Potential for Critical Raw Material Prospectivity in the UK

Decarbonisation and Resource Management Programme

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BRITISH GEOLOGICAL SURVEY

DECARBONISATION AND RESOURCE MANAGEMENT PROGRAMME

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Front cover

West Rigg mine, Westgate, County Durham, a disused ironstone quarry, now a SSSI. The Slitt Vein is exposed at surface and has previously been exploited for lead and fluorite.

Bibliographical reference

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Foreword

Minerals will assume greater importance in contributing to the UK's economic growth and high standard of living over the coming decades. This will be driven by requirements for the UK to bring all greenhouse gas emissions to net zero by 2050, to grow the advanced manufacturing sector, mitigate risks to national security, deliver economic prosperity and create opportunities for UK businesses in critical mineral supply chains domestically and internationally. This report has been produced by the British Geological Survey (BGS) and has been jointly supported by BGS National Capability funding and the Department for Business & Trade-funded UK Critical Minerals Intelligence Centre (CMIC). The CMIC aims to provide up to date, accurate, high-resolution data and dynamic analysis on primary and secondary minerals resources, supply, stocks and flows of critical minerals, in the UK and globally. Its work supports delivery of the UK Critical Minerals Strategy that aims to improve the security of supply of critical minerals by accelerating the UK's domestic capabilities, collaborating with international partners, and enhancing international markets.

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In addition to a range of colleagues at the BGS and the Geological Survey of Northern Ireland (GSNI) who provided information and assistance, the authors would like to acknowledge the assistance of Katy Mee (BGS) for providing GIS expertise. Charlotte Vye-Brown (BGS), Brian Young (formerly BGS and Durham University) and Peter Jackson (Nenthead Mines Conservation Society) are thanked for their assistance in the North Pennine Orefield. Tim Colman (formerly BGS) is thanked for advice and knowledge. Don Cameron (BGS) is thanked for providing data on mineral occurrences. Eva Marquis (University of Exeter) is thanked for reviewing collated data. Eimear Deady and Kathryn Goodenough would particularly like to thank Mark Hatton, Julian Cruickshank, Warren Allison, and Jonathan Lynch (Cumbria Amenity Trust Mining History Society) for facilitating access to historic mines in Cumbria. The authors would also like to thank Gus Gunn (formerly BGS) for reviewing the report. Finally, the authors would like to thank the exploration and mining companies consulted on this work for freely providing advice and specific knowledge.

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Executive Summary

The UK Critical Minerals Strategy (BEIS, 2022) includes a commitment to “begin a national-scale assessment of the critical minerals within the UK. By March 2023, we will collate geoscientific data and identify target areas of potential”. This report provides that national-scale assessment of the geological potential for critical raw materials in the UK. It represents the published output of a study, jointly funded by the British Geological Survey and the Department for Business and Trade, which reviewed available geoscientific data in order to identify areas of potential geological prospectivity for critical raw materials in the UK.

Critical raw materials (CRMs) are those mineral commodities that are both economically important and at risk of supply disruption. The commodities addressed in this report are those identified as critical to the UK by the Critical Minerals Intelligence Centre (CMIC) (Lusty et al., 2021). These CRMs are currently obtained from mining across the world, but at the time of writing none are produced in the UK, although tungsten has been mined in recent years. Some CRMs such as lithium, tin and graphite are typically the primary products of mines, whereas others are produced as co- or by-products of major commodities such as gold, copper or zinc. Current understanding of the UK’s mineral resource endowment rests largely on evidence from historic mining and exploration, together with targeted academic research. The UK has an extensive history of mining that dates to prehistoric times. Gold, barite, fluorite, gypsum, potash and polyhalite are among the commodities that are currently mined, and exploration for many raw materials is occurring across the whole of the UK.

The work presented in this report follows a methodology known as a mineral systems approach, which relies on the concept that all mineral deposits of a certain type were formed by a combination of particular geological processes (McCuaig et al., 2010). The processes that must operate for a mineral deposit to form are identified and translated into mappable target criteria derived from available datasets. Key datasets to be used would typically include geological maps, geochemical soil and stream sediment maps, geophysical maps, and mineral occurrence databases. The UK has full geological map coverage, but other datasets are incomplete, with high-resolution geophysical data only being available for limited areas. New stream sediment geochemistry maps were created as part of this work and are available on the CMIC interactive map portal[1], but the whole country is not covered for all elements. These data limitations mean that this report only provides a knowledge-driven assessment of geological potential for CRM prospectivity across the UK. It provides maps for CRMs (grouped or singly as geologically appropriate) indicating the areas where the geological criteria have been met and thus there is potential for deposits of these CRMs to occur. It is important to note that the maps represent areas of potential prospectivity, not where deposits of critical minerals are guaranteed to be found, and also that mineral deposits could be found beyond the identified prospective areas, where localised geological conditions are suitable. The areas identified in the maps can be considered as targets for more detailed research and exploration. This report focuses solely on the geological potential and does not consider other aspects such as environmental designations and planning considerations that may affect the development of a mineral deposit.

Combining all the individual maps highlights areas that are prospective for several CRMs and are thus priority for further geological investigations. From north to south, these areas include: areas of prospective geology around Loch Maree near Gairloch; parts of the central Highlands and Aberdeenshire; areas of prospective geology in mid-County Tyrone in Northern Ireland; parts of Cumbria; parts of the North Pennine Orefield; areas in north-west Wales and Pembrokeshire; and south-west England. These areas should now be the focus for collection of new geological, geochemical and geophysical data, in order to identify new CRM prospects for detailed investigation.

