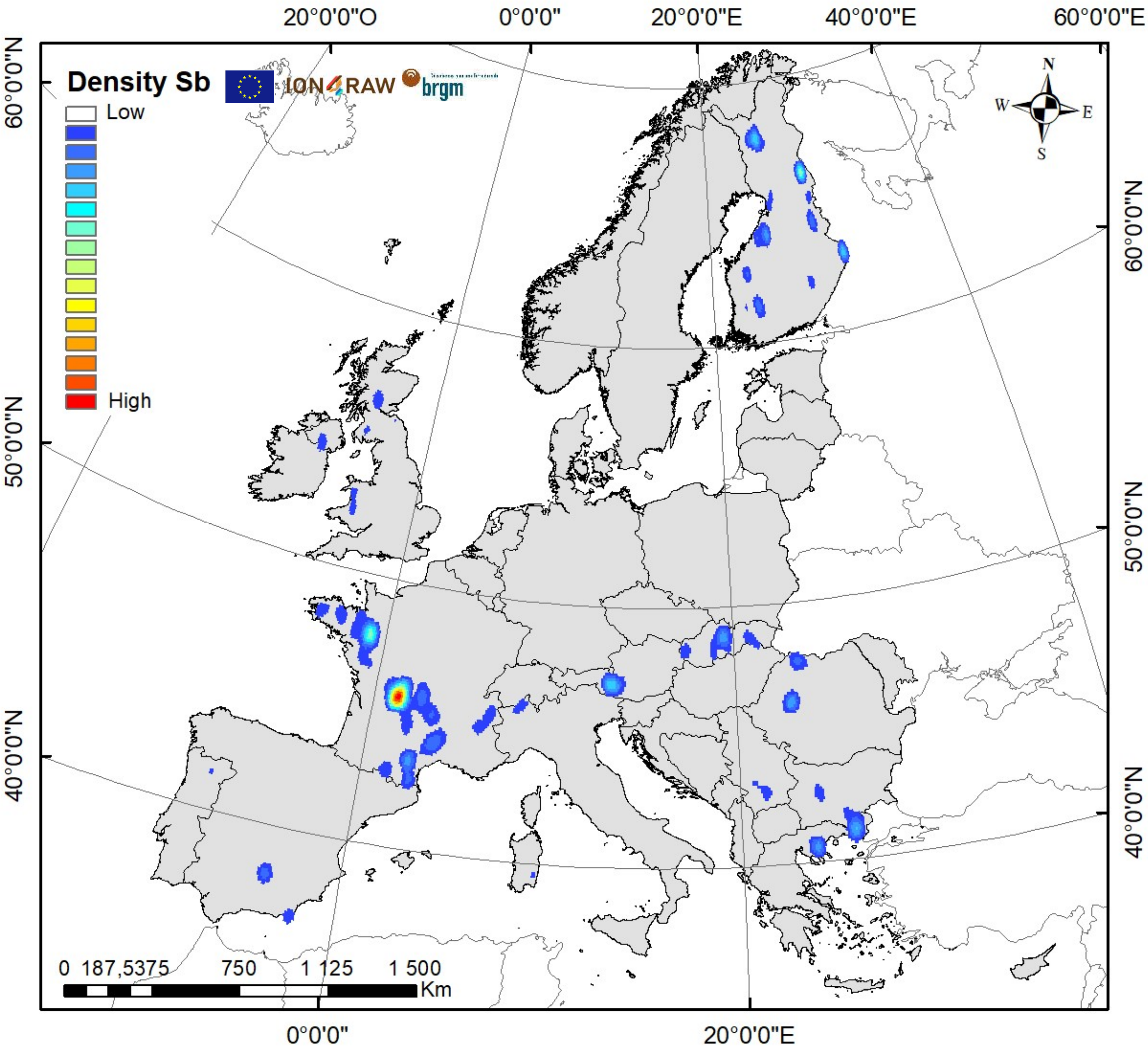

Figure 19 : Map of kernel density of weighted Sb score in Europe by DBQ geostatistical method.

