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Overview of critical metals and minerals in Norway

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Geology for society

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Summary:

This report is an English version of NGU report 2023.021, with updated information, where this is available, is included.
Every three years since 2011, the European Commission has assessed the supply risk and economic importance of raw materials required for the operation and development of industry in Europe. The results are presented in lists of "critical raw materials," which include the minerals and metals that have the highest supply risk and greatest importance for the European economy. In 2023, the European Commission also introduced the term "strategic raw materials" based on expected future production and demand. The EU's lists of critical and strategic raw materials for 2023 encompass 34 minerals and metals and form the basis for the review presented in this report.

Norway has a primary production of critical raw materials and a very important downstream production of critical metals, partly based on Norwegian mineral production. The potential for further Norwegian primary production is significant, but an extensive geological dataset is necessary to clarify the opportunities and facilitate targeted industrial exploration.

Chemical data from known mineral registrations constitute an important knowledge base for assessing the potential for critical and strategic metals and minerals in Norway. In this report, chemical analyses of metal and mineral registrations (including deposits) in NGU's mineral resource databases are compiled and presented in maps as a tool for better understanding the Norwegian potential for critical raw materials. The foundation for this compilation is more than 9,000 analyses from more than 2,100 surveyed registrations of metals and minerals.

The report is part of NGU's mission related to the government's 2023 mineral strategy for making data accessible and facilitating exploration for the industry and the public.

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Disclaimer

This report compiles analytical data that has been collected over a period of more than 30 years, with a large difference in analytical methods as well as by a number of different investigators. A handful of Norwegian deposits are currently under development, and this report is based on the information available at NGU at the time of compilation. NGU accepts no liability to actions third parties take when using information in this report.

Executive summary

Every three years since 2011, the European Commission calculates the supply risk and economic importance of raw materials needed by the EU for the operation and development of industry in Europe. The results are presented in lists of 'critical raw materials', which include the minerals and metals with the highest supply risk and greatest importance to the European economy. In 2023, the European Commission also introduced the term "strategic raw materials" based on expected future production and needs. The EU's lists of critical and strategic raw materials for 2023 include 34 minerals and metals and are the basis for the review of critical raw materials in Norway presented in this report.

Norway has a primary production of critical raw materials and a very important downstream production of critical metals, partly based on Norwegian mineral production. The potential for additional Norwegian production is considerable, but comprehensive datasets and geological understanding are needed to clarify the opportunities and facilitate targeted industrial exploration. Chemical analyses from known mineral deposits constitute an important knowledge base for assessing the potential for critical and strategic metals and minerals in Norway.

In this report, we have compiled chemical analyses of metal and mineral occurrences and deposits from NGU's resource databases and present these data on maps as a tool for a better understanding of where in Norway the potential for the different critical raw materials is. The basis for this compilation is over 10000 analyses from more than 2100 surveyed occurrences and deposits. The report is a part of NGU's mission related to the government's mineral strategy 2023 for making data available and facilitate for the exploration industry and the public

This report is an English translation of report NGU 2023.021.

1. INTRODUCTION

NGU has been collecting data on the occurrences of metals and minerals in Norway's bedrock for more than 30 years. These data have been systematized and archived in NGU's mineral resource databases (https://geo.ngu.no/kart/mineralressurser_mobil/). Based on the data in these databases, this report provides an overview of where critical metals and minerals occur in Norway. The report is a response to the government's mineral strategy (2023) and the strategy's requirements for prioritizing geological surveys aimed at critical raw materials through NGU's allocation letters for 2023 and 2024. Both in Europe and in Norway, governments have prioritized investigations of critical raw materials with a view to increasing domestic production, and for NGU, this will be a prioritized task for many years to come. This report is an English translation of NGU report 2023.021. The raw data used in the tables and figures are identical.

2. BACKGROUND INFORMATION

The rapid development in technological innovation that the world has seen in recent decades has only been possible because an increasing number of metals and other raw materials have been used. However, there is a growing concern about the security of the supply of many of these raw materials. This is not a new situation; for several centuries, there have been periods of concern about the availability (and future supply) of important raw materials and products made from them. In the mid-19th century, Jevons (1866) warned that Great Britain could run out of coal due to the rapid increase in coal-driven industry. During the Cold War, there were concerns related to the Soviet Union's dominance in the production of many critical and strategic materials and that this could result in a resource war (Szuprowicz, 1981). During the same period, South Africa dominated world production of platinum group metals, chromium, vanadium, and manganese while the country was under a trade boycott from many countries due to apartheid.

Since the beginning of the 2000s, market liberalism and monopolization combined with geopolitical unrest, raw material nationalism, and lack of acceptance of the environmental impact that occurs during the production of natural resources, have become important factors (Jowitt et al., 2020). This has resulted in an "outsourcing" with the concentration of the production of many raw materials to countries with lower production costs and less restrictive environmental legislation. This has again led to new concerns about access to necessary raw materials in the short and medium term. A core concern is China's dominance both in the supply and making of products from many important raw materials such as rare earth elements (REE), tungsten, antimony, and many others. Important factors in this matter is also the very large changes and increases in material needs when oil, gas, and coal are to be replaced with electricity as an energy source and energy carrier.

It is important to point out that there is no geological shortage of primary raw materials as metals and minerals. Raw materials become critical and strategic as a result of lack of diversification, lack of societal acceptance, competition, and strategic monopolization.

The realization of this problem led the European Commission to write its first raw material strategy (European Commission, 2008) and subsequently conducted criticality analyses within the industrial mega-sectors in the EU. The first analysis was conducted in 2011, followed by 2014, 2017, 2020, and most recently in 2023 as part of the European Commission's work with the Critical Raw Materials Act (Blengini et al., 2020; European Commision, 2023).

Blengini et al. (2020) presented a very comprehensive study with detailed descriptions of both critical and non-critical raw materials. Similar studies have been published in USA (Nassar & Fortier, 2021), the Nordic countries (Hallberg & Reginiussen, 2018); Eilu et al., 2021;(Jonsson et al., 2022), Canada

(Natural Resources Canada, 2022) and Australia (Australian Government, 2023). The EU's Critical Raw Materials Act has requirements for stimulating of exploration through geological mapping, as well as for the production, processing, and recycling of critical raw materials. For example, Article 18 states:

"Each Member State shall draw up a national program for general exploration targeted at critical raw materials…"

Furthermore:

"The national exploration programs referred to in paragraph 1 shall include measures to increase available information on the Union's critical raw material occurrences, including deep ore deposits."

Critical and strategic metals and minerals addressed in this report come from the European Commission's list from 2023 and are shown in European Commission(2024) and Table 1.

Table 1 Critical minerals ((European Commission, 2024)

Critical raw materials	**Critical raw materials**	**Critical raw materials**
Antimony	Gallium	Phosphate rock
Arsenic	Germanium	Phosphorus
Barite	Hafnium	Platinum Group Metals (PGM)
Bauxite/alumina/aluminium	Helium	Scandium
Beryllium	Heavy Rare Earth Elements (HREE)	Silicon metal
Bismuth	Light Rare Earth Elements (LREE)	Strontium
Boron	Lithium	Tantalum
Cobalt	Magnesium	Titanium metal
Cooking coal	Manganese	Tungsten
Copper	Graphite	Vanadium
Feldspar	Nickel – battery grade	
Fluorspar	Niobium	

Table 2 Strategic raw materials (European Commission 2024)

Strategic raw materials	**Strategic raw materials**
Bauxite/alumina/aluminium	Manganese - battery grade
Bismuth	Nickel - battery grade
Boron (metallurgical)	Platinum group metals
Cobalt	REE metals for permanent magnets (Nd, Pr, Tb, Dy, Gd, Sm, and Ce)
Copper	Silicon metal
Gallium	Titanium metal
Germanium	Tungsten
Lithium - battery grade	Synthetic graphite
Magnesium metal	

Metals and other raw materials are always part of a value chain from mining to the final product. For example, metal production is often located elsewhere (in other countries) than the preceding extraction. If one step in the chain occurs in a setting that is defined as critical, the entire value chain will become critical. The main conditions for reducing criticality are:

1. Increase the number of production sites of the entire value chain from primary extraction to manufacturing in countries with stable political governance.
2. Increase the degree of recycling/reuse. When total consumption increases or is expected to increase, recycling must be combined with increased primary production. See Blengini et al. (2017) for a comprehensive description of the concept and calculation of criticality

2.1 Materials and Methods

This report provides an overview of registrations of critical metals and minerals in Norway that are systematized in NGU's national mineral resource databases. The Norwegian Minerals Act § 7 (Mineralloven, 2010) distinguishes between the state's and the landowner's minerals. Metals with a specific gravity greater than 5 g/cm³, as well as sulfur, titanium, and their ores, are state-owned minerals, while metals with a lower specific gravity and industrial minerals belong to the landowner. NGU's mineral resource databases are divided into three: 1) The Ore Database, which includes occurrences that are state-owned minerals, 2) The Industrial Minerals Database, which includes traditional industrial minerals, and 3) The Natural Stone Database, which includes ornamental stone occurrences, the latter not being covered here. The mineral resource databases contain approximately 4,600 registrations of metals and 2,400 registrations of industrial minerals.

Mineral registrations are mapped and sampled, and ore and mineral samples are analyzed. This is continuous work. The databases provide information on, among other things, location, geology, operating history, and formation processes. For the metallic registrations, NGU currently has a dataset of over 10,000 chemical analyses that include both major and trace metals from more than 2,000 registered mineralizations. Similar data are scarcely available for the critical industrial minerals (with the exception of mineral groups that have been systematically investigated). This is partly because operations on these are based on other parameters such as quality and purity, and partly because data from the industry, e.g., tonnages, is not available.

Analysis data for mineral registrations are based on samples collected over a period of more than 30 years. Therefore, several different analysis methods have been used, resulting in different detection limits for some elements. NGU has also only in the recent years started analyzing some trace element, and have only about 380 mineralizations analyzed for gallium, germanium, indium, and tantalum.

For each registration, several samples have been analyzed, collected from bedrock and/or waste piles outside the mineralizations. Sometimes the samples are from individual blocks, other times they can be composite samples from the waste piles. The samples have usually been analyzed at commercial laboratories abroad. There number of samples from the different registrations varies, from one to over 50 samples. For each registration, we have therefore calculated a median value. This minimizes the effect of an anomalous sample in cases where few samples have been analyzed from a registration.

2.2 Definitions

A mineral occurrence is a locality where geological processes have enriched components to concentrations that are high enough to be economically interesting and potentially profitable. In Norway, we often use the term ore if components in an occurrence can be extracted profitably. The enrichment level necessary for an occurrence to be considered economically interesting varies from 4-5 times for common metals like aluminum and iron to several thousand times for rare metals like gold and platinum (Robb, 2020). Mineral occurrences are divided into different types based on the amount of information available about them. In NGU's nomenclature, we use the following definitions (Dahl et al., 2014):

a) Mineral occurrence: a locality where an enrichment of a metal or mineral above typical levels has been registered.

b) Mineral prospect: one or more localities with enrichment, area-limited, but without a defined tonnage.

c) Mineral deposit: a locality where an enrichment above typical levels has been registered, with information on metal content and tonnage. A mineral deposit will always have a defined area limit. In this report, we use the term registration or mineralization for all types of occurrences, as no economic evaluations can be made based on the collected samples. The term resources/mineral resources are used in accordance with the INSPIRE directive, describing natural concentrations of minerals or rocks that are, or may become, economically interesting due to their inherent properties, such as metal content, quality, etc.

2.2.1 Major Metals, and By-Metals

Most metals appear in groups where a major metal is associated with several by-metals. This is illustrated in Figure 1. The inner circle in the figure shows the major metals, which are the most common metals in an occurrence and usually also the largest value components. The sectors show the by-metals associated with the individual major metals, positioned increasingly further from the center based on their degree of association with the major metals. An important factor related to metal production, especially for critical metals, is that many of the metals are by-metals. This means that the production of the major metal determines how much of the by-metals can be produced. For example, zinc production from an occurrence determines how much indium is extracted. From Figure 1, we also see that, for example, vanadium follows iron, and cobalt follows nickel and copper. This implies that if we want to increase the production of the critical metals vanadium and cobalt, we must increase the production of iron and nickel and/or copper.

This mean, that if we are to extract or explore for cobalt in Norway, we should investigate nickel and/or copper registrations. The relationship between major and by-metals is further elaborated by Nassar et al., 2015.

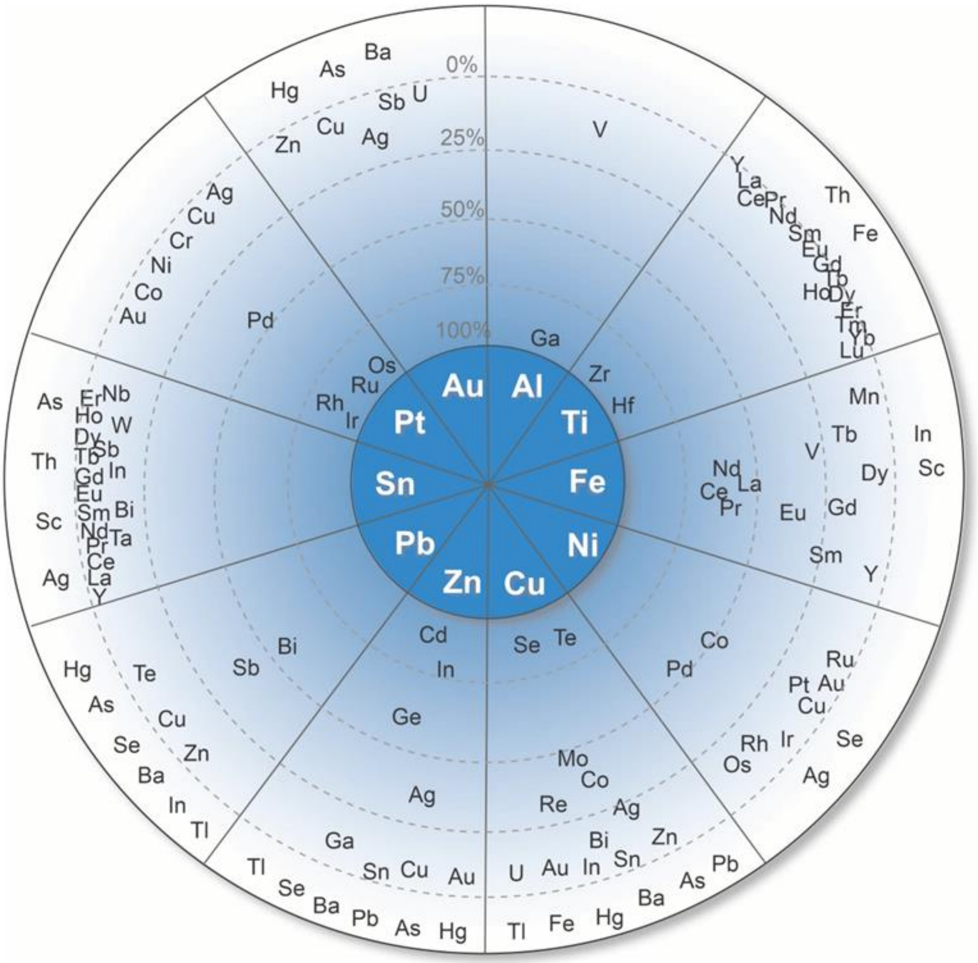

Figure 1 The wheel of metal companionality (Nassar et al., 2015) The principal host metals appear in the inner circle. By-metals are in the outer circle with decreasing percentage of their primary production outward in the sectors.

3. CRITICAL METALS AND INDUSTRIAL MINERALS

In the following chapter, we will describe the different critical metals and minerals where there are occurrences and registrations in Norway. Range of application for the individual materials are only briefly described. Information on usage and market conditions can be found in Latunussa et al., 2020, and for Nordic conditions in particular, refer to Eilu et al., 2021. For a popular science description of the elements and their uses, Emsley (2011) is recommended.

3.1 Metal Groups

Metals are divided into groups based on chemical properties and partly on area of application. This categorizaton is adapted to the metals found in occurrences and registrations in Norway.

1. **Base metals** are non precious metals, iron or ferroalloy metals and oxidize easily in contact with air. Copper (Cu), zinc (Zn), and lead (Pb) are usually considered base metals. Copper is the only one of these considered to be a critical and strategic metal. From Figure 1, we see

that antimony (Sb), gallium (Ga), germanium (Ge), indium (In), and bismuth (Bi) are critical metals that occur as by-metals to the base metals. These all have special properties and can be classified as special metals. In addition, arsenic (As), iron sulfides (Fe-sulfides), and tin (Sn) are included in this group in the database.

2. **Ferroalloy Metals** are metals used for iron alloys. These are mainly cobalt (Co), chromium (Cr), molybdenum (Mo), nickel (Ni), vanadium (V), and tungsten (W). Cobalt, nickel, and tungsten are considered critical metals.
3. **Iron Metals** are the metals iron (Fe), titanium (Ti), and manganese (Mn). Titanium and manganese are critical metals.
4. **Precious Metals** are gold (Au), silver (Ag), and the platinum group metals (PGM) consisting of iridium (Ir), osmium (Os), palladium (Pd), platinum (Pt), rhodium (Rh), and ruthenium (Ru).
5. **Special Metals** are metals exploited for their special properties. The most important of these are beryllium (Be), lithium (Li), niobium (Nb), scandium (Sc), rare earth elements (REE), and tantalum (Ta). All special metals are considered critical.
6. **Energy Metals** are thorium (Th) and uranium (U).

Figure 2 shows how these metal groups are distributed in Norway.