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[1] https://www.ukcmic.org/index.html#interactive-map

1 Introduction

Critical raw materials (CRMs) are those **commodities**[2] that are economically important and at risk of supply disruption. Many CRMs are essential for the technologies that will enable decarbonisation of the global economy, such as electric vehicles and renewable energy infrastructure. The UK critical raw materials list (Lusty et al., 2021) classifies those commodities that are most important to the UK's economy, and which have the greatest risk of supply disruption (Figure 1). The CRMs identified as being of elevated or high criticality include the essential raw materials for lithium-ion batteries (lithium, graphite, nickel, manganese, and cobalt); the rare earth elements (REE), which are used in permanent magnets that are a key component of generators in wind turbines and motors in electric vehicles; tellurium for solar panels; and silicon, gallium and germanium used in semiconductors.

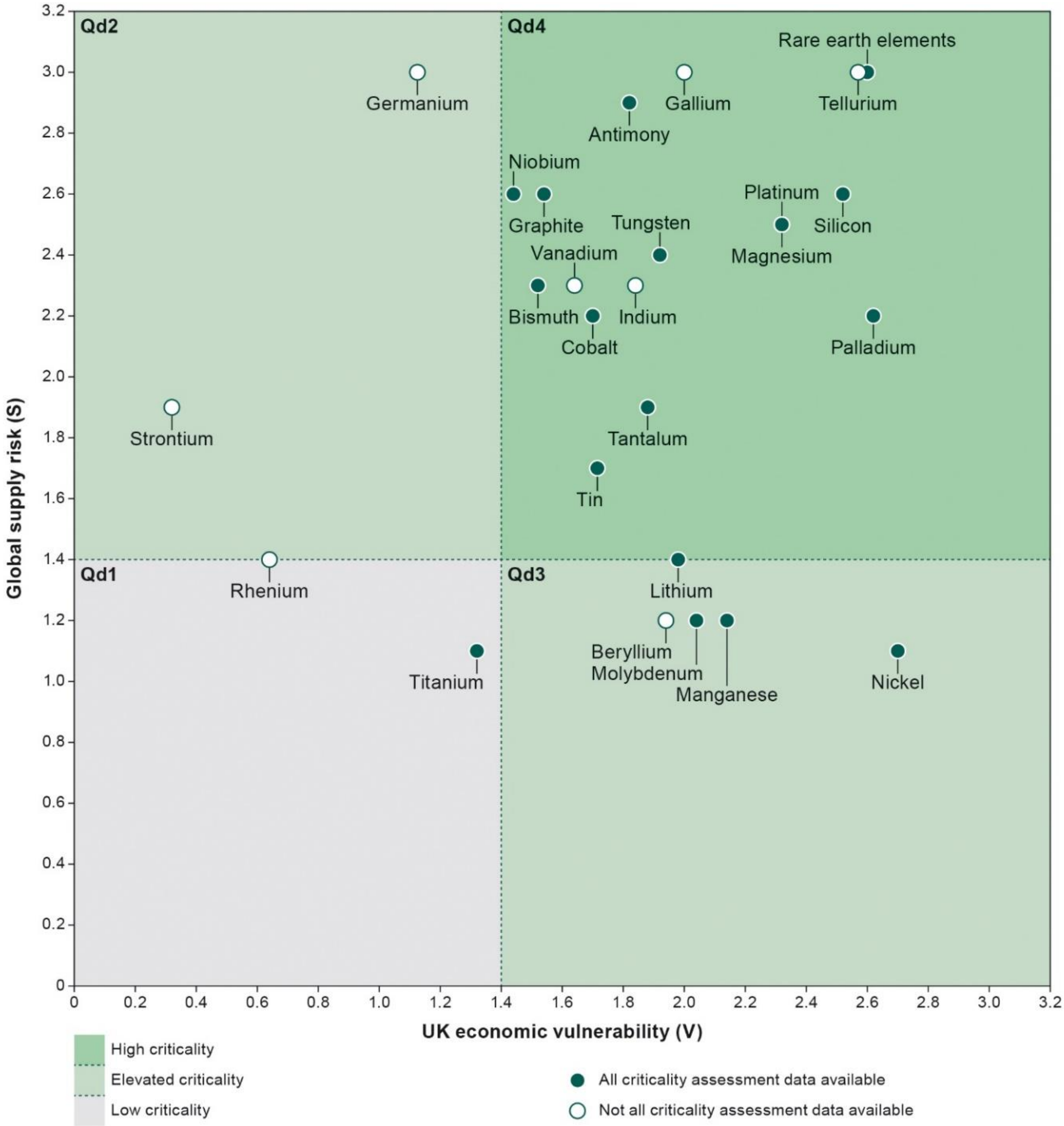

Figure 1 Critical raw material matrix for the UK, from Lusty et al., 2021. CRMs plotting in the top right quadrant are considered to be highly critical for the UK.