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6.7 Germanium

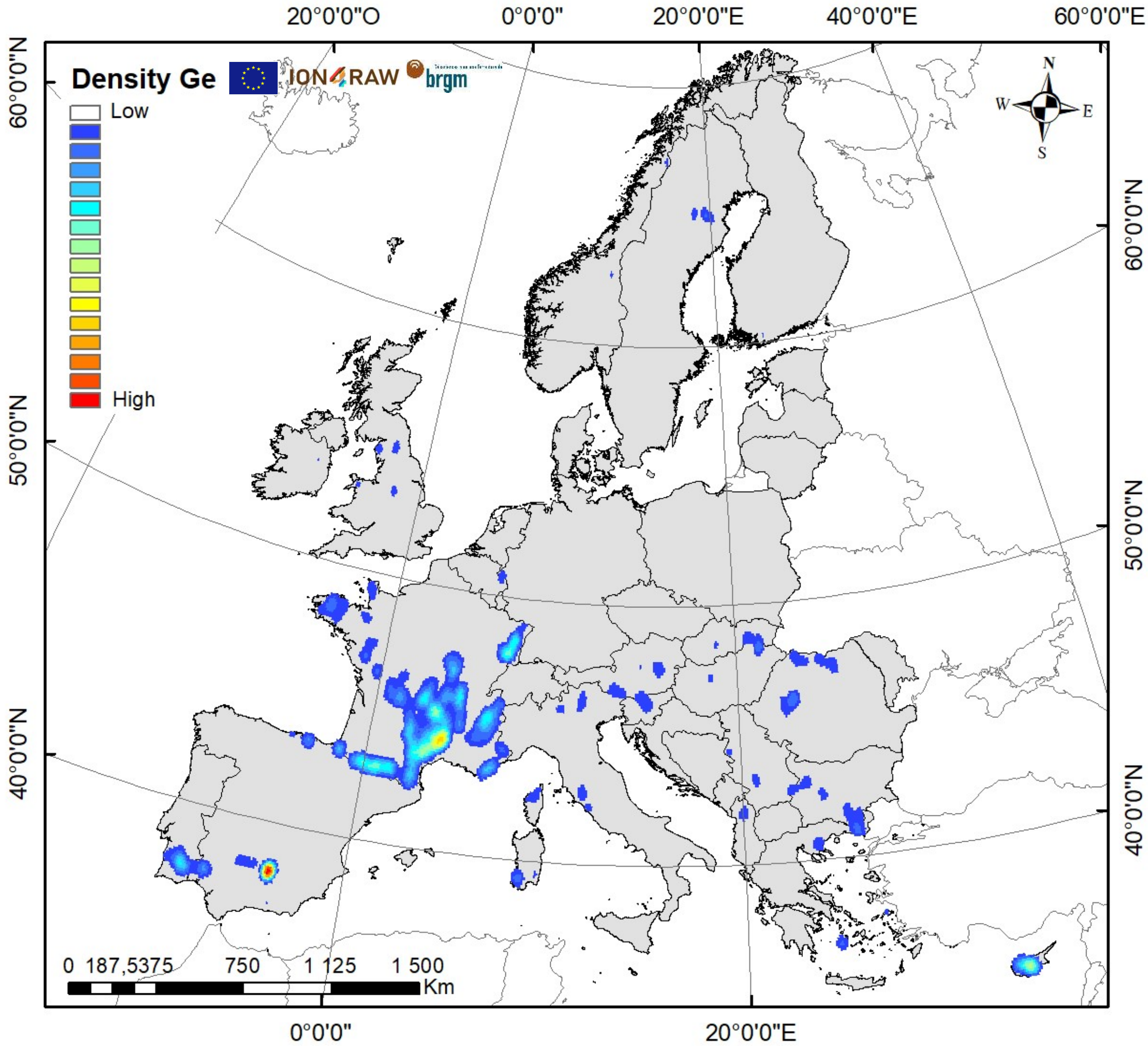

Figure 20 : Map of kernel density of weighted Ge score in Europe by DBQ geostatistical method.