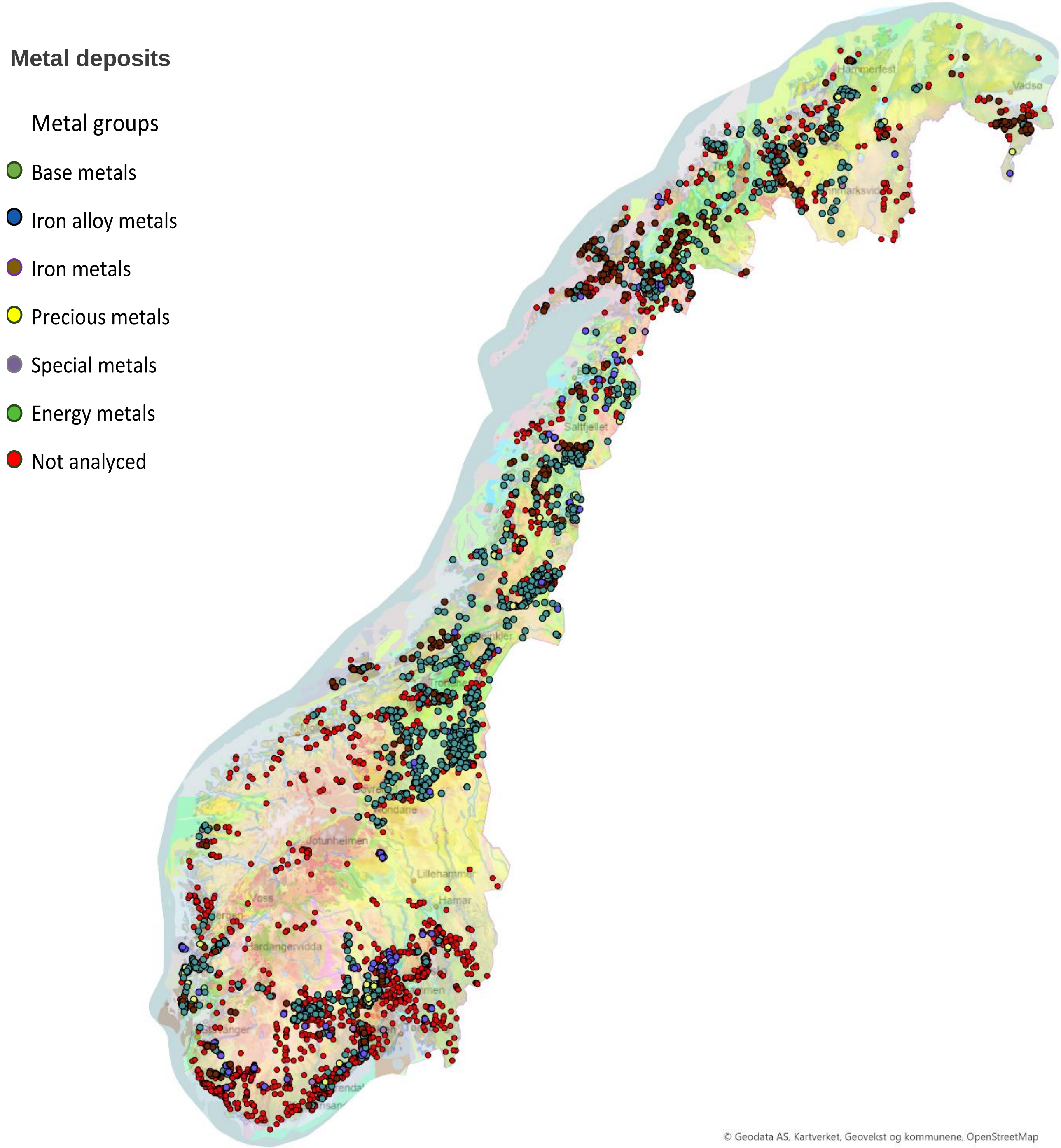

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Figure 2 Occurrences and registrations classified by metal group. Symbols in red indicate registrations that lack analyses. Most of these are also not confirmed. Please note that the density of point also reflects the degree of mapping and the level of knowledge.

3.2 Critical Metals

In this chapter, we describe registrations, occurrences, and observations of critical metals. Reference is made to map figures all presented in chapter 3.3. The maps show the median value for each registration, calculated based on analyses registred in the mineral resource databases. Be aware that the maps only consider the content of the respective metal, not the size of the mineralizations. Small mineralizations with high metal content are plotted as rich but may often still be considered curiosities. Nonetheless, plotting such mineralizations has value as they indicate locations where geological processes have resulted in enrichment, and the observations may indicate areas where unknown, larger deposits may be found, for example, at depth.

3.2.1 Antimony (Sb)

The main use of antimony is as a flame retardant, in combination with bromine or chlorine. Other important uses is as an alloy metal with lead, especially in the production of lead-acid batteries. The most important antimony-bearing mineral is stibnite (Sb_2S_3). In Norway, stibnite is known from, among others, Svenningdalen silver mines and the Kolsvik and Reppen gold deposits (Selbekk, 2010). Additionally, antimony is an element enriched in lead-rich mineralizations. There are 67 registrations with more than 500 ppm antimony in the samples collected for the ore database (Figure 3).

Three of these registrations have only one or two samples and cannot be considered representative. The four registrations with representative values are all lead- or lead-zinc-rich mineralizations. They are vein mineralizations (Susendal, Strømslia), metasomatic mineralizations (Meland), and possibly of exhalative origin (Listaulli) and associated with carbonates (Frostmoen). They are all insignificant and without economic interest, except for Frostmoen where further investigations are ongoing.

3.2.2 Beryllium (Be)

Beryllium is an important metal for some copper alloys, used in the automotive, aerospace, and defense industries. Beryllium-copper alloys are particularly strong and hard. Beryllium is also used in X-ray equipment and particle detectors.

The most important beryllium minerals are beryl ($Be_3Al_2(Si_6O_{18})$) and bertrandite ($Be_4(Si_2O_7)(OH)_2$), but also chrysoberyl ($BeAl_2O4$) and phenakite (Be_2SiO_4) are important minerals. Hambergite ($Be_2(BO_3)(OH)$) is a beryllium mineral first found at Helgeroa in southern Norway (Brögger, 1890).

In Norway, there is only one known area of interest regarding beryllium, Høgtuva in Nordland). A deposit has been identified in Høgtuva, Bordvedåga, containing 350,000 tons with 0.18% Be, and also 606 ppm Nb, 1.3% Zr, and 0.11% Y (Wilberg, 1987). In Høgtuva, there are mineralizations of different types with varying geochemistry and mineralogy. The deposit types are disseminations in 1) granitic gneiss, 2) feldspar-rich horizons in gneiss, 3) feldspar-rich skarn, 4) aplite, 5) pegmatite, and 6) undeformed quartz veins. Beryllium minerals, including phenakite, høgtuvaite, beryl, gadolinite, danalite, genthelvite, and helvite occur in various parageneses in the different mineralization types. The Bordvedåga deposit is an example of type 1), which is the most economically interesting (Schilling et al., 2015). Beryllium is mainly present in the mineral phenakite with smaller amounts in gadolinite, genthelvite, and høgtuvaite. The shape of the Be mineralization is somewhat irregular, but broadly, there are two lenses with rich mineralization separated by a low-grade part. Above, below, and between the ore lenses is what is called the “Y-zone”, enriched in Y, Ce, La, Rb, Li, Zn, Pb, and Co. Any potential mining operation on the deposit must be mainly based on beryllium, but several other elements are also potential by-products. Flotation experiments have shown that the ore can yield a phenakite concentrate with 23% BeO with a recovery of about 80% (Wilberg & Lindahl, 1991). The study also showed that beryllium can be leached from a phenakite concentrate with acid. A map of beryllium registrations is shown in Figure 4

3.2.3 Bismuth (Bi)

Bismuth is an element with limited use in its pure mode but has many different applications as an additive with other substances, including in the cosmetics industry. Bismuth compounds are used in various medicines, alloys, and pigments. Because bismuth has similar properties to lead but is non-toxic, there is an increasing use of bismuth alloys as a replacement for lead. It is also used in shotgun ammunition and is approved as non-toxic shot in both the USA and Norway.

There are very few deposits where bismuth is the primary metal. Bismuth is most often produced as a by-product from base metal deposits, particularly lead-rich ones. Bismuth is found in lead-rich VMS mineralizations, in lead-zinc skarn mineralizations of the Oslo Rift, in lead-rich vein mineralizations, and in orogenic, copper-rich vein mineralizations in the basement rocks of Southern Norway. Of these, only the lead-rich VMS mineralizations have tonnages large enough to be of interest, also for bismuth. Lead-rich VMS mineralizations are particularly prevalent in the sediments of the Aursund Group from Røros and northwards towards Meråker. Here, bismuth occurs as tellurium bismuth (tetradymite, $Bi_2Te_2S_2$), bismuthinite (bismuth glance, Bi_2S_3), and native bismuth. Additionally, bismuth is enriched in a molybdenum mineralization in Rogaland (Skjoldavika) and in precious metal veins in Bindal, Nordland.

Bismuth is particularly common in some of the skarn mineralizations of the Oslo Rift, and the Kjenner, Gjellebekk, Auvi, and Buttedal prospects at Lierskogen are referred to as bismuth mineralizations, but NGU does not have any analyses from these. Mining operations were planned around 1900, and a trial operation was initiated at the old Auvi mine in 1902. It is reported that 250 kg of bismuth ore, mainly consisting of bismuthinite, was produced. There was also an attempt to produce bismuth at Gjuv in Telemark. A map of bismuth registrations is shown in Figure 5.

3.2.4 Cobalt (Co)

The most important use of cobalt today is for rechargeable batteries (about 40%), while other significant uses include various types of alloys, such as superalloys and hard metal alloys. Previously, cobalt was highly important for the production of color pigments (like cobalt blue) and was almost exclusively used for this purpose, but today this is a very minor use (about 5%).

Cobalt is especially enriched in magmatic nickel-copper deposits, but it is also relatively high in some VMS (volcanogenic massive sulfide) deposits and in sedimentary copper deposits.

Norway was a very important producer of cobalt in the 19th century when the cobalt mines at Modum were in operation. The cobalt was used for the production of blue pigment (cobalt blue) for porcelain painting and blue glass. In the 1890s, the ore reserves quickly depleted, leading to the closure of the mines in 1898. There was also a small cobalt plant in Snarum (near Langerud) which was in operation from 1822 to 1848. The formation of the Modum deposits is not completely understood, but there are several theories related to exhalative formation, magmatic fluids, or metasomatic processes. The zone with sulfide mineralization, called fahlband, can be traced from Skuterud and 11-12 km northward to Langerud. The zone is not mapped in detail and there is an unclear potential for new deposits. There is also a similar and parallel zone on the east side of Snarumselva.

There are several other known cobalt resources in Norway, many of which are found in magmatic nickel-copper deposits. The most important are Råna in Ballangen, Ertelia near Hønefoss, and the deposits in Espedalen. There is also enrichment of cobalt in some VMS deposits, especially those associated with basaltic rocks. This includes Løkken in Meldal, Åsoren in Sel, Grimeli in Sunnfjord, the Kvikne area in Tynset, the Sulitjelma area in Fauske, and Vaddas in Nordreisa. There are approximately 700 grams of Co per ton in the estimated remaining 6 million tons of ore at Løkken.

It is likely that much of the cobalt, especially in the VMS deposits, is lattice-bound in pyrite. It is not clear that it will be profitable to extract cobalt from pyrite. However, at Løkken, we know that some cobalt also occurs in the mineral cobaltite (CoAsS).

The highest Co values in Norway are recorded in three small mineralizations represented by only one or two samples. This includes a vein mineralization at Kvænangen (Bergmark Øst) and two small VMS mineralizations on Averøy (Fagerfjell) and near Kongsberg (Tverrelva). A map of cobalt distribution is shown in Figure 6.

3.2.5 Copper (Cu)

Along with iron and aluminum, copper is among the most widely used metals globally. The most important property for copper is that it is a good electrical conductor and resistant to corrosion. Deposits with high copper content are spread across the country, and copper enrichment is found in several different deposit types: 1) VMS deposits, 2) Magmatic Ni-Cu deposits, 3) Sedimentary copper deposits, 4) Orogenic vein deposits.

VMS deposits (VMS - volcanogenic massive sulfide deposits that are exhalative sulfide deposits associated with volcanic activity) collectively constitute the largest copper resources in Norway with a number of larger deposits, which also have additional values in zinc and often also silver. Some are also relatively rich in gold and some trace metals (such as cobalt, selenium, and bismuth). They are found across the country from Rogaland in the south to Troms in the north. The largest VMS deposits are Joma (7.2 Mt remaining resources with 1% Cu), Løkken (6 Mt remaining resources with 2.3% Cu), and Giken in the Sulitjelma area (4.7 Mt remaining resources with 2.25% Cu).

The magmatic deposits (deposits associated with gabbro and other plutonic rocks) typically contain 0.5-0.7% Cu in addition to 0.5-1.0% Ni. The largest of these are Råna (9.15 Mt with 0.13% Cu) and Ertelia (23.26Mt with 0.16% Cu), as well as the deposits in Espedalen.

The sedimentary copper deposits are found in Finnmark and constitute very important copper resources on a national level. Nussir has a resource of 73 Mt ore with 1.1% Cu, while the nearby Ulveryggen has 8 Mt ore with 0.81% Cu. In the Alta-Kvænangen area, there are a number of smaller copper mineralizations in dolomite that are also partly rich in cobalt.

The orogenic vein mineralizations (deposits related to tectonic and metamorphic activity) are found particularly in the basement rocks of Southern Norway. These usually consist of chalcocite (copper glance) and bornite with smaller amounts of chalcopyrite in quartz veins. The mineralizations often also contain a significant amount of molybdenite, silver, and bismuth, as well as gold. They are typically very rich, but the known registrations are to small for commercial operation. Copper-rich quartz-carbonate veins, which are sometimes enriched in gold, are also common in the basement rocks of Troms and Finnmark. Although some of these, like Kåfjord near Alta, were of great significance at the end of the 19th century, they appear small today. A map of the distribution of copper is shown in Figure 7.

3.2.6 Gallium (Ga)

Gallium's most important application is in the production of semiconductors in alloy with arsenic (gallium arsenide, GaAs). For example, some components in mobile phones depend on gallium arsenide. Another important use is in photovoltaic products (e.g., solar cells), together with indium and selenium.

Gallium is an element that occurs with aluminum and is a by-product in the processing of bauxite and alumina. Gallium also occurs in zinc-rich ores. Norway previously had a small production of gallium when Norwegian aluminum plants produced aluminum metal based on Søderberg electrodes (Lundberg, 1986). Norsk Hydro's smelter at Vigeland produced, for example, about 200-250 kg of gallium per year in the late 1960s. Today, there are almost no Søderberg plants left. No deposits have been found in Norway with significant enrichment of gallium (hence no map).

3.2.7 Germanium (Ge)

The most important use of germanium is in infrared optics. Germanium is transparent to infrared radiation. Defense technology, satellite technology, and medical products are the largest users of germanium. The metal is also used in fiber optics, solar cells, and LED lighting.

Germanium is a metal extracted during the refining of mainly zinc-rich ores. No deposits with economically interesting germanium grades have been found in Norway. The highest median values are only 3 ppm. However, trace metals, including germanium have only been analyzed by NGU the recent years. Therefore, germanium values are for only available for about 20% of the sampled registrations and no map have been prepared for this report.

3.2.8 Indium (In)

Indium is used in touch screens and thin films on solar cells, but also in special low-temperature alloys, LED lighting, and batteries. This is due to the properties of indium-tin oxide, which is transparent while conducting electricity. The metal is an element that enters the crystal structure of sphalerite and is therefore extracted during the refining and smelting of zinc ores. There are very few indium minerals, the most common being roquesite ($CuInS_2$).

No deposits with particularly high indium content have been found in Norway, only six registrations have more than 20 ppm In in median value, and only Listaulli in Telemark has more than 50 ppm (62 ppm). As with germanium, only 20% of the sampled registrations have been analyzed for indium. A map of indium registrations is shown in Figure 8.

3.2.9 Nickel (Ni)

Approximately 60% of the world's nickel production is used in alloys with iron to produce stainless steel. Nickel is also important in alloys for rechargeable batteries.

In Norway, nickel is exclusively associated with magmatic nickel-copper deposits. Several such deposits have previously been operational in Norway: Flåt near Evje, Ertelia near Hønefoss, Råna in Ballangen, Espedalen, Hamn on Senja, Nystein and Meinkjær in Bamble, Romsås, Hosanger near Bergen, and Skjækerdalen in Verdal. Among these, Flåt and Råna have accounted for the majority of production, with 63,500 tons of nickel metal. In total, approximately 70,000 tons of nickel have been extracted in Norway.

The known nickel resources in Norway is to 21.4 million tons, with an average content of 0.5% nickel. The resources are mainly found in Råna (9.15 million tons with 0.52% Ni), Ertelia (Ringerike) (2.698 million tons with 0.83% Ni), Dalen (Espedalen) (7.8 million tons with 0.29% Ni), Stormyra (Espedalen) (1.16 million tons with 1.09% Ni), and Vakkerlien (Kvikne) (0.4 million tons with 1.0% Ni). Active exploration is underway in both Råna and several other deposits in the nickel provinces of Bamble, Ringerike, Espedalen, and Kvikne.

Skåkåsen, Lillefjellklumpen, Skograudberget, Måløy, and Rombaksbotn are all smaller mineralizations with limited known resources. A map of nickel distribution is shown in Figure 9.

3.2.10 Niobium (Nb)

80% of the world's production of niobium are used into iron alloys (ferroniobium). This significantly increases the strength of the material used for iron beams and pipes, which allows these to be made thinner and smaller, resulting in considerable weight savings. In Norway, niobium was produced from the mineral pyrochlore at the Søve mines near Ulefoss between 1953 and 1965. The niobium concentrate, consisting of Nb_2O_5, was entirely exported to the USA, where it was used in the rocket and jet engine industry. In total, 1.15 million tons of ore were produced, yielding just under 2000 tons of Nb_2O_5 (Amundsen, 2015).

Known niobium resources in Norway are distributed among the Sæteråsen, Fen (Søve), and Høgtuva deposits. The vast majority of the quantified resources are found in Sæteråsen near Larvik. The deposit consists of the volcanic rock trachyte, which is especially rich in niobium, as well as in rare earth metals such as cerium, lanthanum, and yttrium. These elements are concentrated in the minerals euxenite, pyrochlore, chevkinite, fergusonite, and apatite. A rough estimate of possible ore resources in Sæteråsen, based on analyses of four diamond drill holes, gives a total tonnage of about 8 million tons with 0.245% Nb, 0.18% Ce, 0.11% La, 0.075% Y, 0.069% Nd, and 0.049% Th (Ihlen, 1983). At Søve, a remaining resource of 1.4 million tons with 0.16% Nb has been estimated, and in Bordvedåga in Høgtuva, which is mainly a beryllium deposit, there is also some niobium (606 g/t Nb). Vollen in Mostadmarka southeast of Trondheim - is an insignificant vein mineralization in greenstone enriched in, among other things, niobium and tantalum. Niobium registrations are shown in Figure 10.

3.2.11 Platinum Group Metals (PGM)

Platinum group metals (PGM) include platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir), and osmium (Os). Of these, palladium and platinum are the most common, with their production being ten times higher than that of the others. Pd, Pt, and Rh are important as catalysts in the exhaust systems of combustion engines. Additionally, PGMs are used in the electronics and jewelry industries. There is also increasing use in fuel cells and hydrogen production.

PGMs are mainly associated with magmatic nickel-copper deposits in mafic and ultramafic rocks, but also chromite deposits. In Norway, small PGM resources are known, with Karenhaugen in Finnmark being the only location with significant known resources (estimated at 1 million tons with 0.87 g/t Pd and 0.31 g/t Pt). Porsvann is a similar Cu-PGM mineralization near Karenhaugen. Vir'dnemuot'ki is a smaller Cu-Pd mineralization in gabbro. Lillefjellklumpen in the Grong field is the richest known PGM mineralization in Norway. It is located in gabbro along the contact with greenstone, with a median value of 8 analyses being 3.7 ppm total PGM (Pt+Pd) (Grønlie, 1988). The mineralization likely represents a magmatic sulfide segregation associated with a gabbro intrusion, later remobilized through a tectonic event and redeposited in its current position. The size is insignificant. Figure 11 shows a map of registrations with the total content of PGMs.

3.2.12 Rare Earth Elements (REE)

Rare earth elements (REE) consist of the elements lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu). These are further grouped into light rare earth elements (LREE), which include La, Ce, Pr, Nd, Sm, Eu, and Gd, and heavy rare earth elements (HREE), which include Tb, Dy, Ho, Er, Tm, Yb, and Lu. In some contexts, yttrium and scandium are also considered rare earth elements.