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[2] Words in bold will appear in the glossary

Although there is limited mining for CRMs in the UK at the time of writing, there is an extensive record of historic mining, and geologically the UK has the potential to be prospective for many CRMs. The UK Critical Minerals Strategy (BEIS, 2022) includes a commitment to “begin a national-scale assessment of the critical minerals within the UK. By March 2023, we will collate geoscientific data and identify target areas of potential”. This report provides that national-scale assessment of the **geological potential** for critical raw materials in the UK. It draws on available geoscientific data, and takes a mineral systems approach, to identify broad target areas for further study. It does not provide deposit-scale analysis or rank particular deposits or areas as being of most significance. In this report, we consider the commodities recognised as being of high criticality and elevated criticality by Lusty et al. (2021).

2 Major mined raw materials and by- and co-products

All mineral and metal raw materials must initially be recovered by mining of a **mineral deposit**; that is, a natural accumulation of a particular mineral at unusually high concentration in the Earth’s crust. A mineral is defined as a chemical compound with distinctive chemical and physical properties, such as quartz (SiO_2). Many of the individual critical raw materials discussed in this report are metallic elements, which do not occur in nature in their native (pure) form but may be constituent parts of a range of different minerals. Mineral deposits occur in a range of geological environments, and mineral deposits that can be shown to have formed through a similar set of geological processes are termed **mineral systems** (section 4). The location of a mineral deposit is determined by geological processes, but the development of that deposit into a mine is dependent on a range of other factors, relating to political, economic, social, environmental and legal considerations. Information on global mine production can be obtained from the BGS ‘World Mineral Production’[3] statistical publications and archive.

The majority of CRMs listed in the UK Criticality Assessment (Lusty et al., 2021) are not mined as major commodities, but they typically can be recovered as by- and co-products from ore-forming minerals. **Ore-forming minerals** are those mined for major commodities, such as galena (PbS) for lead (Pb), sphalerite (ZnS) for zinc (Zn), or chalcopyrite ($CuFeS_2$) for copper (Cu). Other metals produced as major commodities include iron (Fe), tin (Sn), tungsten (W), gold (Au), titanium (Ti), aluminium (Al), manganese (Mn), uranium (U), and chromium (Cr) (Goldring and Juckes, 2001). Some CRMs, including lithium (Li), niobium (Nb) and platinum group elements (PGE) may be produced as major commodities. Co-products are those raw materials produced alongside the major commodities that contribute materially to the economics of a deposit, whereas by-products are typically lower value commodities that make up <0.1% of an ore deposit and rarely form viable ore deposits on their own (Nassar et al., 2015). Each ore-forming mineral can be host to multiple by- and co-products (Figure 2). Those commodities typically produced as by- and co-products have enhanced criticality, as their market is inelastic and dependent on the demand and production of their hosting major commodity.

Of the 18 CRMs deemed to be of high criticality to the UK, 11 (>60%) were produced as by-products globally in 2008 (Nassar et al., 2015). In some cases, even where CRMs are a possible by-product (for example antimony (Sb) from gold or bismuth (Bi) from copper) producers are unlikely to increase by-product production despite high demand since the financial return is simply not high enough (Fu et al., 2019). However, with changing market conditions, or the emergence of new technologies that can modify value profiles, this dynamic can change. Therefore, it is essential to understand which ore-forming minerals and mineral systems may host specific co- and by-products to better assess the potential for CRM. This will also inform how primary ore can be processed with maximum economic and environmental efficiency to recover potential associated CRMs; a concept termed ‘full-value mining’.