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6.8 Selenium

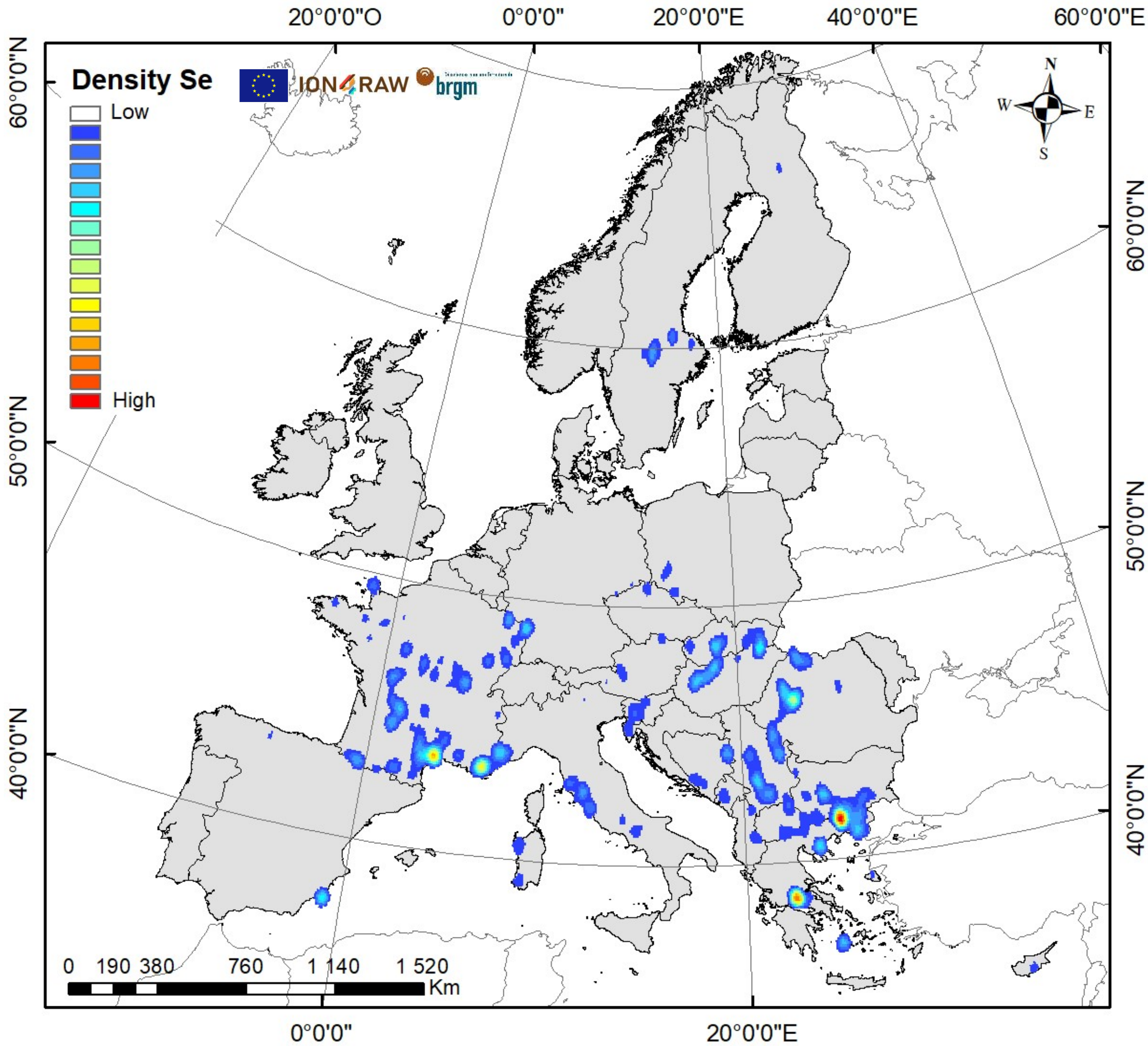

Figure 21: Map of kernel density of weighted Se score in Europe by DBQ geostatistical method.