In this report, we summarize the main uses of rare earth elements without going into detail, see Table 3. Interested readers are recommended to refer to Emsley (2011) or the chapters on rare earth elements in Latunussa et al., (2020).

Table 3 Selected applications of Rare Earth Elements, from (Emsley, 2011)

Element	Application
Lanthanum (La)	Various types of special glass
Cerium (Ce)	Polishing agents
Praseodymium (Pr)	Optics and lasers
Neodymium (Nd)	Magnets
Samarium (Sm)	Magnets and catalysts
Europium (Eu)	Optics and lasers
Gadolinium (Gd)	Optics and microwaves
Terbium (Tb)	Semiconductor technology
Dysprosium (Dy)	Magnets
Holmium (Ho)	Special optics
Erbium (Er)	Lasers
Thulium (Tm)	Lasers and nuclear technology

Element	Application
Ytterbium (Yb)	Laser technology
Lutetium (Lu)	Catalysts

Rare earth elements are among the most critical metals we have, as China controls most of the value chain from mineral extraction to processing and separation. Rare earth elements are complex to produce as pure individual metals, and traditionally, a very environmentally challenging liquid-liquid separation is used (Wall et al., 2017).

There are four occurrences in Norway showing a total rare earth element content of over 1000 ppm. These are the Fen Complex, Biggejav'ri (see chapter on scandium), Gloserheia pegmatite deposit (Åmli, 1977), Sæteråsen (see chapter on niobium), and. The potential for rare earth elements in the Fen Complex is described by Dahlgren (2019). Two exploration companies have third-party evaluated inferred resource estimates on the deposit. These include Rare Earths Norway's 559 Mt with 1.57 wt.% TREO (REE | Rare Earths Norway), and REE Minerals' 95 Mt inferred resources with a n average of 1.3 wt.% TREO (REE Minerals) . For the map presentation in this report, we have combined analyses from two long boreholes in the Fen Complex (Coint & Dahlgren, 2019).

There is no doubt that the Fen Complex contains significant resources of rare earth elements, and if the deposit will be developed and processed in Norway, it could contribute significantly to reducing the criticality of rare earth elements in Europe. A map showing the total content of rare earth elements is presented in Figure 12.

3.2.13 Scandium (Sc)

Scandium is an element related to rare earth metals and yttrium. Its primary uses are in fuel cells and in aluminum-scandium alloys.

Scandium is enriched in apatite-rich deposits, REE (rare earth element) deposits, and pegmatite deposits, as well as in the waste products from alumina production, known as "red muds." The first scandium mineral identified in the world, thortveitite ($(Sc,Y)_2Si_2O_7$), was found in a pegmatite in Iveland in 1910, and 50 kg of it was produced until 1961 (Selbekk, 2010). Scandium-bearing pegmatites are also known in the Evje area and Tørdal (Bergstøl & Juve, 1988), with limited prospecting carried out in these areas.

The largest scandium deposit in Norway is Biggejav'ri in Finnmark. Here, Sc-REE mineralization occurs in a radioactive albitite. A Cr- and V-rich variant of davidite-loveringite is the most significant Sc-REE bearing mineral. Bastnaesite, orthite, monazite, xenotime, thortveitite, and various U-minerals occur as accessory minerals (Olerud, 1988). Regional surveys, alteration types, and isotope analyses indicate a metasomatic-hydrothermal formation from metamorphic solutions derived from continental crust. The Sc-REE mineralizations likely occurred simultaneously with the albitization of the metavolcanics. The deposit is estimated to contain 50,000 tons with a grade of 130 g/t Sc. An overview of scandium registrations is shown in Figure 13.

3.2.14 Tantalum (Ta)

Tantalum is a relatively rare element and has the fourth highest melting point of any metal. Its primary applications are in capacitors for electronics and in superalloys along with tungsten (Latunussa et al., 2020).

Tantalum is found in minerals belonging to the microlite group $(NaCa)_2Ta_2O_6(OH)$ and in columbite-tantalite $(Fe,Mn)(Ta,Nb)_2O_6$, two minerals in complete miscibility. The commercial product "ColTan" is a collective term for columbite-tantalite. Tantalite is the tantalum-rich end member, and columbite is the niobium-rich end member. Tantalum-bearing minerals typically occur alongside tin, lithium, and niobium. In Norway, columbite-tantalite is found as an accessory mineral in many pegmatites (Selbekk, 2010).

To date, no deposits in Norway have been found where tantalum occurs in economically interesting quantities. The highest values found so far are less than 30 ppm and are from a vein mineralization in Mostadmarka (Vollen, see 3.2.7) and a molybdenum mineralization in the Oslo Rift (Skrukkelia). A map showing tantalum in Norway is presented in Figure 14.

3.2.15 Titanium (Ti)

Titanium metal has high tensile strength and low weight, making it suitable for aerospace applications. Titanium dioxide (TiO_2) is a white pigment resistant to sunlight and has good covering power, due to its high refractive index, making it the most important pigment in almost all types of paint.

In terms of critical raw materials, titanium as a metal is what is critical. Norway has large deposits and production of titanium minerals but no production of titanium metal. Norwegian production of titanium minerals is used to produce titanium dioxide (TiO_2) for pigment, making Norway one of Europe's most important producers. Titanium dioxide is produced from the mineral ilmenite ($FeTiO_3$), a major mineral in iron-titanium deposits. Titania A/S's deposits at Hauge in Dalane have been the main producers of ilmenite (with magnetite and nickel sulfides as by-products) for many years. Norge Mineraler A/Sare developing 3 deposits in the Egersund area of southernmost Norway with an aggregated tonnage of 1938 Mt with 4.54% TiO_2 (and addition 1.81 % P_2O_5 and 0.07% V_2O_5 respectively).

The Engebø (Engebøfjellet) rutile and garnet deposit is planned to open in 2024, with rutile (TiO_2) as one of the main products, suitable for both pigment and titanium metal production. Resources are estimated to be 254 Mt with on average 2,5% TiO_2

The deposits described above show that Norway has several world class deposits of (iron) titanium and associated elements.

When producing titanium metal, an upgraded titanium slag is usually made initially, which can be refined into so-called titanium sponge. Titanium sponge can be used as raw material for titanium metal. Strict requirements are imposed on raw materials for titanium slag and further processing into metal. This is done using the Kroll process, which is industrially complex (Earlam, 2020). TiZir A/S's production of titanium slag and iron in Tyssedal uses imported ilmenite from sand deposits in Senegal. Nordic Mining's rutile concentrate will be suitable for titanium sponge production, and there are plans to sell part of the production for this purpose (Maurice Kok pers. comm.). Norwegian rutile production can thus help reduce the criticality of titanium metal in Europe.

Norwegian iron-titanium-vanadium deposits have been investigated since the 1960s and up to the 2000s (Geis, 1965; Korneliussen & Foslie, 1985; Korneliussen et al., 1985; Lindberg, 1985; Priesemann & Krause, 1985; Robins, 1985; Sanetra, 1985; Wilson, 1985; Duchesne & Korneliussen, 2003).

Maps of titanium deposits and registrations are shown in Figures 15, 16 and 17. In NGU's database, there is a distinction between element and oxide analyses. We have also included analyses of titanium in magnetite concentrate (slig) with data from the Elkem. The map does not distinguish between registrations with titanium bound to ilmenite or titanium bound to rutile, even though the economic thresholds are very different.

3.2.16 Tungsten (W)

Approximately 50% of tungsten production goes into the manufacture of tungsten carbide, which is an important hard metal allo. The metal is also used in various iron and steel alloys.
Tungsten is enriched in certain molybdenum mineralizations in Southern Norway, skarn mineralizations in Helgeland and the Oslo Region, and various base metal mineralizations that are likely influenced by hot solutions from granites (e.g., Vallebukta, Trekvisla, Byttingsdalen). There have been periods of quite extensive prospecting for the tungsten-bearing mineral scheelite ($CaWO_4$) in Norway. However, chemical analyses of tungsten-bearing samples are scarcely recorded in NGU's databases. Scheelite is a rather heavy mineral and is found as grains in the heavy mineral fraction in sediments. Two areas have been particularly investigated, the Helgeland coast in Nordland (Stendahl et al., 1992) and Ørsdalen in Rogaland (Heier, 1955).
The Ørsdalen W-Mo occurrence was periodically operational from 1904 to 1954 and produced 33,000 tons of raw ore, yielding 105 tons of concentrate with an average of 60-65% WO_3 (Bjørlykke, 1953). The best-studied occurrence in Helgeland is Målvika, where tungsten is found in skarn-altered carbonate rocks, and the resource is estimated to consist of 750,000 tons with 0.44% WO_3 (Müller & Furuhaug, 2008). Despite quite extensive prospecting over many decades, no new economically viable tungsten deposits have been found in Norway. A map of tungsten in the database samples is shown in Figure 18.

3.2.17 Vanadium (V)

Vanadium is always extracted as a by-product from iron and iron-titanium deposits (Figure 1). Vanadium becomes a by-product during the smelting of iron from vanadium-bearing iron deposits. Its primary application is in iron alloys. With an increased use of vanadium redox batteriesfor stationary energy storage systems, , the demand for vanadium will rise. These batteries exploit the vanadium's ability to exist in four different oxidation states.

In iron deposits, magnetite is the key vanadium-bearing mineral. Therefore, maps showing the total vanadium content may not represent the correct resource potential. For vanadium, we present maps for both the total content and vanadium in magnetite concentrate (slag) with data from the company Elkem (Korneliussen et al., 1985).

There are several iron-titanium-vanadium deposits and registrations in Norway, especially in northwesternand southern Norway. Among these, Rødsand and Sjøholt and the deposits under development by Norge Mineraler (https://www.norgemineraler.com/) in the Egersund area are considered the most important. The company have identified resources of 1938 Mt with 0.07 % V_2O_5. Iron and iron-titanium deposits have been extensively investigated by NGU, and there is substantial report material in NGU's archives; see the chapter on titanium. Information on vanadium in Norwegian iron-titanium-vanadium mineralizations is not updated and is poorly systematized.

Maps of vanadium registrations are shown in Figure 19 and 20.

3.2.18 Zirconium (Zr)

Most of the zirconium production is used directly as the mineral zircon because it is very heat resistant. Only a small portion is converted into the metal zirconium. During World War II, Norwegian zircon deposits ($ZrSiO_4$) were investigated by German companies. Several deposits were then investigated in Langesundsfjorden. From a deposit on Stokkøya, a few hundred kilograms of zircon were extracted during World War II, but the deposit is far too small for profitable operation today. The operation and the deposit are described by Horvath (1943).It is known that alkaline intrusive rocks and volcanic rocks in the Oslo Region can be locally enriched in zirconium, and zircon deposits have been sought after several times without any major enrichments being found (Oftedahl & Bollingberg, 1958; Korneliussen & Raaness, 2006). The highest content of zirconium in our databases is in the Sæteråsen deposit near Sandefjord (Ihlen, 1983), see descriptions for Niobium. There is also significant enrichment of zirconium in the beryllium deposit at Høgtuva in Nordland.

NGU is currently conducting detailed investigations of alkaline and monzonitic rocks in several locations in Norway. Interesting enrichments of zircon have been found at several localities. A map of zirconium is shown in Figure 21.

3.3 Maps of critical metals

Location names on the maps can represent both individual deposits and a metallogenetic area.

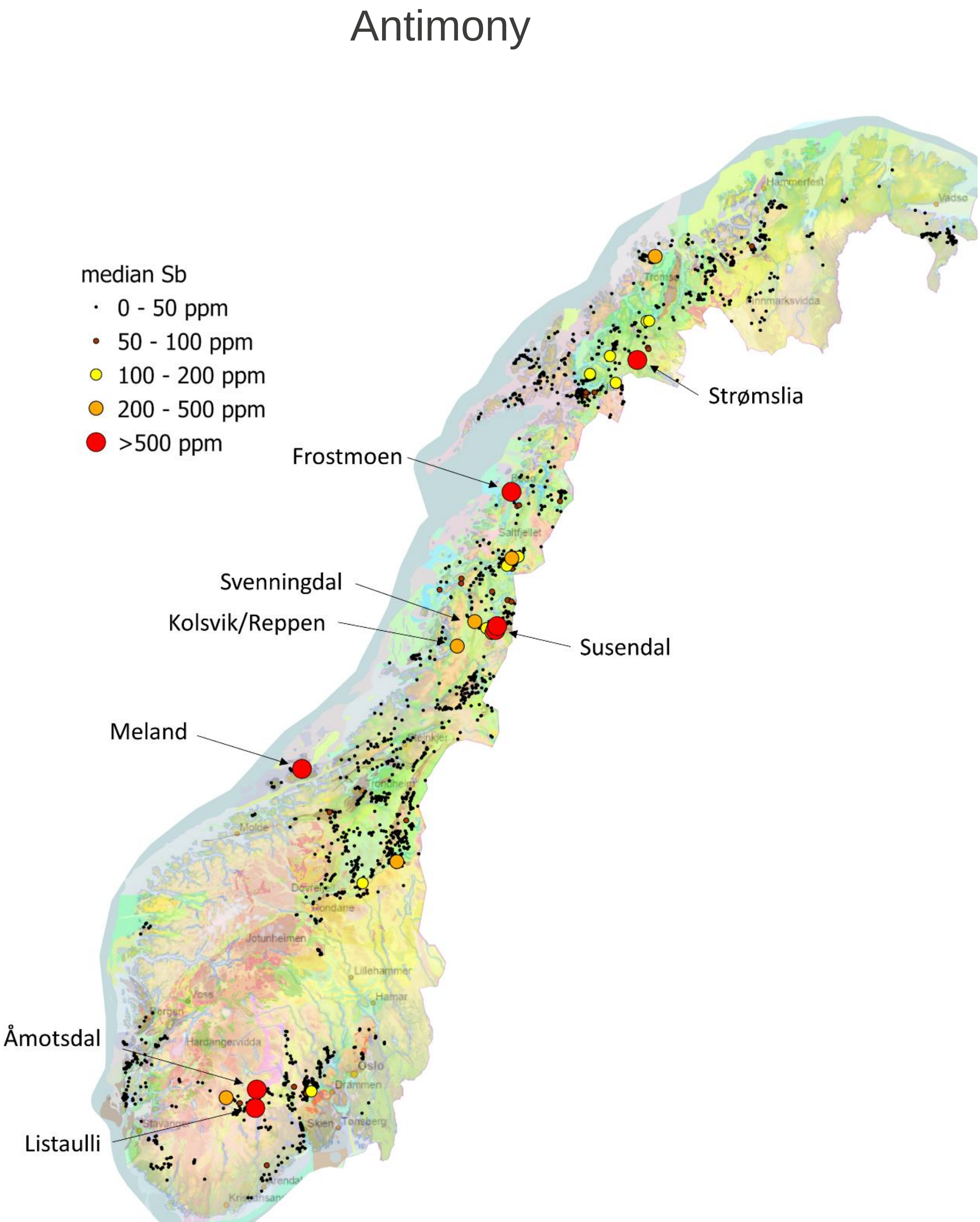

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Figure 3 Median content of antimony in mineral registrations.

Beryllium

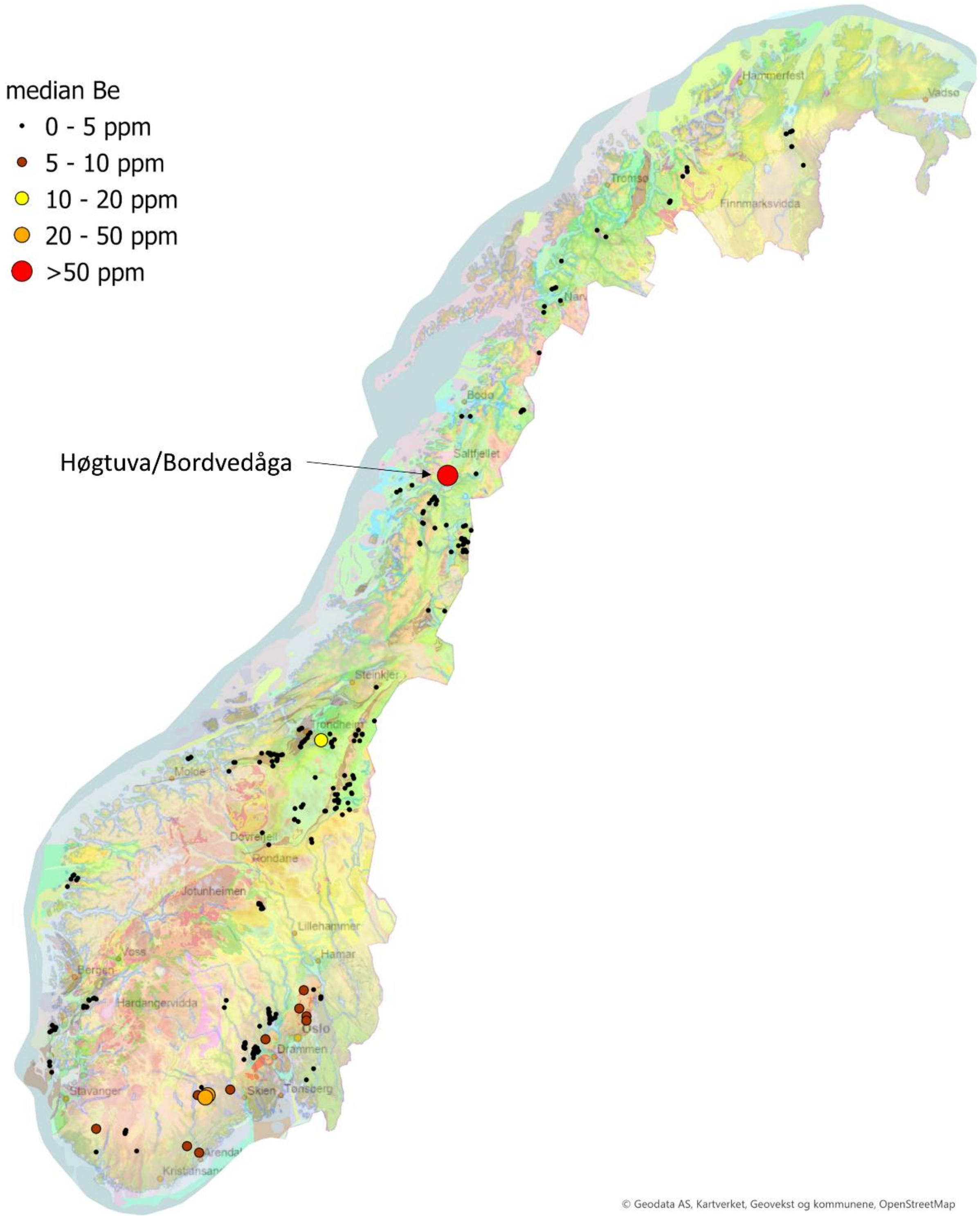

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Figure 4 Median content of beryllium in mineral registrations.