[3] https://www2.bgs.ac.uk/mineralsuk/statistics/home.html

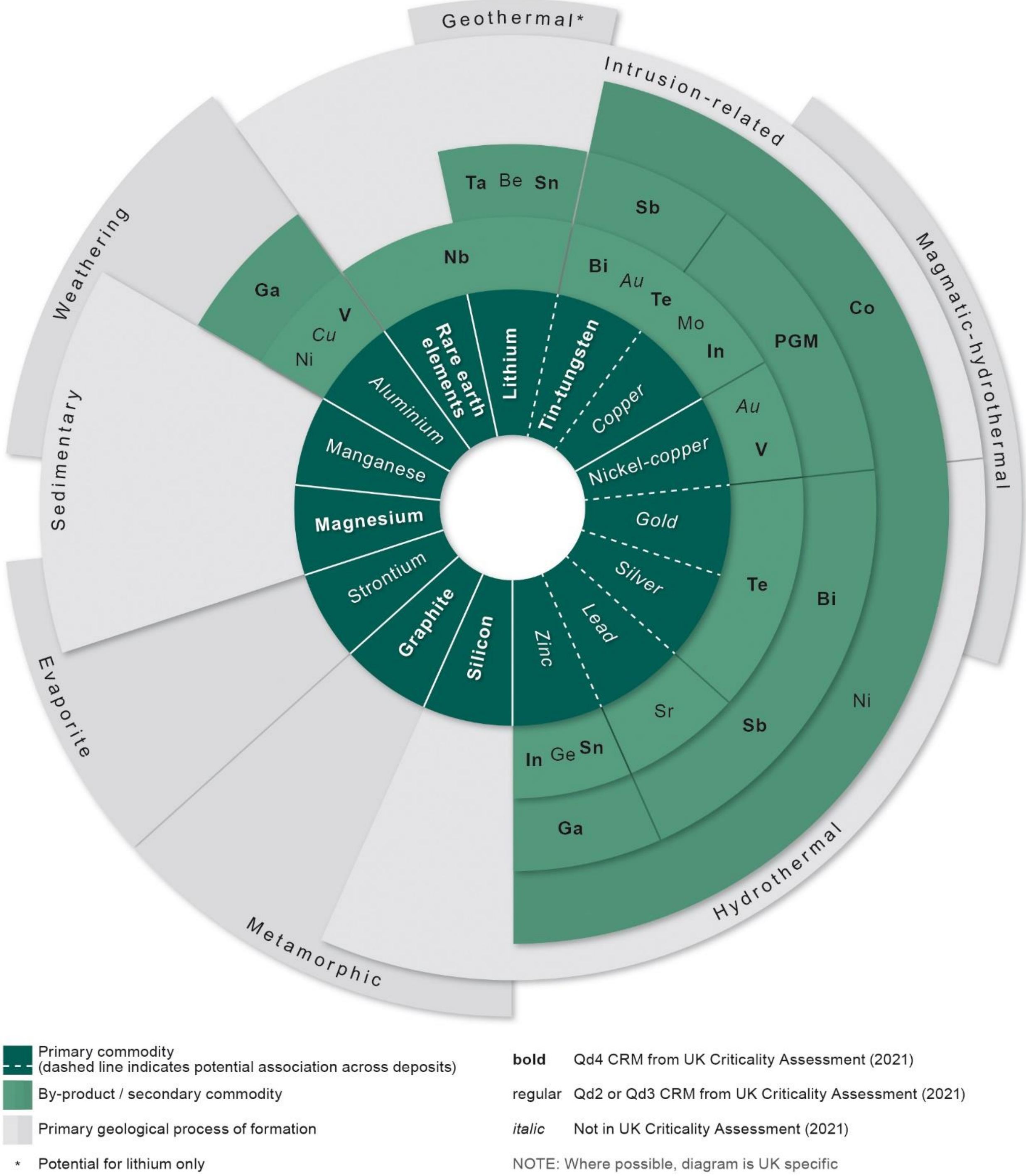

Figure 2 Major mined commodities (centre, dark green) shown with potential co- and by-product commodities and their primary geological process of formation.

2.1 RECYCLING AND ALTERNATIVE SOURCES

There is some potential for derivation of CRMs from alternative sources, including using waste from mining and processing, and recycling end-of-life products. In many cases, CRMs may not have been extracted by historic mining, and thus there is significant potential to produce them through the reprocessing of mine waste (van der Ent et al., 2021). Similarly, CRMs could be recovered in significant quantities during processing of the major commodities. For example, by-products of the Cu electrolytic refining process could potentially produce sufficient Sb, Bi, and Te to supply much of the world's needs (Moats et al., 2021).

Recycling is a vital component of raw material supply chains, especially for major commodities such as aluminium and copper. However, recycling of CRMs is more challenging. Less than 1% of rare earth elements (REE) are recycled from end-products such as permanent magnets, lighting, batteries, and catalysts with the remainder going to waste (Eggert et al., 2016; Jowitt et al., 2018). The International Energy Agency suggests that by 2030, only around 1–2% of the anticipated raw material demand for electric vehicle batteries will be met from recycling (IEA, 2022). Thus, recycling and the development of CRM-specific recycling capabilities will play a significant role in decarbonising future economies, but achieving this will take time; and lack of incentive for improving mining recovery efficiency may limit by-product availability (Fu et al., 2019).

An approach that focuses on extraction of CRMs throughout the whole value chain, including mining and processing waste, scrap material, and end-of-life recycling, has the potential to help alleviate the risk of supply disruption and hence criticality. This highlights the importance of understanding secondary resources as potential hosts of CRMs. However, in the immediate future, primary mining will continue to represent the main source of CRM supply.

3 Geology of the UK

The geological history of the UK spans two-thirds of the history of the Earth, from rocks formed 3000 million years ago (Ma) to sediments formed in the last few thousand years (Woodcock and Strachan, 2009). Very broadly, the oldest rocks in the UK are found in the north-west of Scotland, and the youngest in the south-east of England. Key geological processes that have led to the formation of mineral deposits include **igneous** processes such as the eruption of volcanoes and the **intrusion** of hot **magma** into the crust beneath them; **metamorphism** of rocks, at high temperatures and pressures; and the formation of **hydrothermal** systems, where hot fluids circulate through fractures in the crust, potentially leading to the formation of mineral **veins**.

The UK’s oldest rocks are found in the Lewisian Gneiss Complex, chiefly exposed along the north-western coast of Scotland and on the Outer Hebrides. The Lewisian Gneiss Complex is dominated by **felsic gneisses**, but also includes **mafic-ultramafic** rocks and **metasedimentary** rocks. The majority of these lithologies were formed around 3000–2500 Ma (during the Archaean era) and affected by metamorphism and deformation during the Palaeoproterozoic around 1900–1600 Ma.

Much of the Scottish Highlands is underlain by rocks formed during the Meso- to Neoproterozoic between 1200 and 600 Ma. The rocks of the mainland north of the Great Glen **Fault** (Figure 3) are dominated by sandstones, formed in major river systems eroding an ancient mountain chain some 1200–1000 Ma, which have been variably metamorphosed. In contrast, the north-west of Northern Ireland and the Central Highlands of Scotland (between the Great Glen and Highland Boundary faults) are underlain by a much more variable package of metamorphosed **sedimentary** rocks of the Dalradian Supergroup, deposited in an ancient ocean named Iapetus. This geological **terrane** is highly prospective for a range of commodities (Smith et al., 2003). Rocks formed during the Proterozoic Era are also found in smaller areas in England and Wales, particularly on Anglesey and along the Welsh Borders.