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6.9 Indium

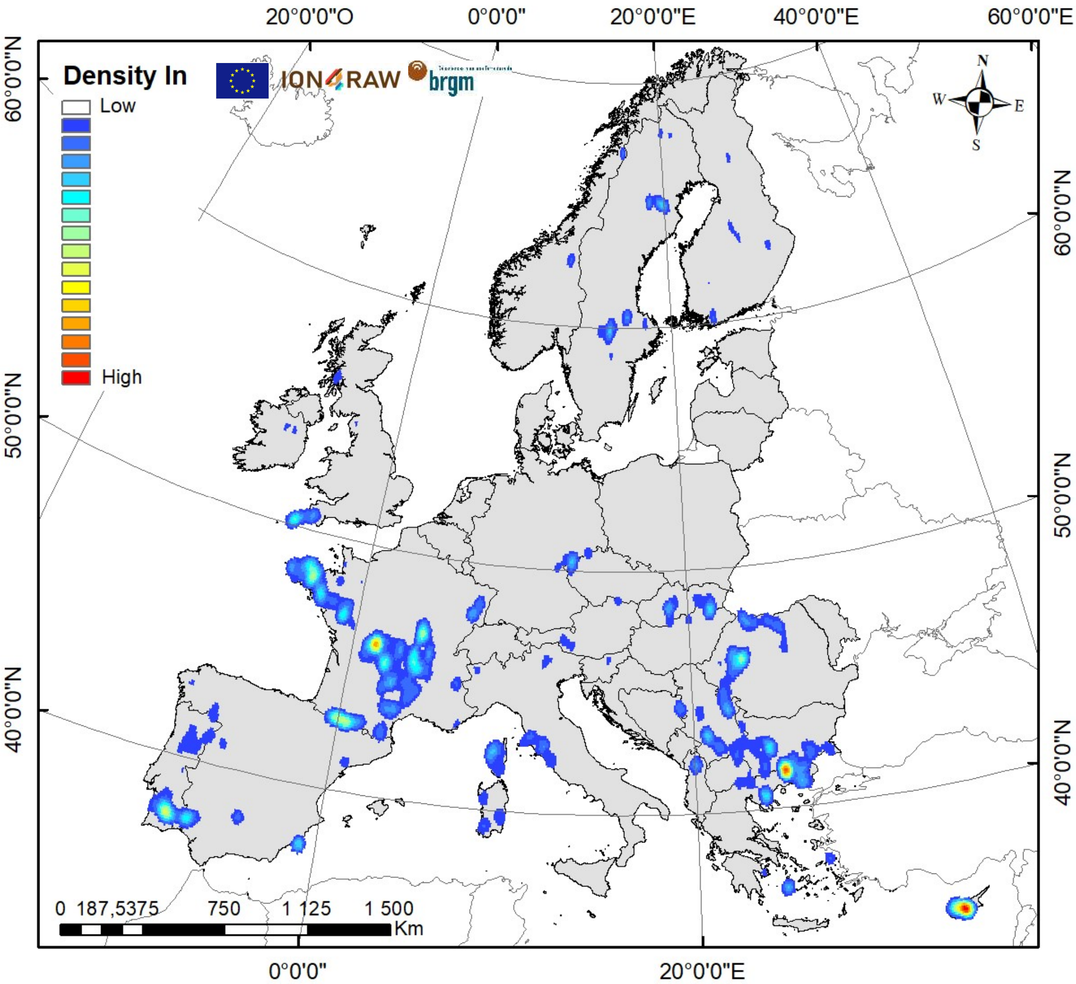

Figure 22: Map of kernel density of weighted In score in Europe by DBQ geostatistical method.

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