Bismuth

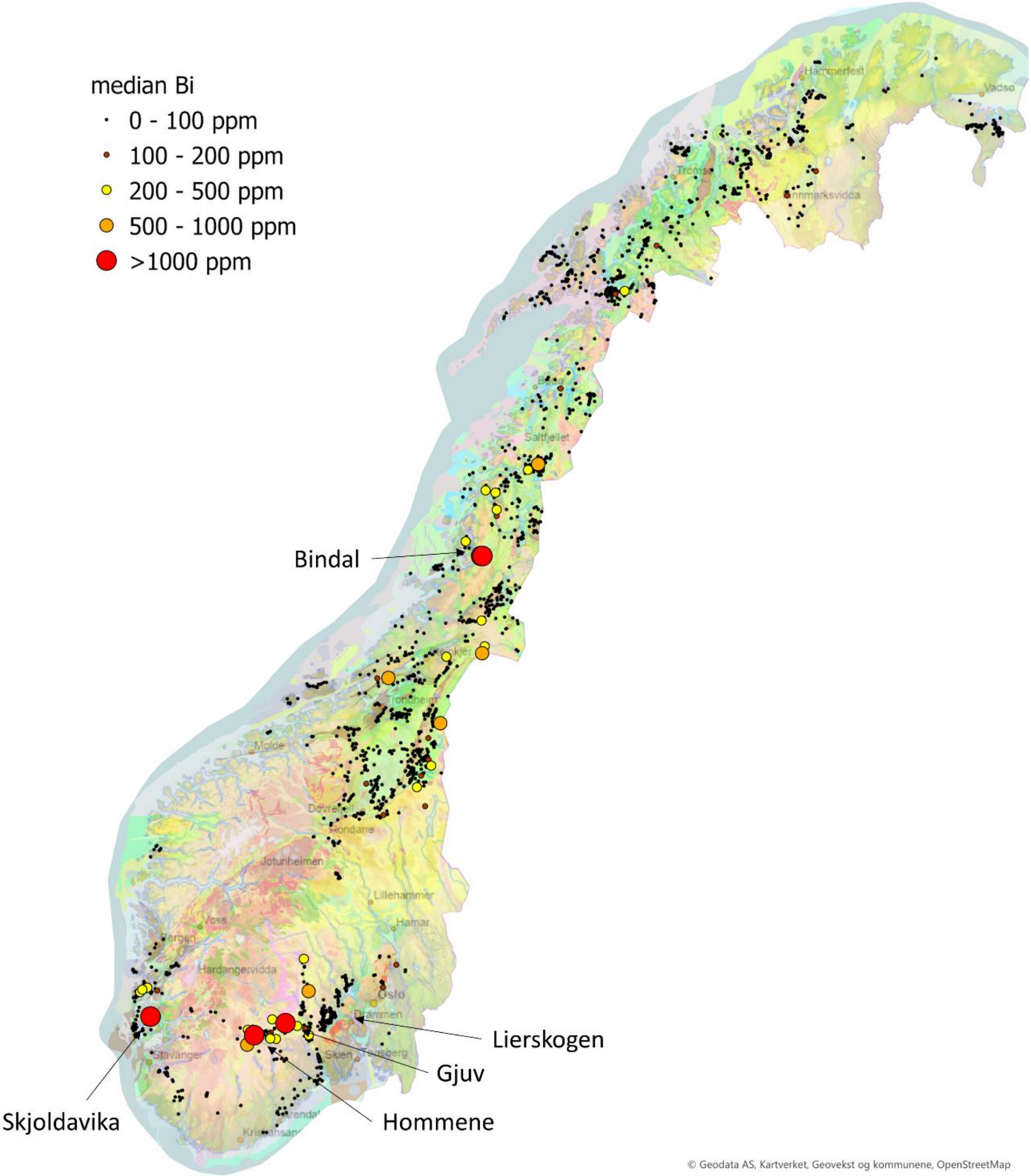

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Figure 5 Median content of bismuth in mineral registrations.

Cobalt

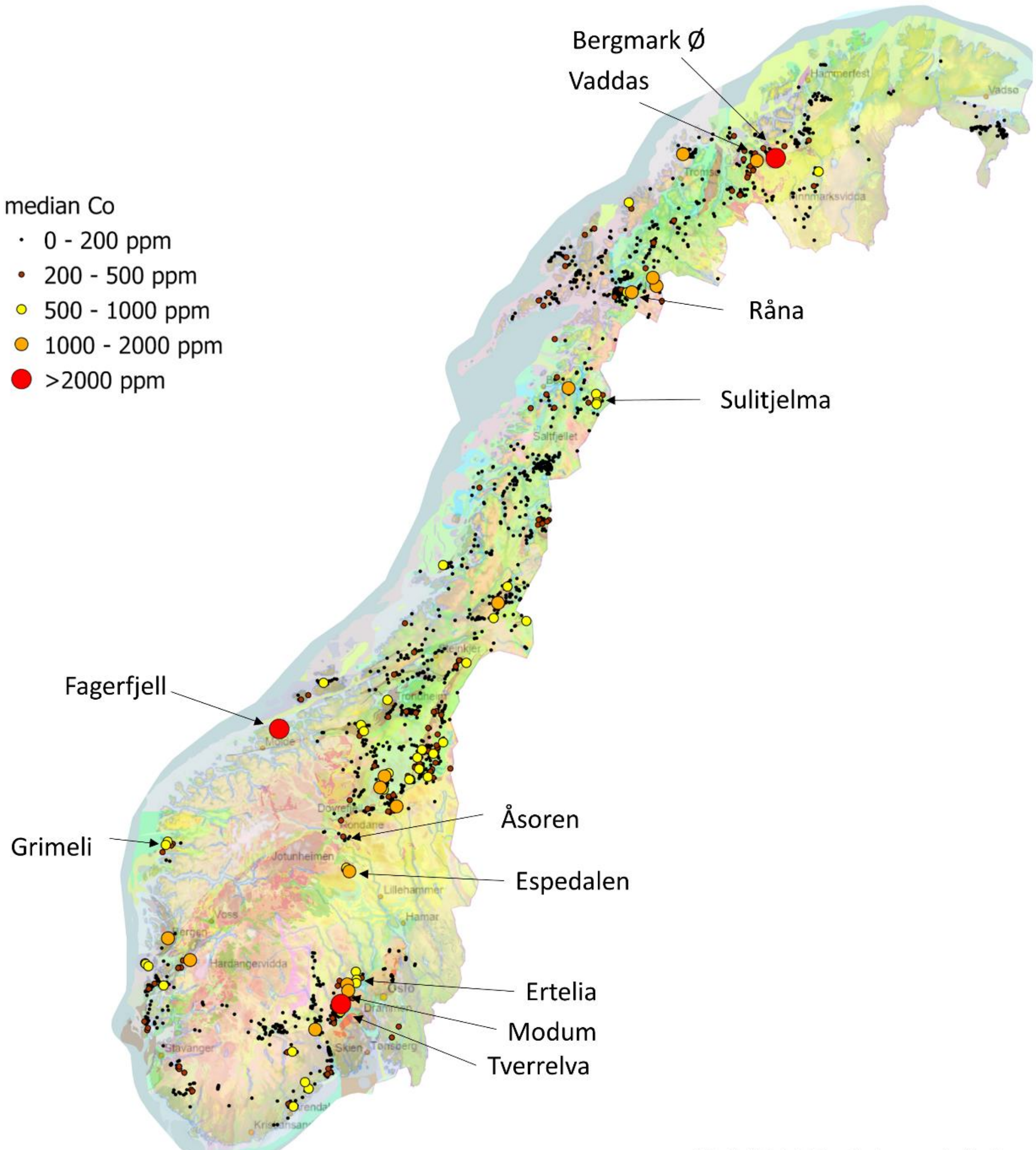

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Figure 6 Median content of cobalt in mineral registrations.

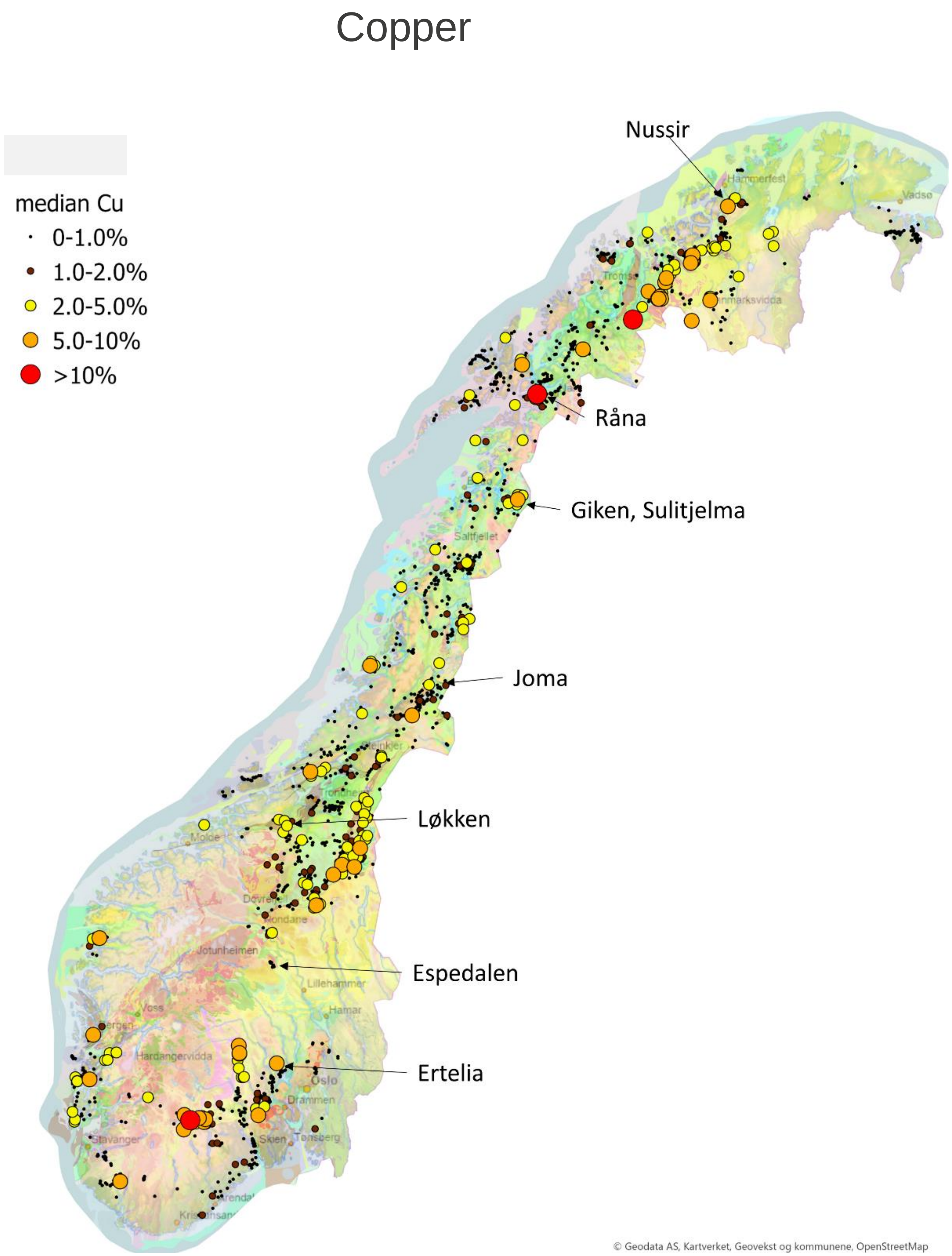

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Figure 7 Median content of copper in mineral registrations.

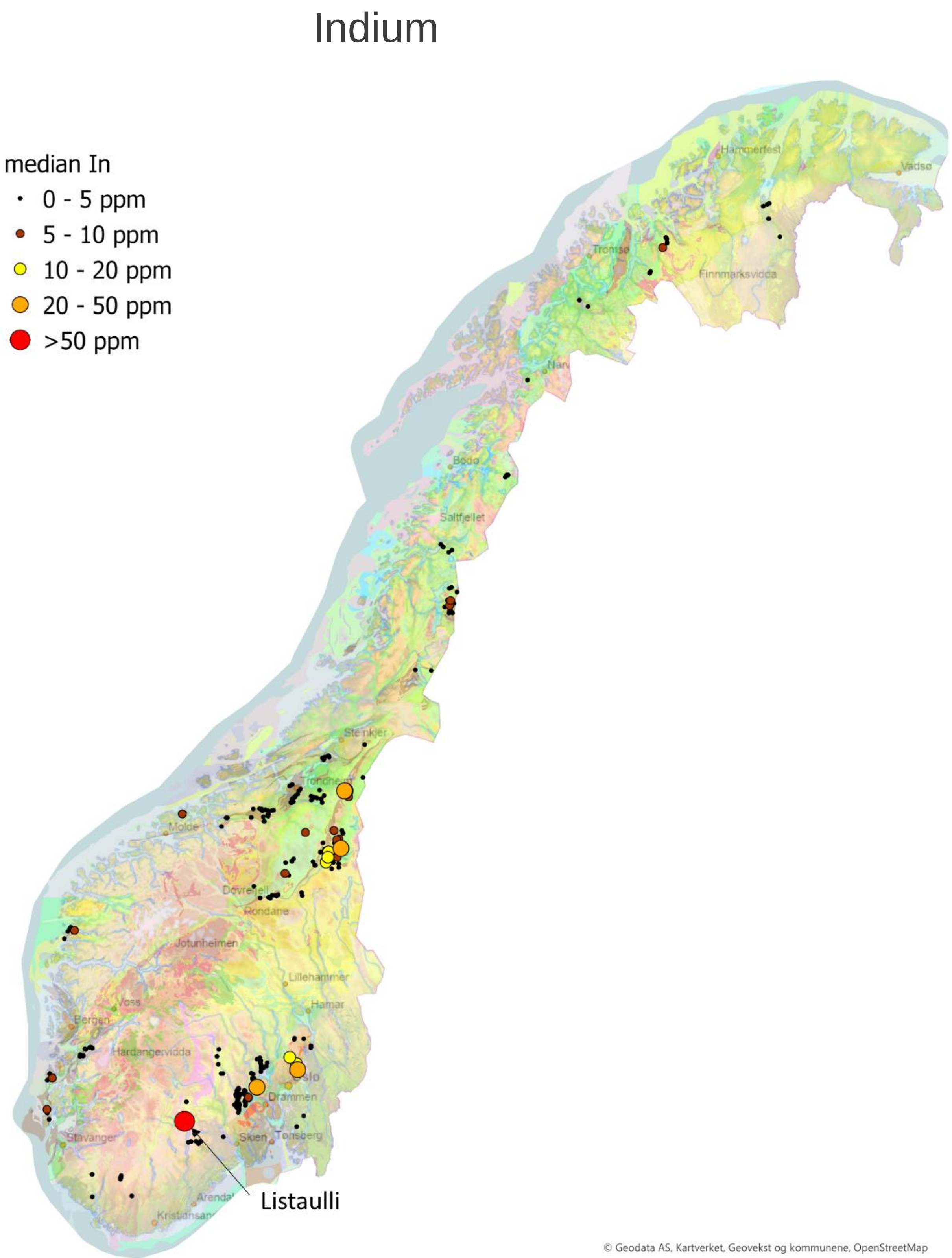

Figure 8 Median content of indium in mineral registrations.

Nickel

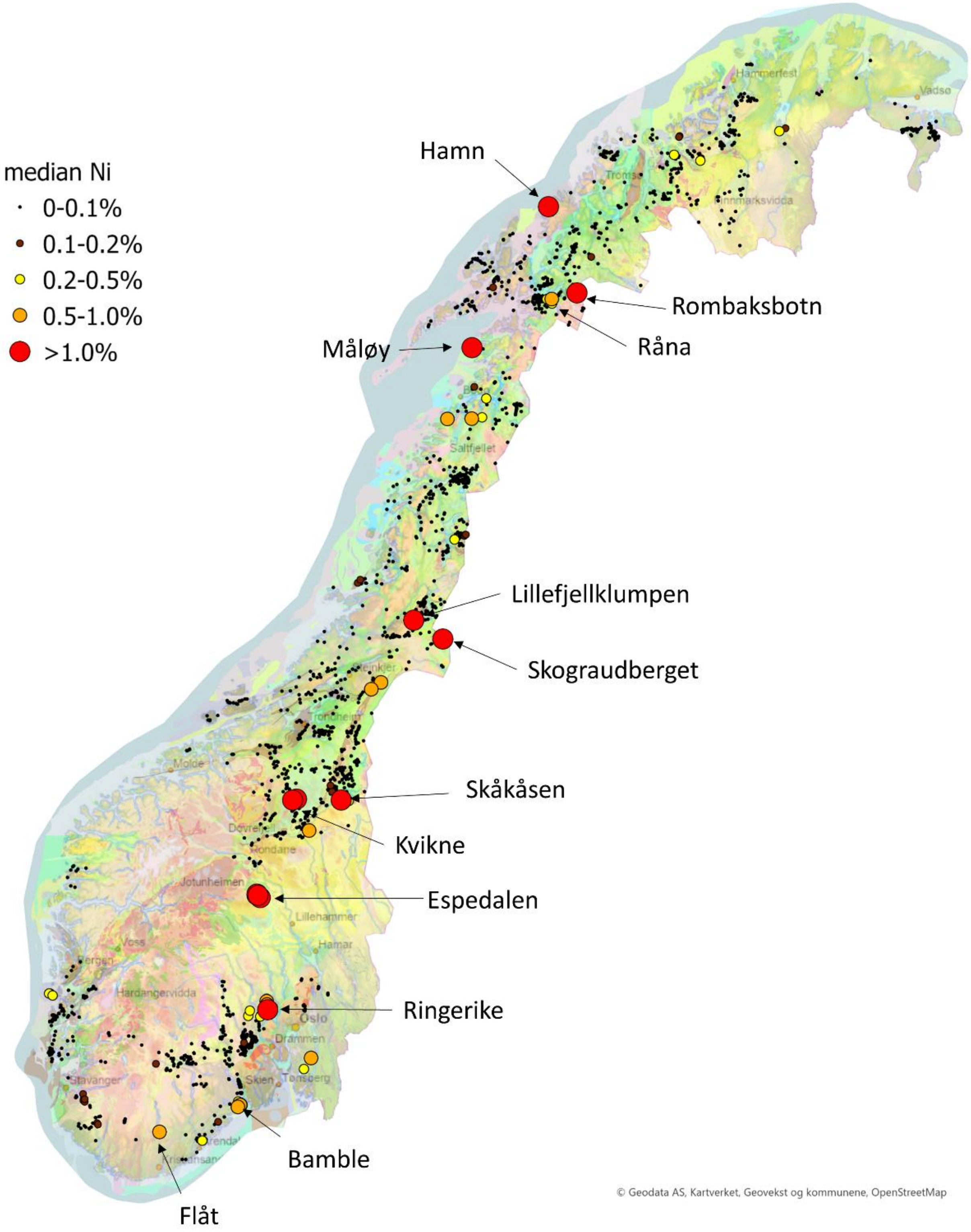

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Figure 9 Median content of nickel in mineral registrations.