A major event in the geological history of the UK was the closure of the ancient Iapetus ocean around 430 Ma (the Caledonian **Orogeny**), bringing what is now England adjacent to Scotland and Northern Ireland along a **suture zone**. This continental collision led to the metamorphism of most of the Proterozoic rocks of Scotland and Northern Ireland. Fragments of ocean floor, known as **ophiolites**, are preserved in a few places including Shetland, south-west Scotland, and Northern Ireland. The sedimentary rocks of the Southern Uplands of Scotland, and the southern part of Northern Ireland, were deposited on the floor of the Iapetus ocean during the Ordovician and Silurian periods and were subsequently squeezed and compressed between the two continents as the ocean closed. On the southern side of the Iapetus ocean, sedimentary rocks were laid down in the Welsh and Lake District basins during the Cambrian and Ordovician periods, with the late Ordovician being marked by the eruption of major volcanoes that now form the mountains of the Lake District and Snowdonia. Following continental collision, during final closure of the Iapetus ocean, volcanic activity developed across the Iapetus suture zone and the area to the north during the Devonian period. Volcanic rocks of this age occur at Ben Nevis, Glencoe and in the Ochil and Cheviot hills, whilst **granite plutons** across the Scottish Highlands and the Southern Uplands were formed at depth beneath volcanoes. This period of volcanic activity was associated with the formation of extensive hydrothermal systems which generated a variety of mineral deposits (Spence-Jones et al., 2018).

During the Carboniferous period (358–299 Ma), much of the UK lay within a major continent which was gradually extending (**rifting**). Sedimentary rocks, including coal, limestone and mudstone, were laid down in shallow basins across central Scotland, the southern part of Northern Ireland, and the Pennines in northern England. Periodic volcanic activity generated important landscape features such as the Whin Sill of northern England, and Arthurs Seat in Edinburgh. The North Pennine Orefield formed in association with this volcanic activity (Dempsey et al., 2021), and other lead-zinc veins across the UK may have been generated at the same time. The most geologically active part of the UK at this time was south-west England, which was affected by a continental collision occurring to the south of the UK (the Variscan Orogeny). In this area, sedimentary rocks were deposited in basins during the Devonian and Carboniferous, then subsequently deformed and metamorphosed. A fragment of ocean floor material was preserved in this area as the Lizard ophiolite. Continental collision led to the emplacement of granite plutons and the formation of hydrothermal systems, generating the Cornubian Orefield.

Through the Permian and Triassic (299–201 Ma), the UK lay within a supercontinent, with sedimentary rocks deposited in **terrestrial** rift basins. From the end of the Triassic onwards, subsidence during the Jurassic and Cretaceous periods led to the deposition of marine sedimentary rocks across south-east and eastern England, and in the Irish and North seas. During the Cenozoic (66 Ma to present), the opening of the North Atlantic led to the development of volcanism across north-west Scotland and Northern Ireland.

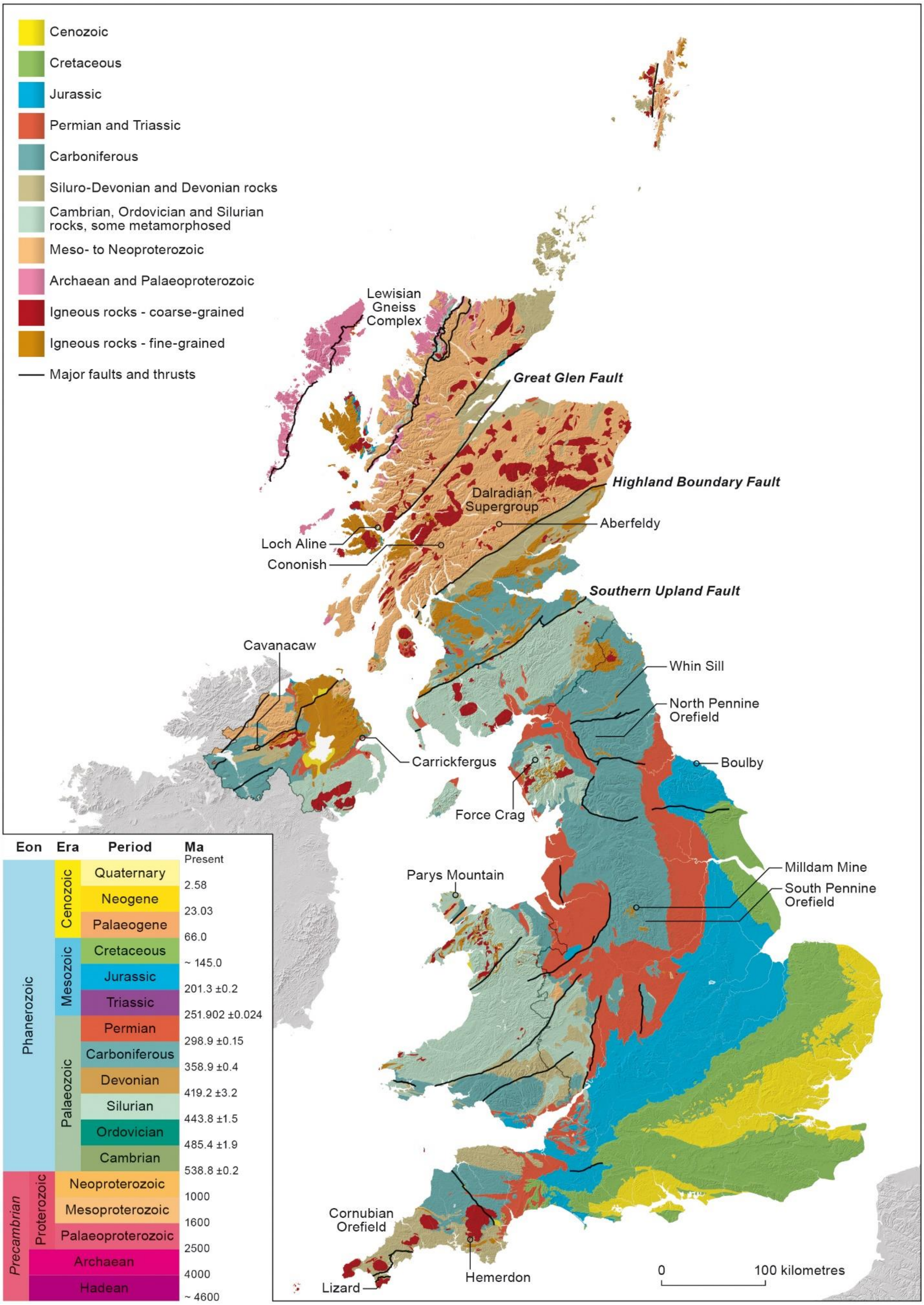

Figure 3 Simplified geology of the UK; inset shows the subdivisions of geological time. Key localities and geological structures mentioned in the text are shown.

4 Mineral Systems

Current understanding of the UK's mineral resource endowment rests largely on evidence from historic mining and exploration, plus targeted research. Many of the CRMs that are now of interest have only become important with the advent of certain modern technologies. As a result, these commodities have not been the subject of any sustained, systematic UK exploration. Thus, to assess the potential prospectivity of the UK for CRMs, a mineral systems approach has been used. This approach is based on the concept that all mineral deposits were formed by a combination of particular geological processes (McCuaig et al., 2010). The approach begins by identifying the essential processes that must operate for a mineral deposit to form, and then translating those processes into mappable target criteria that can be identified in available datasets. Where detailed datasets (e.g., geophysical, geochemical, and geological surveys) are available across the whole of the region to be assessed, data-driven prospectivity modelling can be carried out for each specific mineral system (e.g., Lawley et al. 2022).

The UK is covered by a patchwork of relevant data of different ages and at different scales (see section 6). In particular, high-resolution geophysical data is lacking for much of the country. Due to the limitations on data availability, this report provides a knowledge-driven prospectivity assessment. The commodities on the UK critical raw materials list have been assigned to a series of mineral systems with distinct geological attributes (e.g., mafic-ultramafic igneous complexes for Ni and PGE), and expert geologists have then identified the mappable target criteria for those mineral systems. Subsequently, the available datasets have been used to map areas that meet those criteria and are considered potentially prospective for the associated critical raw materials. The individual criteria are discussed below for each relevant mineral system in turn. The maps presented here do not represent areas where deposits of critical minerals are guaranteed to be found; they simply represent areas where the geological criteria have been met and thus there is potential for deposits to occur. It is also important to note that mineral deposits could be found beyond the identified prospective areas, where localised geological conditions are suitable.

This assessment solely considers the geological prospectivity of an area and does not consider other parameters which would be essential for exploration or mining permitting. Such factors might include National Park boundaries, areas of outstanding natural beauty (AONB), sites of special scientific interest (SSSI) and other protected areas; urban areas, infrastructure, or any other planning limitations. An essential part of any exploration or mining licence is the social licence to operate (SLO) which refers to a local community's acceptance or approval of a project or a company's ongoing presence, beyond formal regulatory permitting processes (Prno, 2013). Bide et al. (2022b) published best practice recommendations for securing a sustainable supply of CRMs for the UK, including how to improve the environmental, social and governance (ESG) performance of the mining industry.

5 History of UK mining

The first known UK instance of mining for a specific commodity is that of flint mining from around 4000 BCE (Edinborough et al., 2020). Thereafter, copper, gold, tin, and lead were the first metals mined in the UK from the Early Bronze Age (Timberlake, 2017). Examples include mining in Wales, at localities such as Parys Mountain, and alluvial tin and gold extraction in several areas around Cornwall and Devon (Carey et al., 2022; Penhallurick, 1986).

Small-scale domestic iron mining operations were common in the Iron Age across Britain (Stetkiewicz, 2016). With the arrival of the Romans, larger iron mining operations and mining of copper, gold, silver and lead intensified (Bayley, 1992; Jones and Lewis, 1971; Tylecote, 1964). Alloying and recycling of metal was an essential part of industry in post-Roman UK (Cleere, 1981; Pollard et al., 2015). Copper, tin, zinc, and lead were the most common metals used in alloys of this time, though arsenic, antimony, gold, and nickel have been detected (Pollard et al., 2015). Supply of raw materials, including alloys, pewter, and glass from continental Europe and Scandinavia bolstered UK stock through the Middle Ages (Bayley, 1992).