Niobium

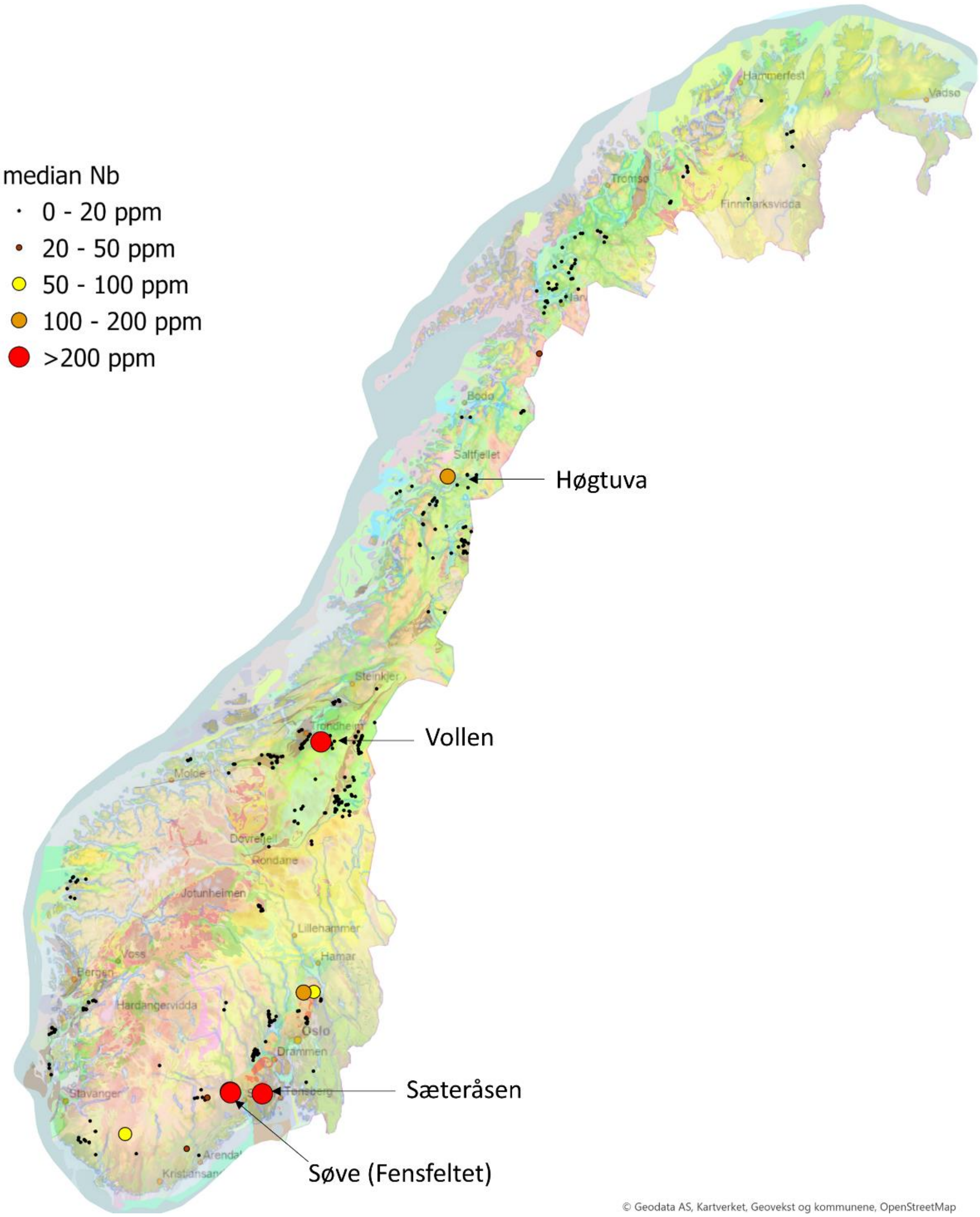

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Figure 10 Median content of niobium in mineral registrations.

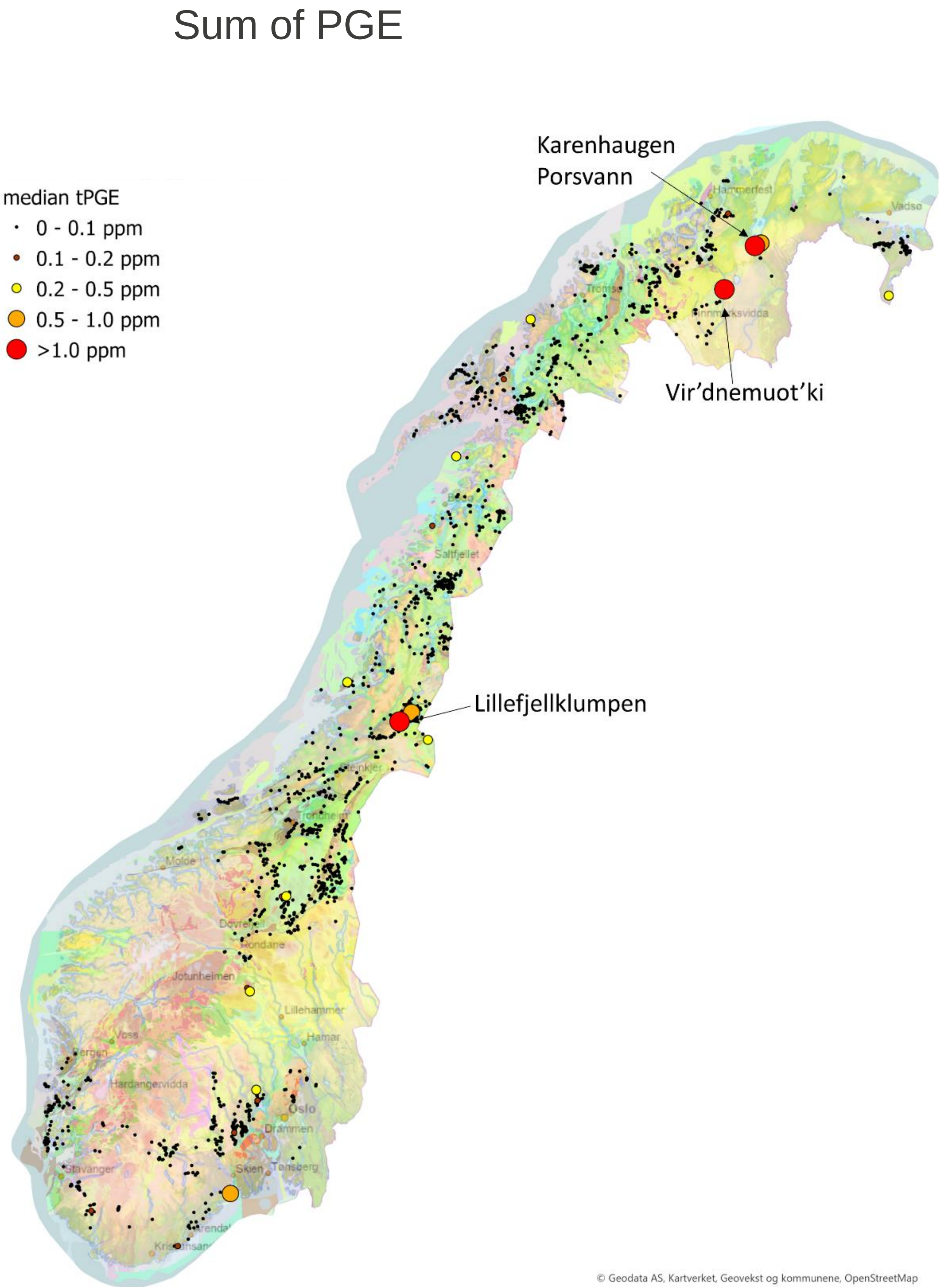

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Figure 11 Median content of total PGE (tPGE) in mineral registrations.

Sum of REE

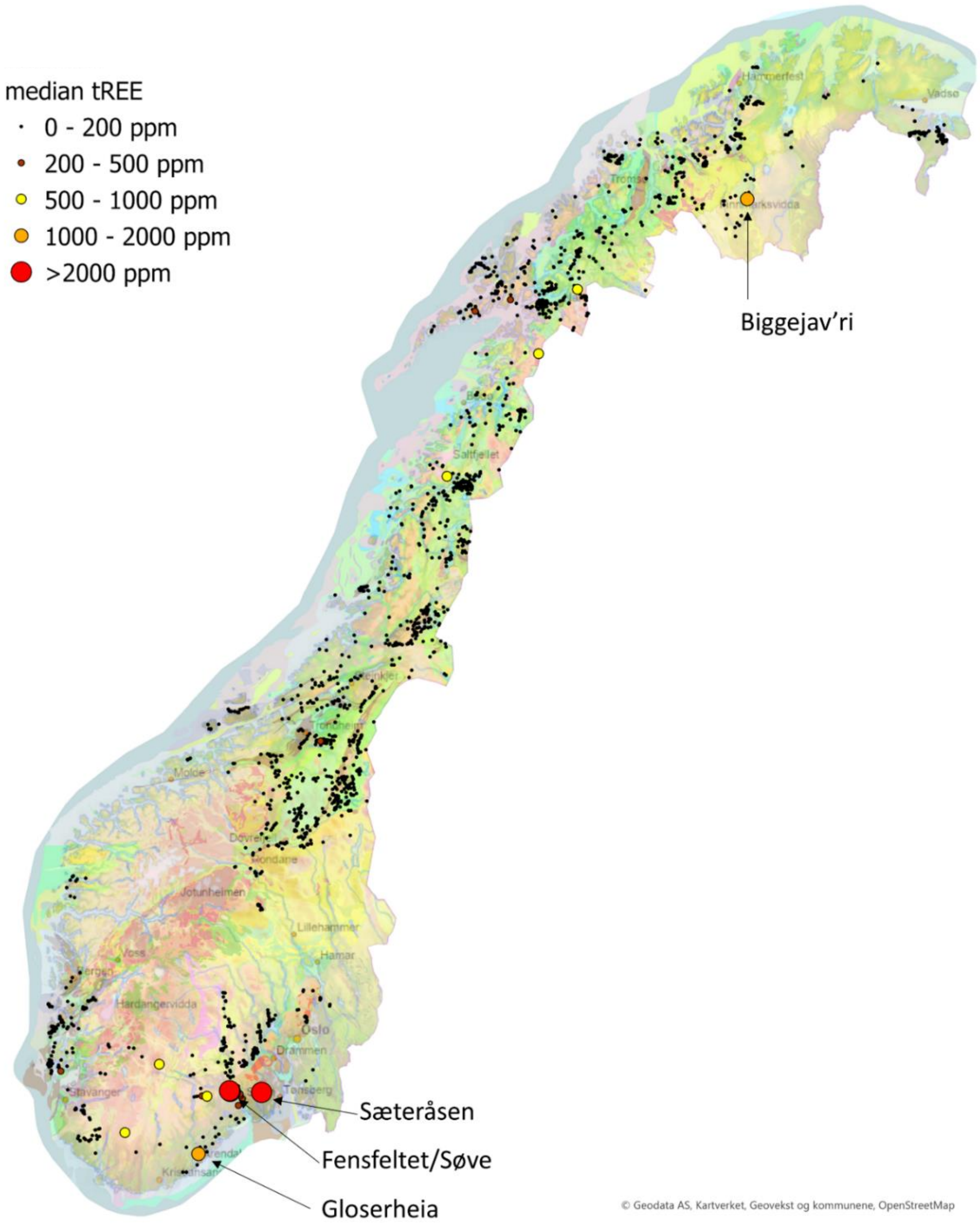

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Figure 12 Median content of tREE in mineral registrations.

Scandium

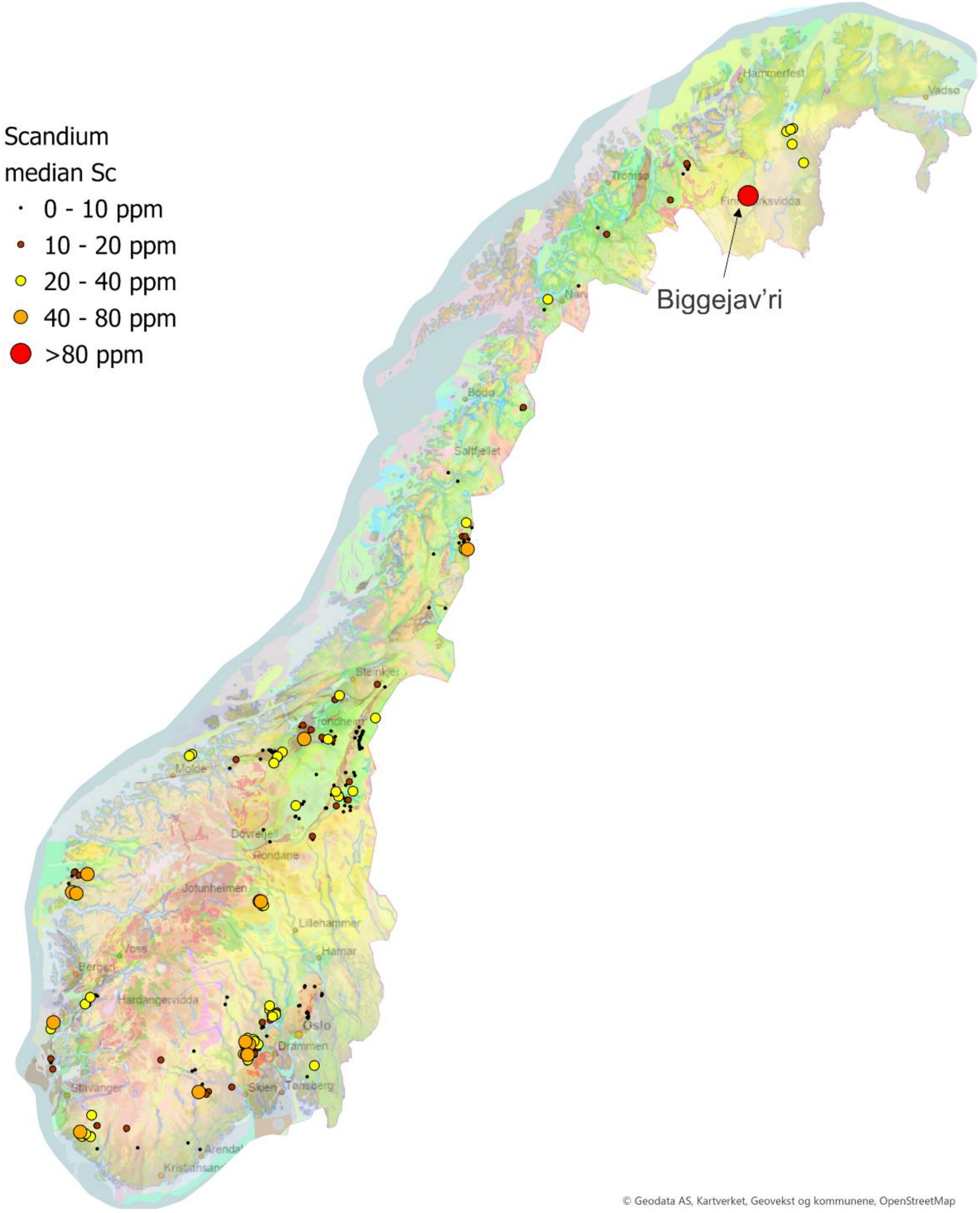

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Figure 13 Median content of scandium in mineral registrations.

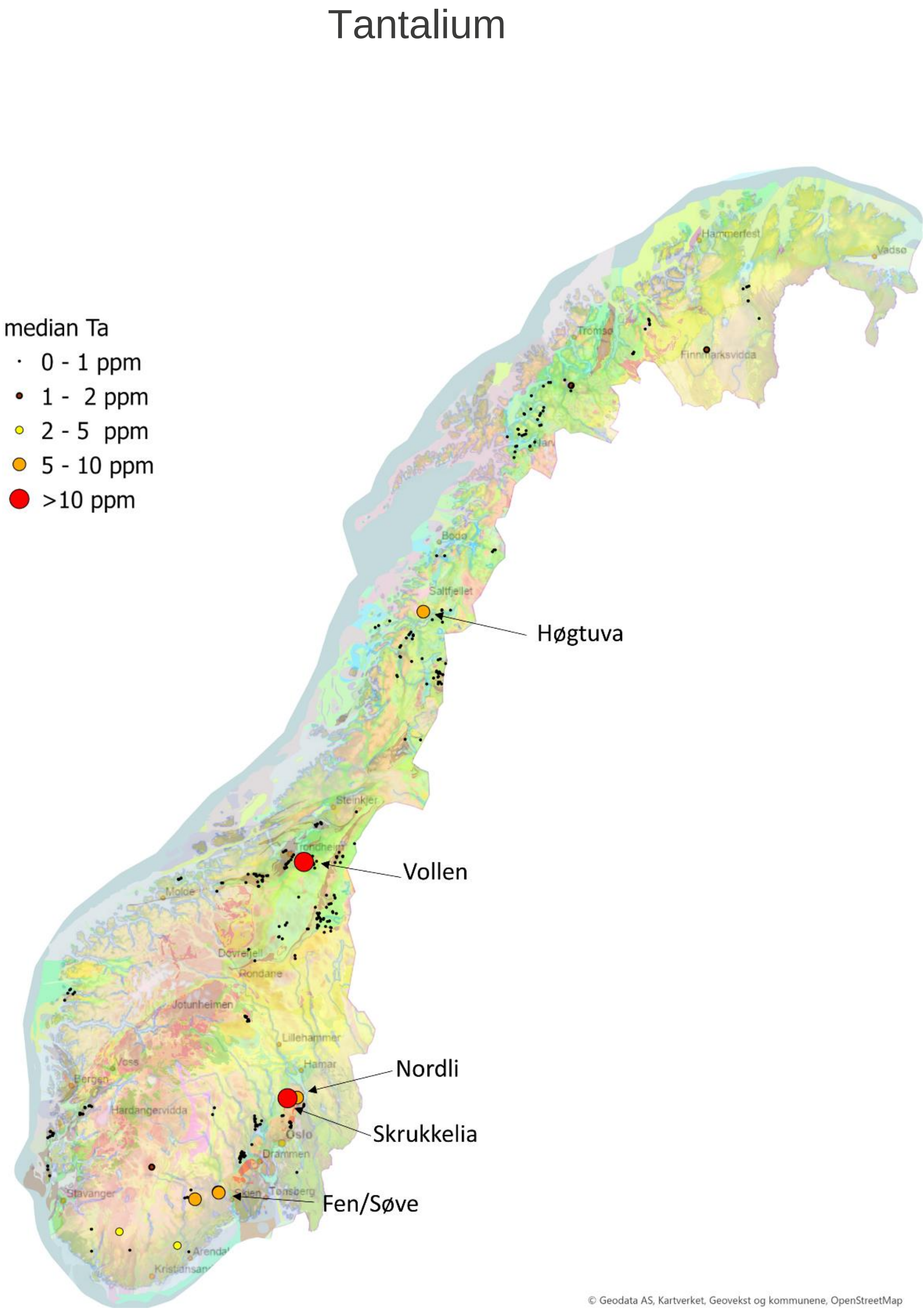

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Figure 14 Median content of tantalium in mineral registrations.