From the 18th to late 19th centuries, mining across the UK increased significantly, driven in part by the advent of efficient steam engine use in mining of iron, copper, tin, and zinc (Jenkins, 1945). Non-**ferrous** metallic mining in the UK at this time was primarily focussed on vein and **alluvial** deposits producing millions of tons of gold, lead, zinc, copper, and tin across Cornwall and Devon, Somerset, North and Central Wales, Shropshire, the North and South Pennine Orefields, Cumbria, and many parts of Scotland, and across Counties Armagh and Down in Northern Ireland. Metals now considered to be CRMs, such as antimony, tungsten, nickel, cobalt and manganese were also extracted across the UK at this time, albeit to a lesser extent (Brown and Pitfield, 2014; Dines, 1956; Duller et al., 1997; North, 1962; Wilson and Flett, 1921). Iron extraction from Jurassic and Cretaceous ironstones of central and eastern England eclipsed all non-ferrous mining from the 18th century onwards, reaching a peak in the early 1970s (Goldring and Juckes, 2001). Iron and **bauxite** were worked extensively from the Palaeogene **laterite** in County Antrim, Northern Ireland from the mid-19th century to 1945.

The decline of UK metal mining began in the late 19th century as metal prices and emerging overseas markets rendered production uneconomical (Kincey et al., 2022). By the 1960s almost all UK metal mining had ceased, with only a few prominent mines like South Crofty and Wheal Jane in the Cornubian Orefield mining tin, tungsten, and arsenic (Dines, 1956). Force Crag, the last lead-zinc-baryte mine in Cumbria, closed in 1991, and the final metal mine in south-west England, South Crofty, produced tin sporadically until its closure in 1998. Despite the closure of many mines, mineral exploration continued (at varying levels of intensity) throughout the 20th century (Colman and Cooper, 2000). Significant discoveries of copper, gold, tin, potash and barite were made during the 1960s, 1970s and 1980s. At the time of writing, ongoing metal mining includes gold extraction at Cononish near Tyndrum in Scotland and at Cavanacaw near Omagh in Northern Ireland, and lead as a by-product of fluorite mining at Milldam Mine, Derbyshire. The tungsten-tin mine at Hemerdon was recently operational (2015–18) and is in the process of redevelopment (2020–present). Industrial minerals are also mined at several locations, including barite at Aberfeldy and silica sands at Loch Aline in Scotland; halite at Carrickfergus, County Antrim in Northern Ireland; potash and polyhalite at Boulby in north Yorkshire; and gypsum in Staffordshire. Anglo American is constructing the major Woodsmith polyhalite mine in north Yorkshire. Exploration for gold, tin, tungsten, lithium, rubidium, potassium, caesium, barite, silver, copper, zinc, lead, nickel, cobalt, and PGEs is underway.

6 Available data

The geological prospectivity of the UK for CRMs was assessed using a wide range of data and literature including material held by BGS, publications in academic journals, and grey literature available online. Geological maps and associated memoirs represent one of the most important data sources. A combination of 1:625,000 maps for GB, 1:50,000 for UK, and 1:250,000 geological maps for Northern Ireland were used to identify relevant lithologies and geological units across the UK. These maps are available online through the BGS GeoIndex[4]. Only limited data are available for the Isle of Man, which has not been assessed in detail.

The BGS Geochemical Baseline Survey of the Environment (G-BASE[5]; Johnson and Breward, 2004) is the national strategic **geochemical** mapping programme in Great Britain. This programme involved the collection and geochemical analysis of stream sediment (UK-wide) and soil (Northern Ireland, England and Wales) samples at a consistent density across the country (Everett et al., 2019). Beginning in the late 1960s in northern Scotland and moving southwards

[4] https://mapapps2.bgs.ac.uk/geoindex/home.html
[5] https://www.bgs.ac.uk/geology-projects/applied-geochemistry/g-base/

across the country, the primary focus was mineral exploration, but the project developed as an environmental baseline. The analytical methods used, and hence the elements that were analysed, changed through the course of the project (Everett et al., 2019). The final G-BASE samples were collected in southern England in 2014, as part of the Tellus SW project, where along with stream and soil geochemical samples, a high resolution airborne **geophysical** survey and LiDAR survey were carried out. In Northern Ireland, geochemical baseline data were collected as part of the Tellus survey from 2004-2006. This work completed the Northern Ireland survey of stream sediment and water sampling started in 1994 by BGS on behalf of the Department of Economic Development and Department of Environment. Soil geochemical data from the Tellus survey, available free for download from the OpenDataNI portal[6], was used to support the assessment in Northern Ireland.

For the purposes of this assessment, stream sediment geochemistry maps were prepared and made available online through the CMIC interactive[7] map portal. These maps show interpolated concentrations of 31 chemical elements analysed in approximately 111 000 stream sediment samples collected across the UK. Sampling was carried out annually from 1968 to 2013. Some elements have coverage for the entire country, but other elements have only partial coverage. These map layers are designed to visually highlight geochemical anomalies — areas where significantly high values of each element were measured in stream sediment samples. Stream sediment geochemical mapping is a key survey method for mineral reconnaissance and accordingly it can be used to identify potential targets for critical raw materials. It is important to note that the visualisation scheme used here is relative: it shows the location of samples that have high concentrations in comparison with most others in the dataset. This means that, in isolation, the layers should not be taken as verifying the presence of any prospective mineral deposit(s). Likewise, high values of any potentially harmful element should not be taken to indicate the presence of contaminated land or watercourses. While element concentrations are primarily influenced by natural factors, including bedrock geology, **weathering** processes and mineralisation, human effects such as urbanisation, industry, mining and agriculture are also important influences. For example, in the case of lead (Pb), copper (Cu) and antimony (Sb), high values are associated with some of the UK's most heavily urbanised and industrialised areas such as Leeds, Bristol, Glasgow and Birmingham. Further information on the preparation of the geochemical anomaly maps can be found on the CMIC website[8].