Titanium in bulk rock

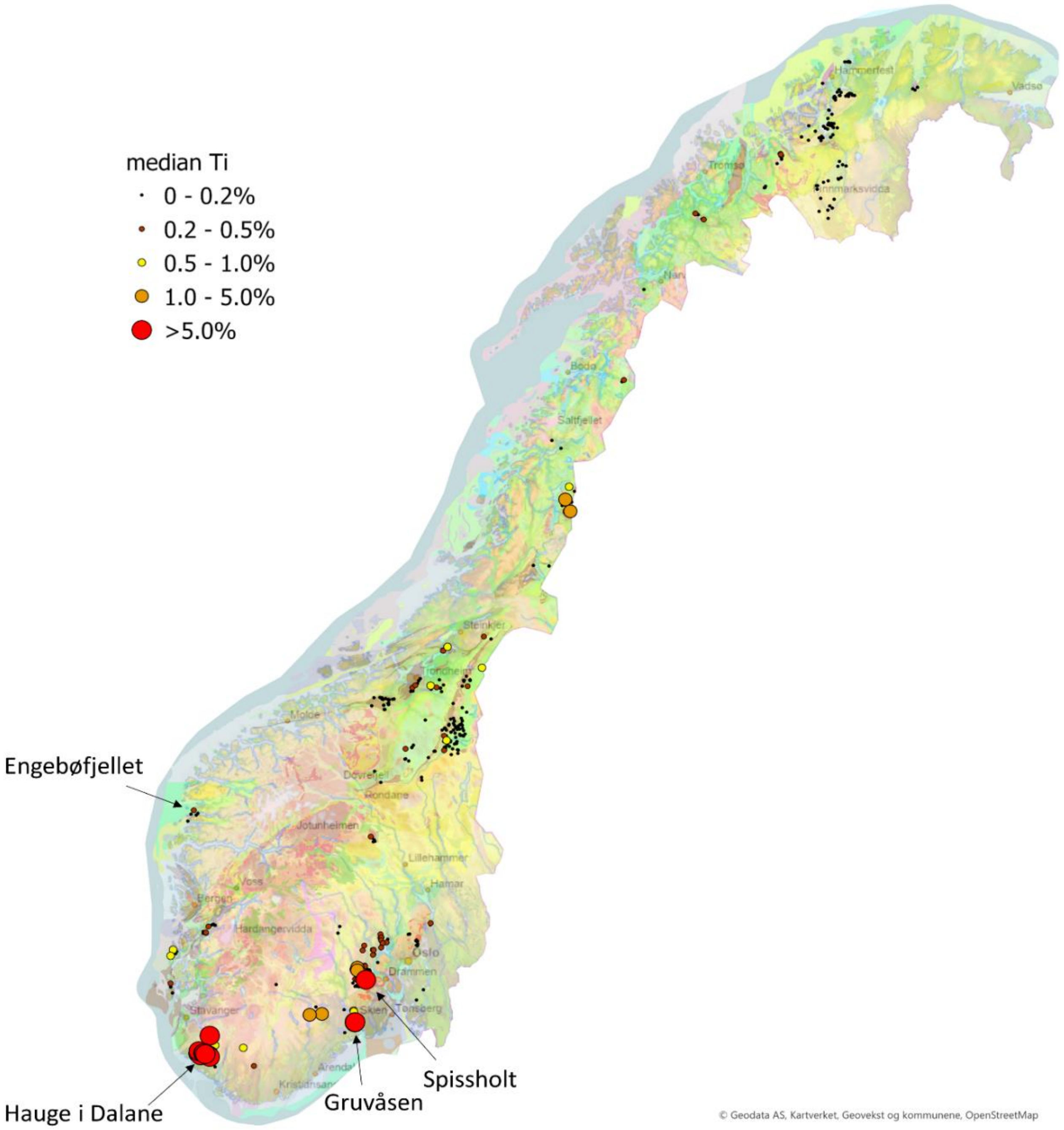

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Figure 15 Median content of titanium from element analysis in bulk rock

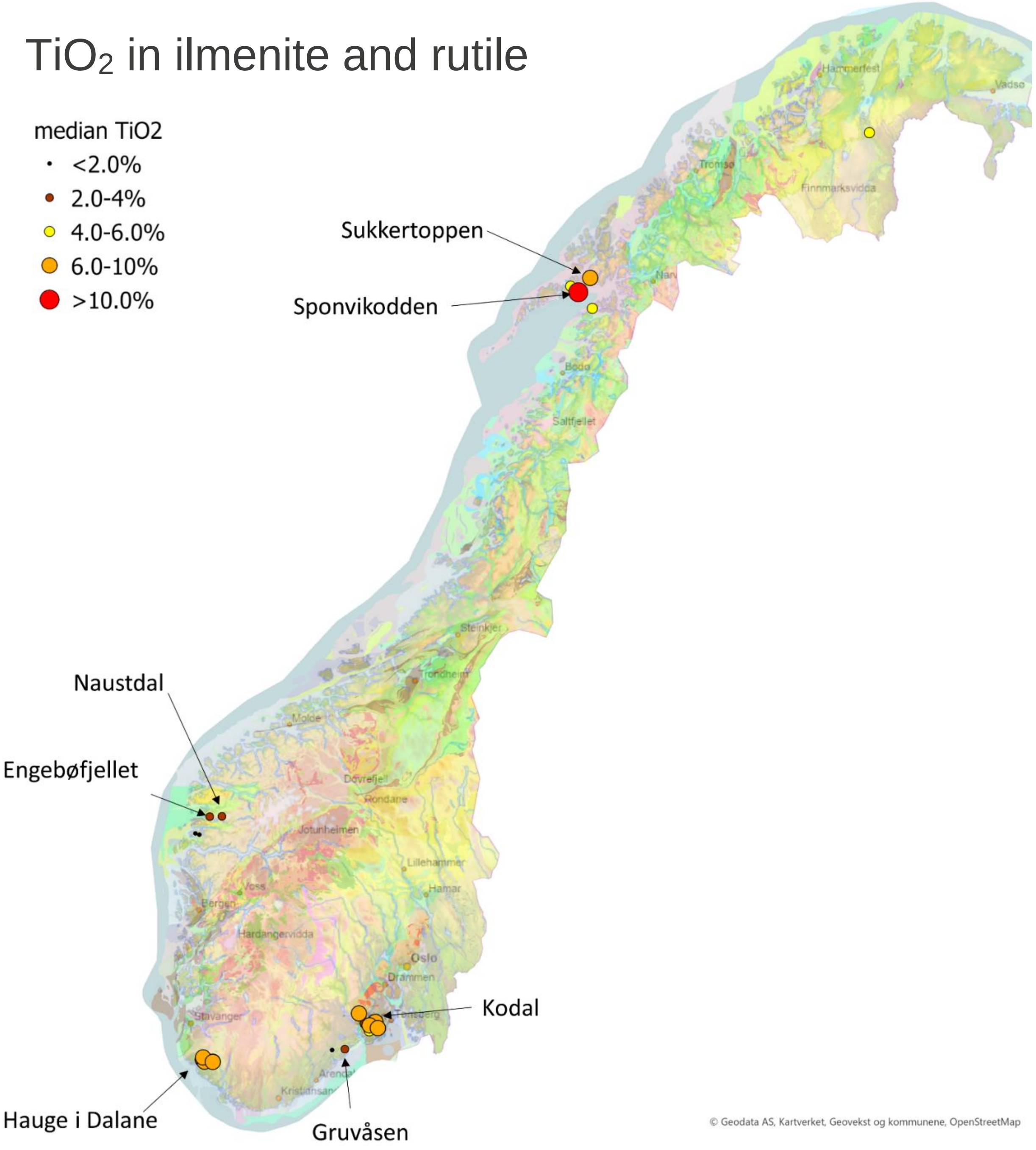

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Figure 16 Median content of TiO_2 in ilmenite and rutile.

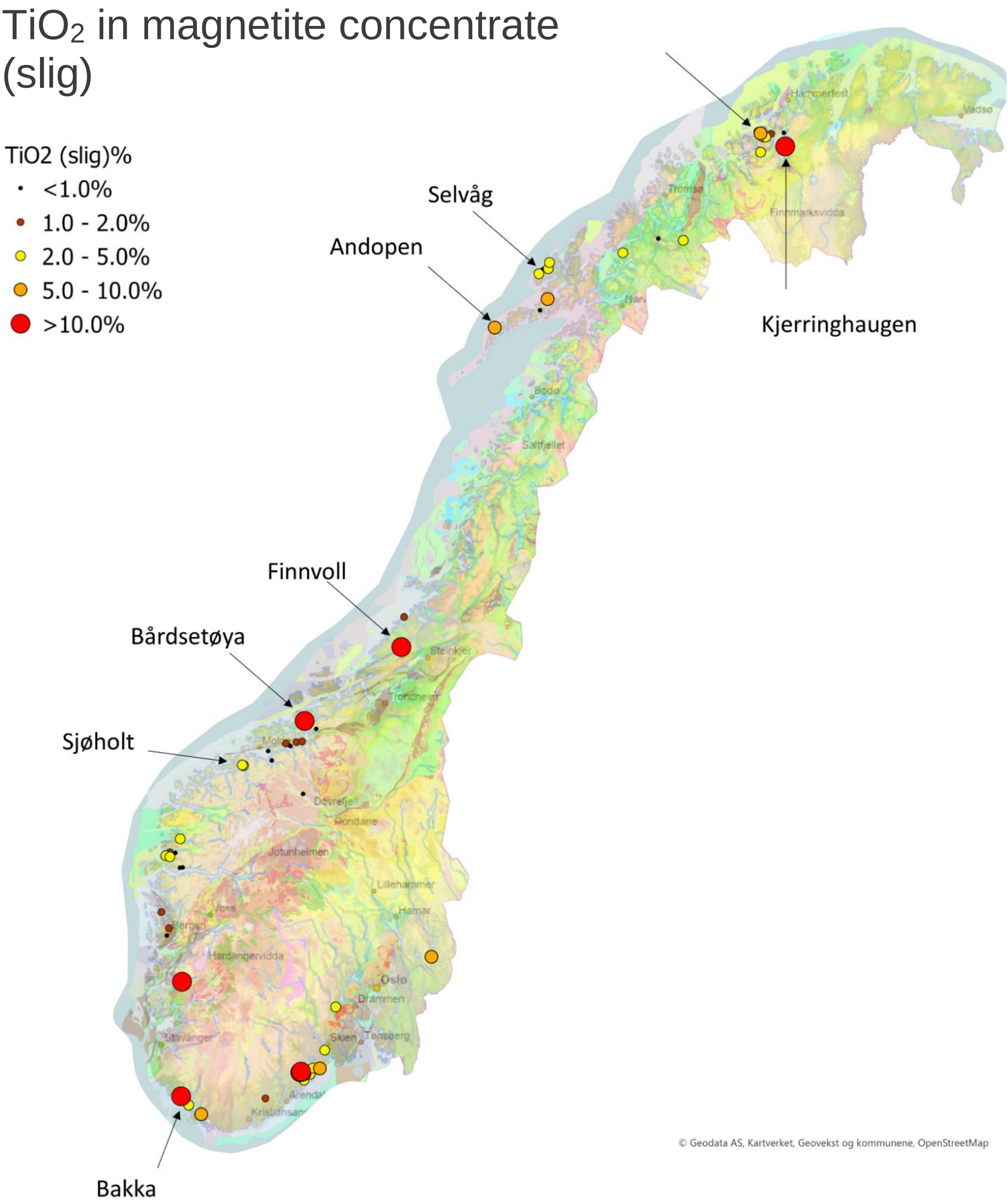

Figure 17 TiO$_2$ in magnetite concentrate (slig)?

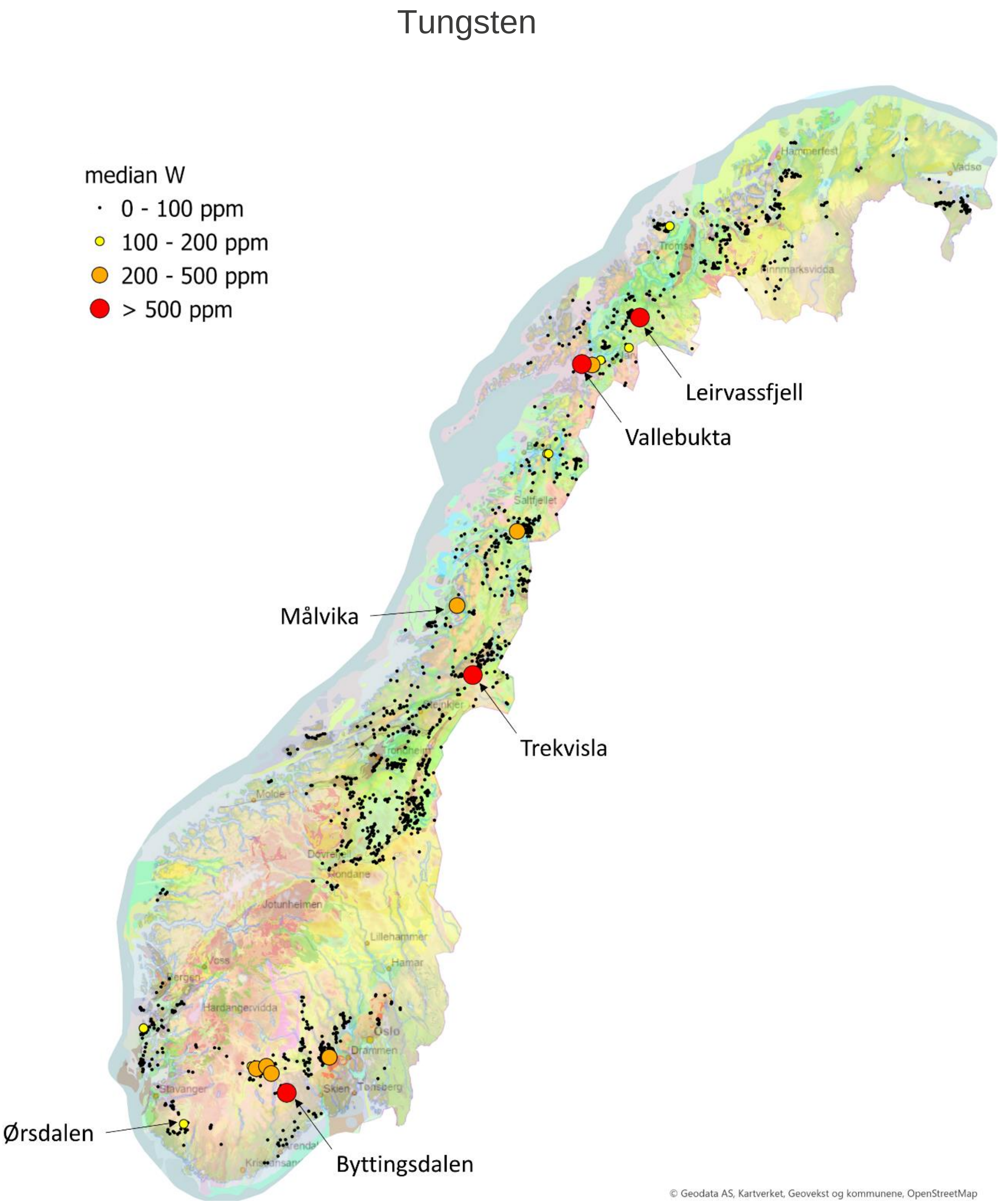

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Figure 18 Median content of tungsten in mineral registrations.

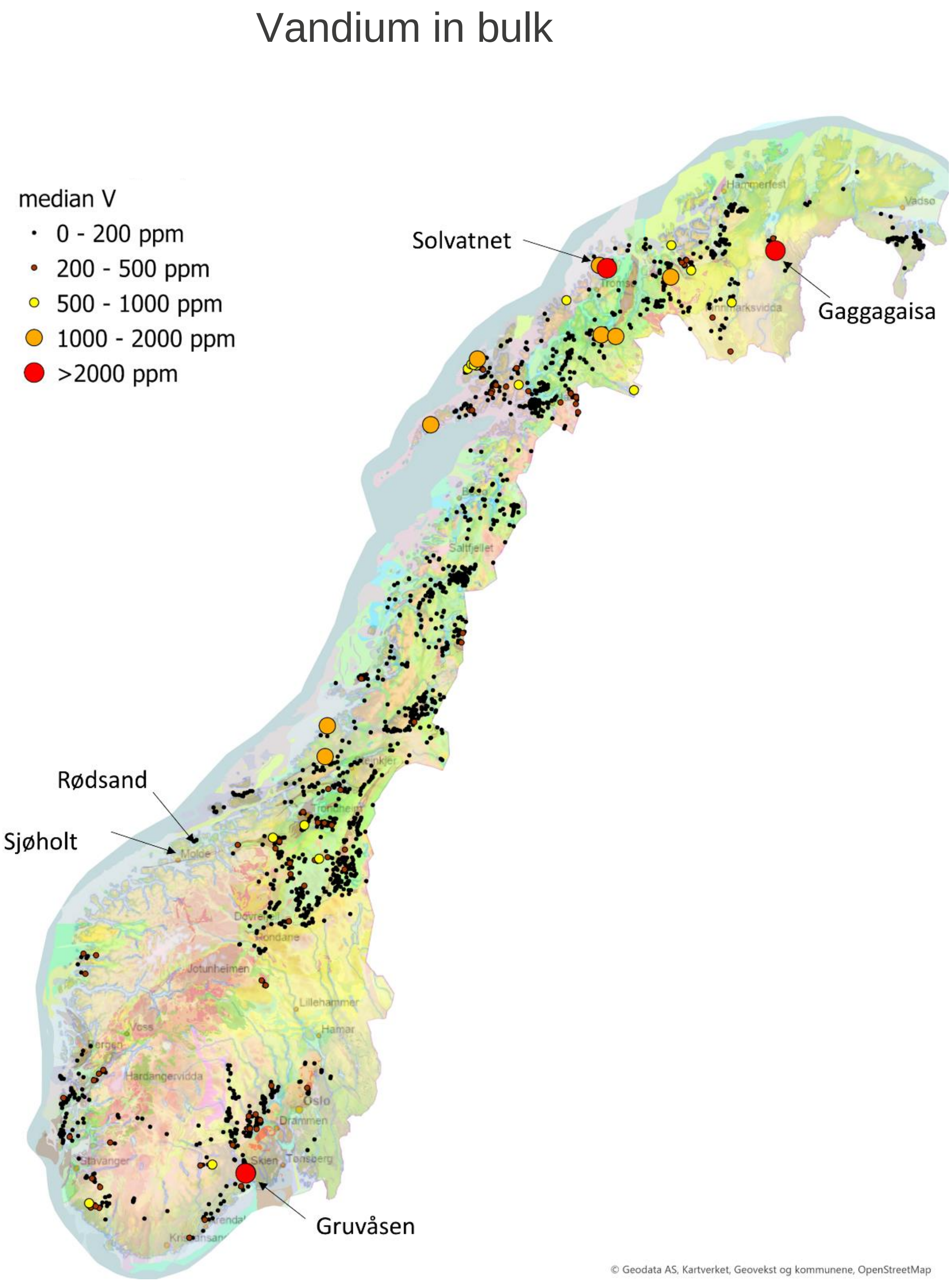

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Figure 19 Median content of vanadium in bulk analysis from mineral registrations.

Vanadium in magnetite concentrate (slig)

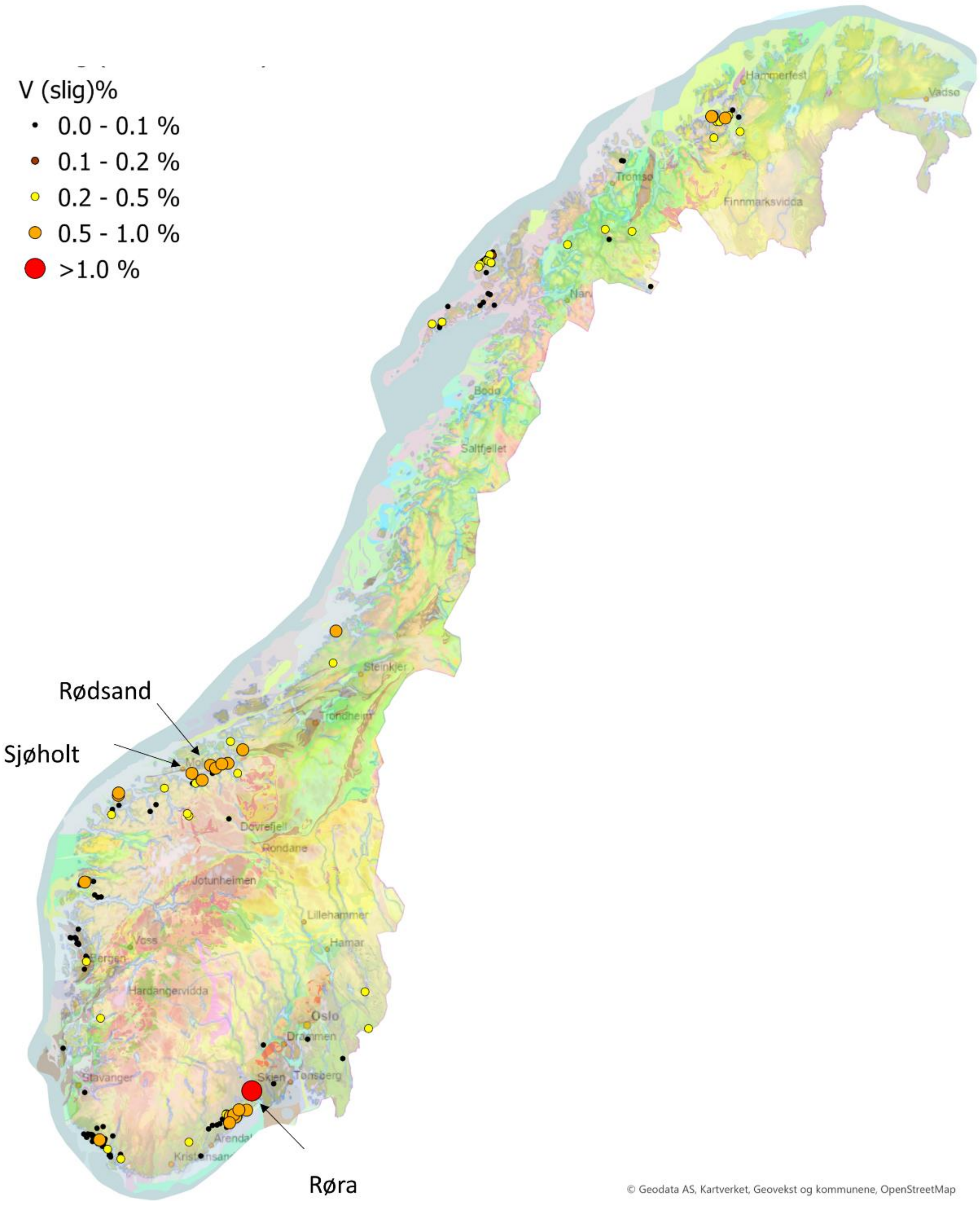

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Figure 20 Vanadium in magnetite concentrate (slig).

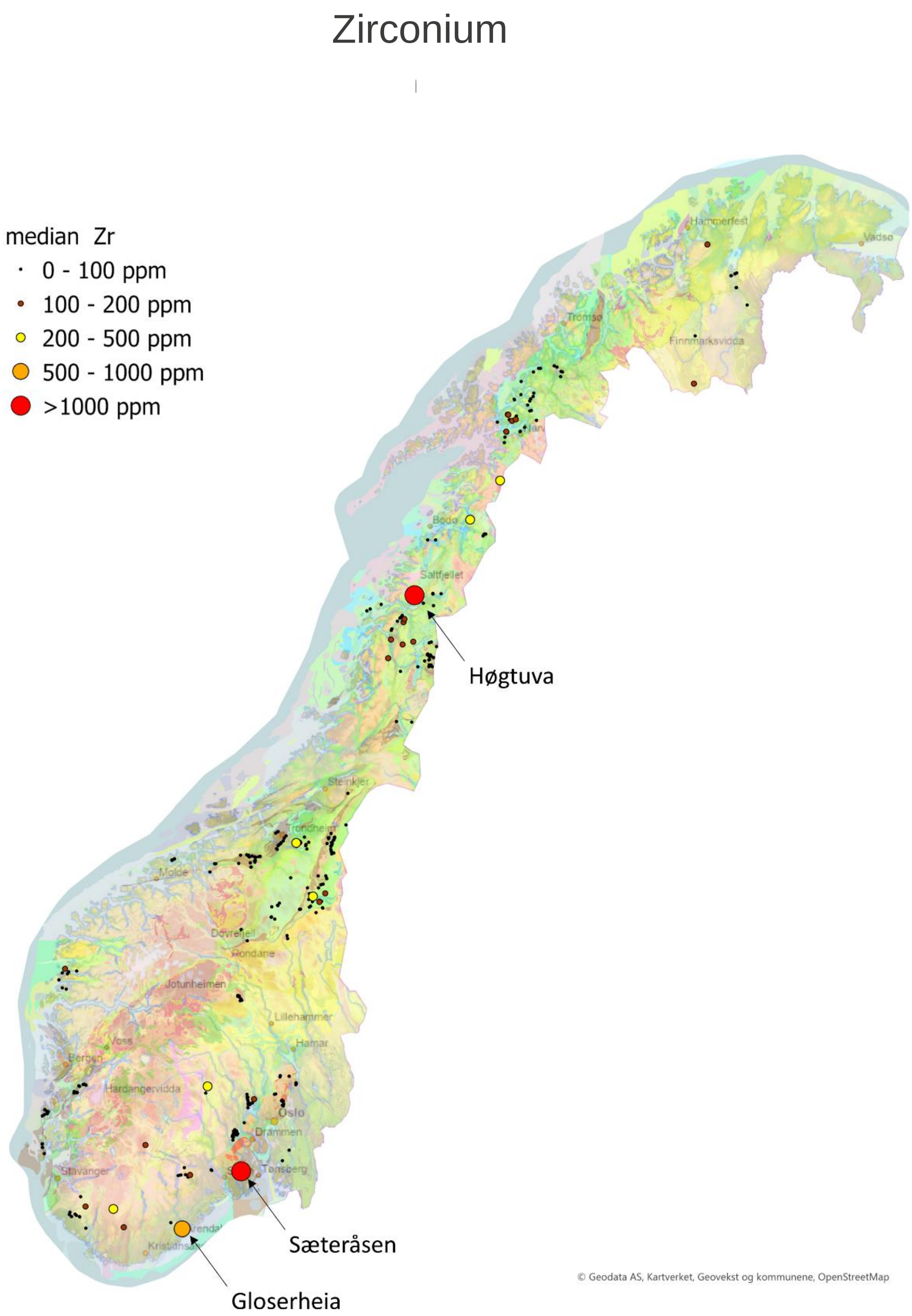

Figure 21 Median content of zirconium in mineral registrations.

3.4 Critical industrial minerals

Industrial minerals are defined as any rock, mineral, or naturally occurring substance with economic value, excluding metals, mineral oil, coal, and gemstones (Evans, 2009). Unlike metals where metal content and purity usually are the most significant factors, industrial minerals are mostly used for their physical and chemical properties such as whiteness, hardness, specific gravity, heat resistance, etc. For most industrial minerals, many buyers have their own and often confidential quality requirements. Therefore, presenting maps showing variation in content, as done for metals, serves no purpose.

Table 4 lists industrial minerals defined as critical with occurrences in Norway.

Table 4 Critical industrial minerals in Norway

Mineral/rock
Barite
Dolomite (magnesium mineral) *
Feldspar and nepheline syenite
Fluorspar
Natural graphite
Olivine (magnesium mineral) *
Phosphate
Quartz (silicon metal grade) **

*Implies production of magnesium metal

** Implies production of silicon

Nepheline syenite and graphite are currently in production as critical minerals in Norway. Norway is a major producer of olivine ($MgSiO_4$) and dolomite ($CaMg(CO_3)_2$). Olivine and dolomite minerals as such are not defined as critical, but dolomite is an important mineral for the production of magnesium metal, and olivine could also become important for magnesium metal production if the technology for this is commercialized.

All occurrences and registrations of critical industrial minerals are shown in Figure 22.

Critical industrial minerals

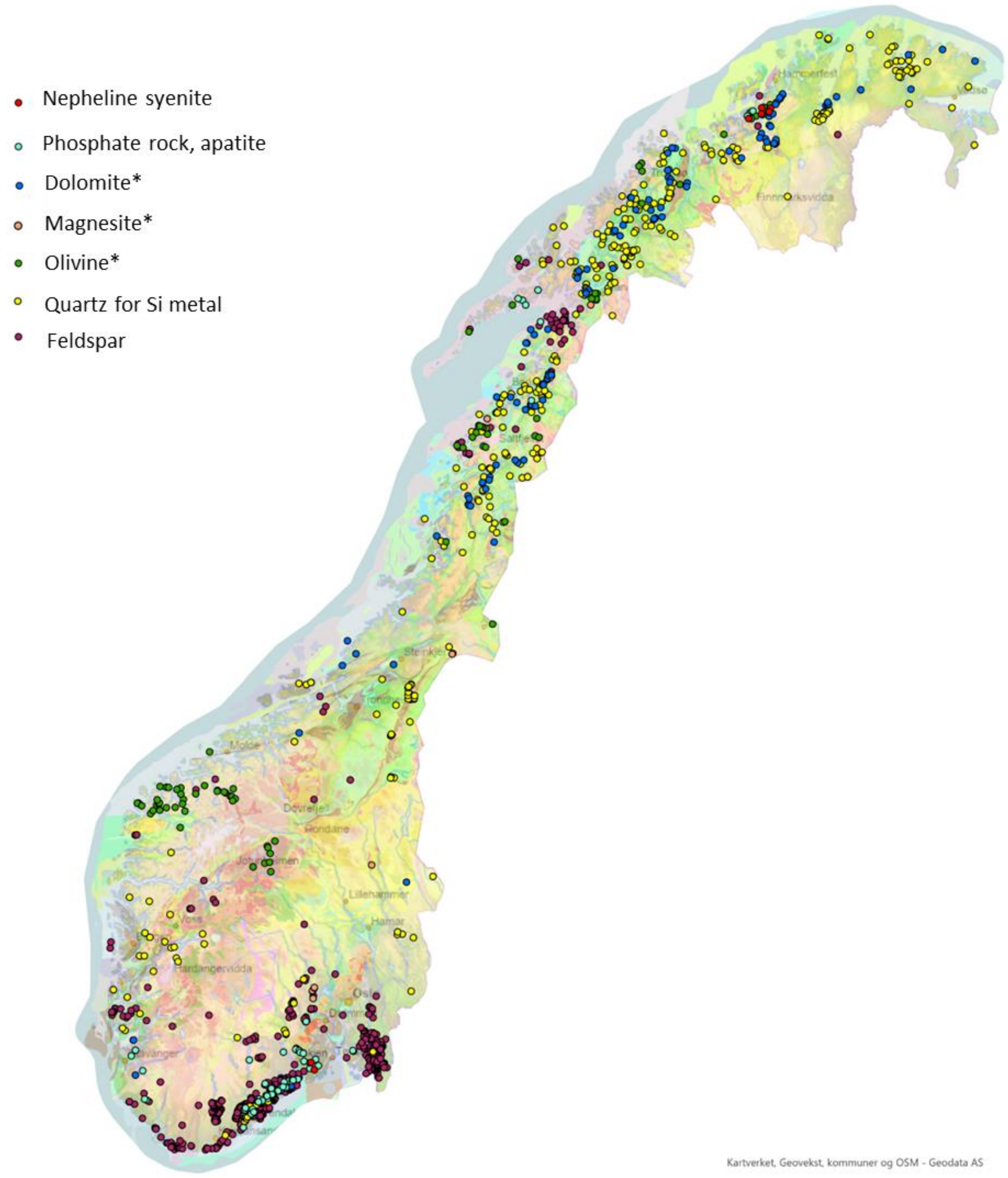

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*Figure 22 Map of the most important critical industrial minerals. *Note: Dolomite, magnesite and olivine requires production of Mg metal.*

3.4.1 Barite ($BaSO_4$)

Barite is a mineral primarily used for its high specific gravity and is also known as heavy spar. Its main application is in drilling fluids for the oil industry, due to its high specific gravity. Norway imports a significant amount of barite. There are a few registrations of barite in Norway, with the most important being at Heskestad in Lista. This occurrence has been investigated thoroughly, but viable tonnages suitable for mining have not been found. Extensive prospecting for barite was conducted in the Varanger Peninsula in the 1980s. Barite was found in several places, but none of the registrations were deemed interesting enough to warrant detailed further investigations (Bølviken et al., 1988). There is also barite in lead-zinc mineralizations in the Bamble field (Styggedalen) and in silver deposits in the Kongsberg area, particularly at Nord-Vinoren and Åslandsåsen, but these are too small to be economically viable. A map of registered barite occurrences in Norway is shown in Figure 23.

3.4.2 Feldspar minerals including nepheline syenite

Feldspar minerals including nepheline syenite have their most important end use in glass and ceramic industries.

Feldspar minerals are among Norway's and Scandinavia's most common industrial minerals. Almost a third of registered industrial mineral occurrences in Norway are feldspar minerals. Up to about the 1960s, there was extensive feldspar production in Norway. Many hundreds of occurrences were mined, primarily focusing on small deposits where feldspar varieties (albite and potassium feldspar) were hand-separated. In this period, NGU mapped most of the feldspar occurrences in Norway (Andersen, 1926, 1928; Barth, 1930; Broch, 1934; Bjørlykke, 1939). During the 1980s, most feldspar deposits relying on manual sorting were shut down. The last major operating feldspar deposit, Glamsland near Lillesand, was closed in 2011. Today, there is only a small production of feldspar in Norway. These and similar occurrences elsewhere in Scandinavia were operational during a time (mostly before 1970) when cost levels and market conditions were very different from today. It is not clear what economic significance these registrations have had and will have in the future. A map of Norwegian feldspar occurrences and registrations is shown in Figure 24.

Nepheline syenite is a rather rare rock type geologically, but Norway has vast resources of it. The most important deposit in Norway is on Stjernøy in Finnmark, where mining has been ongoing since the early 1960s. The deposit currently supplies approximately 300,000 tons or 6% of Europe's annual nepheline syenite consumption. Its primary use is for the glass and ceramic industries. Nepheline syenite competes here with feldspar but has the advantage of a lower melting point, thus saving energy.

In addition to Stjernøy, there are several smaller registrations in the Seiland Province and large deposits in Lågendalen north of Larvik. In the latter area, Norsk Hydro conducted surveys for exploitation in the 1970s (Myhre, 1975; Lindberg, 1976). Concentrates of nepheline syenite have strict quality requirements.

A map of NGU's registered occurrences and registrations of nepheline syenite is shown in Figure 25.

3.4.3 Fluorspar (CaF_2)

Fluorspar/fluorite is an important material to produce synthetic cryolite (Na_3AlF_6), which is used as a flux in aluminum production.

Fluorspar occurrences in Norway are all hydrothermal vein deposits. These occurrences are relatively small but often rich in fluorspar. Small-scale mining has occurred at several occurrences, and slightly larger mining operations at a couple of fluorspar occurrences in Norway. The largest known deposits are Tveitstå near Dalen in Telemark and Lassedalen near Kongsberg. Norsk Hydro conducted extensive surveys of Norwegian fluorspar occurrences in the 1970s without finding viable deposits. NGU currently sees increasing interest among exploration companies for fluorspar in Norway, and some surveys have been conducted, particularly in Lassedalen. A map of Norway's fluorspar occurrences is shown in Figure 26.

3.4.4 Graphite

The main use of graphite is as a refractory material for the metallurgical industry, and graphite is also crucial as an anode material in batteries. Graphite for batteries is also produced synthetically, but the price of synthetic graphite is currently about twice that of natural graphite. Graphite is one of the most important minerals for the green shift, and Norway has been a significant producer in Europe for almost 100 years.

Europe's largest producer of natural graphite is located at Trælen near Skaland on Senja. Norway's total graphite resources are considerable, and surveyed deposits are estimated to contain approximately 240 million tons of graphite ore, with a potential to extract up to 20 million tons of graphite. The deposits are mostly located in areas with highly metamorphic rocks of early Proterozoic age (older than 1800 million years), mainly in Lofoten-Vesterålen, Senja, and northern Helgeland. Graphite registrations elsewhere in the country are considered of lesser significance (Gautneb et al., 2023). There is significant potential for increased graphite extraction in Norway.

An overview of Norway's graphite occurrences is shown in Figure 27, the deposits that are or have been in operation in recent times are marked.

3.4.5 Magnesium minerals; olivine, dolomite, and magnesite

Olivine and dolomite are not considered critical minerals on their own but are, or can be, important raw materials for magnesium metal, which is one of Europe's most critical metals.

Norway was previously a major producer of magnesium metal from Norwegian raw materials (dolomite and seawater). Production ceased in 2001, and throughout the 2000s, all European production of magnesium metal ceased due to Chinese competition, making magnesium metal one of the most critical in Europe. In addition to dolomite, there has been a small production of magnesite (in Buskerud near Modum and Snarum).

If magnesium metal production should commence in Europe in the future, Norway has very large resources of several types of raw materials. Norway is the world's largest producer of olivine ($(Mg,Fe)_2SiO_4$) from Åheim, and the olivine resources are possibly the largest in the world. Additionally, there are very large resources of dolomite ($CaMg(CO_3)_2$). Production of magnesium metal from olivine was thoroughly investigated by the company SilMag in the 1990s. At that time, no application was found for the silica component (SiO_2) in olivine (which constitutes about 46%), and the project was terminated. A map of registrations and occurrences of magnesium minerals in Norway is shown in Figure 28

3.4.6 Phosphate Rocks, Apatite

Phosphate-bearing rocks are used for their content of apatite ($Ca_5(PO_4)_3(F,Cl,OH)$). Phosphate (PO_4^{3-}) is one of the most important components in fertilizers. Norway has very large resources of phosphate-bearing rocks containing apatite. There are mainly three types of apatite occurrences in Norway:

1. Hydrothermal vein deposits
2. Apatite-bearing carbonatites and alkaline complexes
3. Apatite-bearing iron-titanium deposits

Historically, hydrothermal vein deposits were important, especially during periods of import difficulties. Before and during World War I, several apatite occurrences were in operation (Bugge, 1922). Ødegårdens verk in Bamble was the most important and was in operation from 1870 to 1926 and also briefly during World War II.

The most significant occurrences we know of apatite-bearing alkaline complexes are the Misvær complex in Beiarn (Ihlen, 2009) 2009), and the Lillebukt complex on Stjernøy in Finnmark, while the Fen complex at Ulefoss is an apatite-bearing carbonatite complex (Gautneb & Ihlen, 2009). The largest resources of apatite-bearing rocks in Norway are associated with iron-titanium deposits. The most significant known occurrences occur south of Bjerkreim in Rogaland and in the Kodal deposit near Larvik (Ihlen et al., 2012). These occurrences have phosphate rock resources exceeding 3 billion tons. The size suggests these are world-class deposits and contain apatite as one of several valuable components. Should the current explorations in Bjerkreim lead to production, Norway would become a significant producer of phosphate raw materials (https://www.norgemineraler.com/). Norwegian apatite occurrences may also be important sources of rare earth elements (REE) (Ihlen et al., 2012). A map of registered apatite occurrences and registrations is shown in Figure 29.

3.4.7 Quartz for Silicon metal

Silicon metal is produced by melting quartz with carbon as a reducing agent. Norway produces approximately 35% of the EU's consumption and 6% of global production of silicon metal.

40% of the raw materials (quartz) for Norwegian silicon metal production are imported, including from Spain (Jonsson et al., 2022). The uses of silicon metal depend greatly on its purity and quality. Silicon with a purity of around 95% is used for alloys, while semiconductor components in electronics require a purity better than 99.9999%.

Quartz is a very common industrial mineral in Norway; however, the quality requirements for raw materials for silicon metal are strict, and only a limited number of Norwegian occurrences meet the requirements. Norwegian quartz occurrences are shown in Figure 30. The Mårnes and Tana deposits are quartzite deposits, while Nasafjell and Nesodden are hydrothermal quartz (Størseth & Wanvik, 1991; Wanvik, 2002; Ihlen & Müller, 2011). Quartz occurrences and registrations are shown in Figure 30

3.5 Maps of critical industrial minerals

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Figure 23 Map of barite occurrences in Norway.

Feldspar

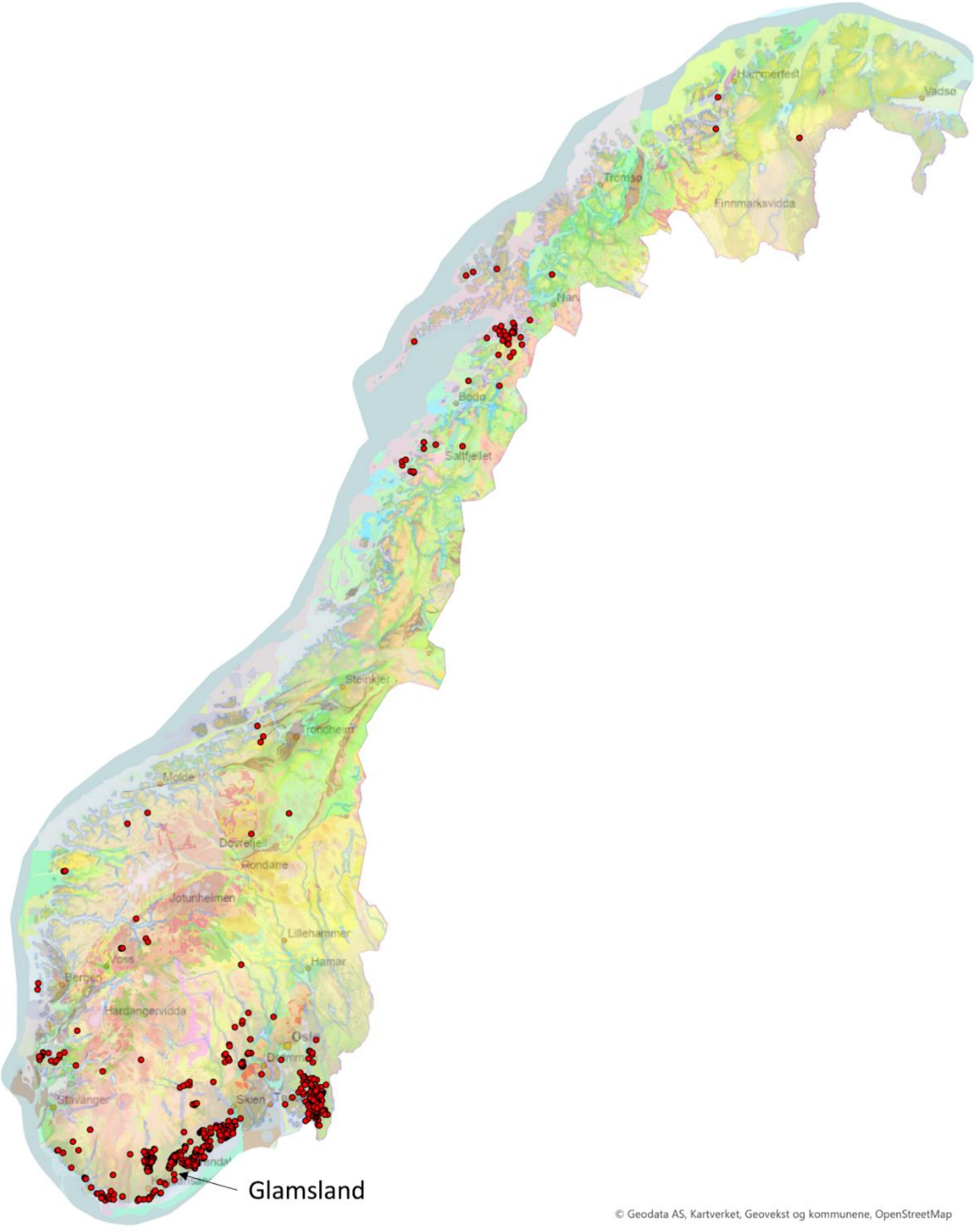

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Figure 24 Map of feldspar occurrences in Norway.

Nepheline syenite

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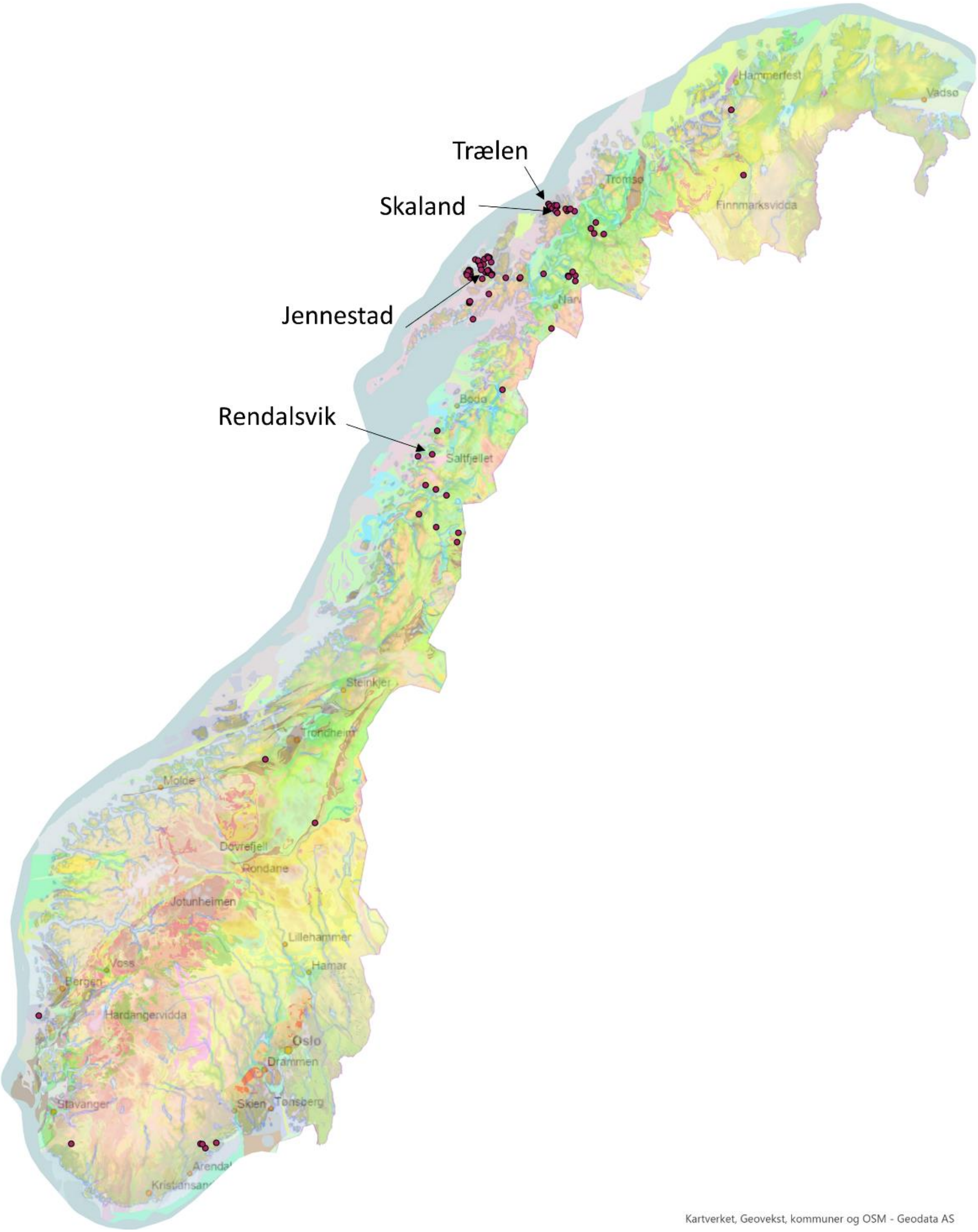
Figure 25 Map of nepheline syenite occurrences in Norway.

Fluorspar

Kartverket, Geovekst, kommuner og OSM - Geodata AS

Figure 26 Map of fluorspar occurrences in Norway.

Graphite



Kartverket, Geovekst, kommuner og OSM - Geodata AS

Figure 27 Map of graphite occurrences and mines in Norway.

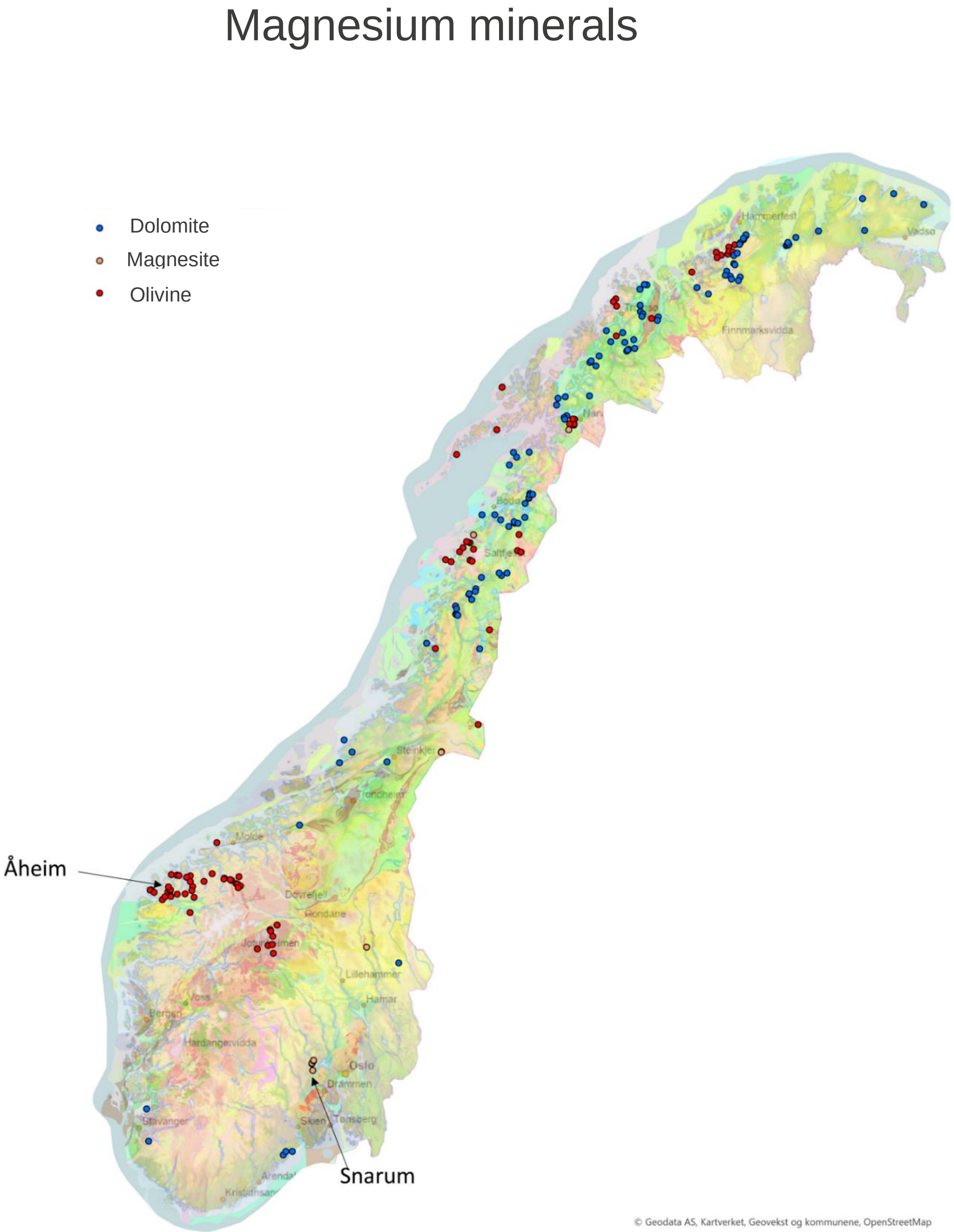


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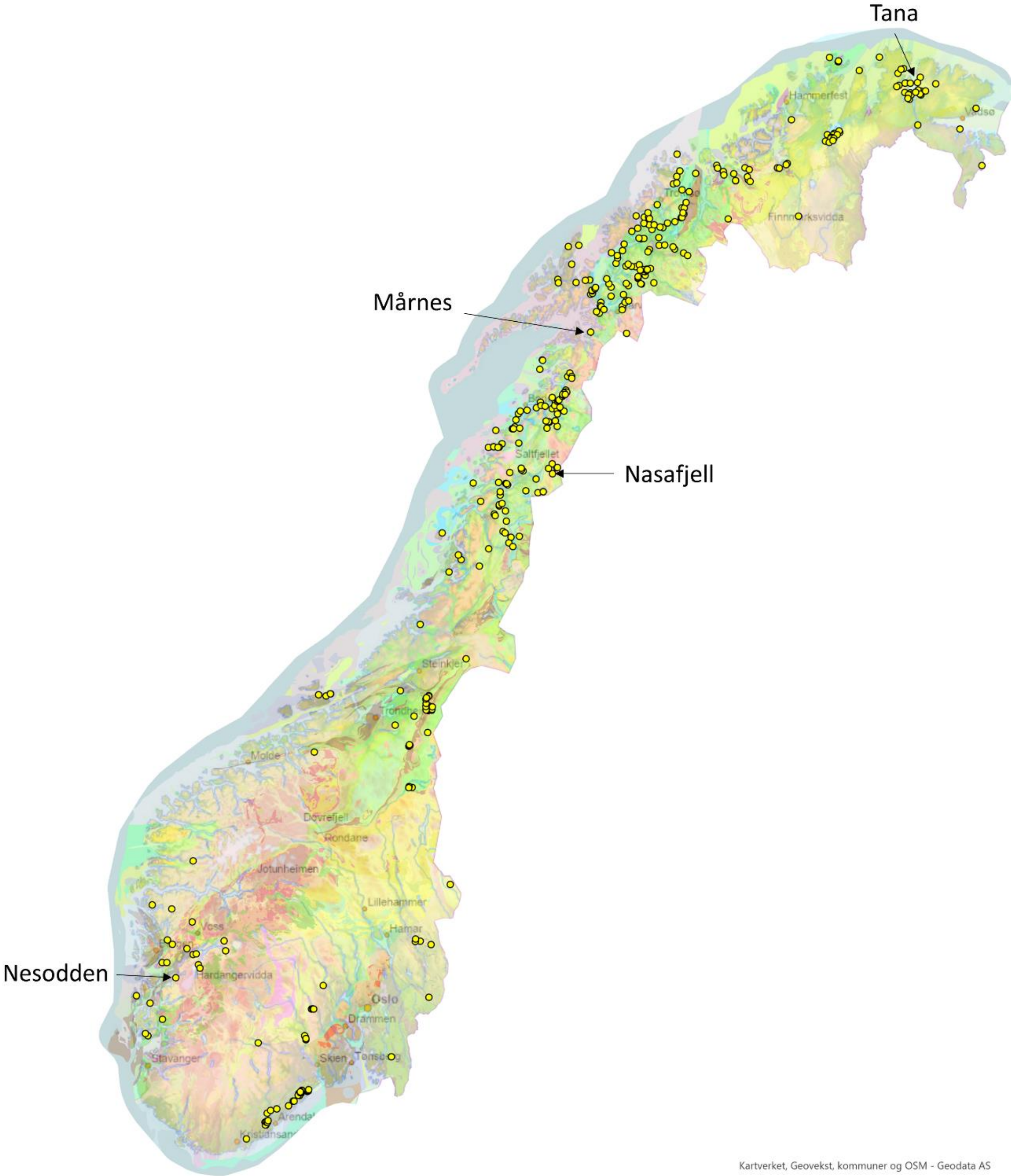
Figure 28 Map of magnesium minerals in Norway.

Phosphate rock

Kartverket, Geovekst, kommuner og OSM - Geodata AS

Figure 29 Map of phosphate rock and apatite occurrences in Norway.

Quartz



Kartverket, Geovekst, kommuner og OSM - Geodata AS

Figure 30 Map of quartz occurrences in Norway.

4. RESULTS AND RECOMMENDATIONS FOR FURTHER WORK

In the chapters above, we have outlined where critical and strategic metals and minerals occur in Norway, based on chemical analyses of samples from the occurrences and deposits. Norway's resources and reserves of critical metals and minerals cannot be quantified based on these data alone. For several of these raw materials, there are inferred, indicated, and measured resources based on surveys conducted by the mining industry. This applies, among others, to copper, nickel, cobalt, niobium, titanium, REE and beryllium. For potential production of magnesium metal, Norway has large and well-documented resources of olivine and dolomite.

Norway possesses significant resources of rare earth metals, nepheline syenite, and graphite. There are also resources of vanadium, fluorspar, and quartz for silicon metal. The chemical analyses from resource databases have not revealed interesting concentrations of the elements antimony, gallium, germanium, indium, or tantalum. Nevertheless, there may be resources containing these elements since many mineral registrations have not yet been sampled or analyzed.

4.1 Further Work

This report provides an overview of parts of the knowledge base for critical minerals in Norway and is an important basis for prioritizing further mineral resource mapping by the Geological Survey of Norway (NGU).

The work on critical metals and minerals will be a priority for NGU for many years, and this report form the basis for increasingly comprehensive overviews of these raw materials. The overviews in the report also contribute to defining metallogenic provinces, which are areas where geological conditions have or could have led to the concentration of various minerals and metals. Facilitating information for exploration companies and other industries interested in bringing new deposits into production, thereby reducing Europe's supply risk to critical materials, will be among NGU's most important tasks in the years ahead.

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