Historic exploration datasets in the form of reports from the Mineral Exploration and Investment Grants Act (MEIGA) and Mineral Reconnaissance Programme[9] (MRP) run by the British Geological Survey during the 1970–1990s provided additional information for the assessment. MRP reports are available through the BGS GeoIndex[10]. The MEIGA was the basis under which the DTI (Department for Trade and Investment) gave grants for mineral exploration for non-ferrous metals, fluorspar, barium minerals and potash, and the results of more than 150 projects carried out under this scheme between 1971 and 1984 are available on open file at BGS. The Mineral Occurrences database, the ‘Metallic Minerals (Wales)’ dataset and the BritPits database (‘Mines and quarries’) provided data on active and historic mines across Great Britain, and are available on the BGS GeoIndex[10]. Data on the mineral occurrences of Northern Ireland[11] are available in greater resolution as these are published separately. Publicly available data from company websites, reports and scientific journals, plus **CRIRSCO** (Committee for Mineral Reserves International Reporting Standards)-compliant reported data on **resources** and **reserves** were used to support this assessment (Bide et al., 2022a). Many stakeholders also contributed, including mining heritage groups and industrial partners.

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6 http://www.opendatani.gov.uk/
7 https://www.ukcmic.org/index.html#interactive-map
8 https://ukcmic.org/portal-layer-documentation/stream-sediment-geochemistry-for-the-uk.html
9 https://www2.bgs.ac.uk/mineralsuk/exploration/potential/mrp.html
10 https://mapapps2.bgs.ac.uk/geoindex/home.html
11 https://gsni-data.bgs.ac.uk/geonetwork/srv/eng/catalog.search#/metadata/2e20349a-fd0d-44e6-ac15-c45629b5cf29

7 Individual CRM prospectivity assessments

This section summarises the mappable target criteria and the datasets used to identify potentially prospective areas for each CRM. Where certain CRMs occur within the same mineral system they have been grouped together. All the CRMs that are recognised as being of high or elevated criticality for the UK (Lusty et al., 2021) are included, with the exception of niobium. Niobium is most commonly mined in an unusual rock-type called **carbonatite**; only one very small area of carbonatite exists in the UK, at Loch Urigill in the north-west Highlands of Scotland (Young et al., 1994), and it is known to be low in niobium. It is thus considered that the UK has no prospectivity for niobium.

7.1 ANTIMONY (Sb)

Antimony (Sb) is concentrated in a variety of geological settings. It is produced as a primary product from hydrothermal quartz-stibnite (SbS) vein deposits and as a by-product of **polymetallic** hydrothermal vein mineralisation, particularly in association with lead mineralisation. Hydrothermal vein deposits can form in several different types of system, including the peripheral parts of **orogenic gold** and other gold-hosting deposits, and in **porphyry** deposits (Hofstra et al., 2013; Seal II et al., 2017). In addition to the vein-related mineralisation, **volcanogenic massive sulfide** (VMS) deposits can be enriched in Sb (Taylor et al., 1995) but Sb has not previously been considered as a by-product of metal production from these systems. Antimony mineralisation can also occur alone with no apparent association with other mineral deposits.

Mappable prospective geology for VMS deposits includes volcanic rocks considered to have formed in a submarine setting or on a continental margin, such as Ordovician volcanic rocks in North Wales, Pembrokeshire and Cumbria, volcanic layers within the Dalradian Supergroup of the Central Highlands, the Tyrone Igneous Complex of Northern Ireland, and the rocks of the Loch Maree Group near Gairloch. Mapping polymetallic hydrothermal veins is based on known vein occurrences. The details of prospective geology have been used in combination with the stream sediment geochemical maps[12] for antimony and the related major commodities (Figure 2) as the basis for identifying the areas of prospectivity. Areas of known Sb mineralisation have also been used to inform this assessment. Some areas where elevated concentrations of Sb are recognised in stream sediments do not match any areas of prospective geology and may instead be related to anthropogenic contamination.

The Central Highlands and Southern Uplands areas of Scotland, Counties Fermanagh and Armagh, Northern Ireland, and Central Wales have potential for Sb related to gold. In particular, quartz-stibnite veining is known at Glendinning and at Fountain Head mine at Hare Hill in south-west Scotland (Boast et al., 1990; Duller et al., 1997). The Southern Uplands of Scotland are also prospective for Sb related to porphyry mineralisation, such as at Black Stockarton Moor (Brown et al., 1979). In south-west England, the volcano-sedimentary rocks of the North Devon and Tavy basins have known Sb mineralisation and have associated elevated Sb stream sediment values. Lead-antimony mineralisation has been exploited in many parts of the country, such as in west County Armagh in the 1800s (Schwartz and Critchley, 2012), at Wadebridge in north Cornwall, in south-west England (Clayton et al., 1990; Clayton and Spiro, 2000), and to a limited extent at the Bwlch mine, Deganwy in north Wales (Bevins et al., 1988). Antimony mineralisation in the UK has also been exploited from polymetallic veins and sedimentary-hosted mineralisation in south-west England (Dines, 1956).

[12] https://www.ukcmic.org/index.html#interactive-map

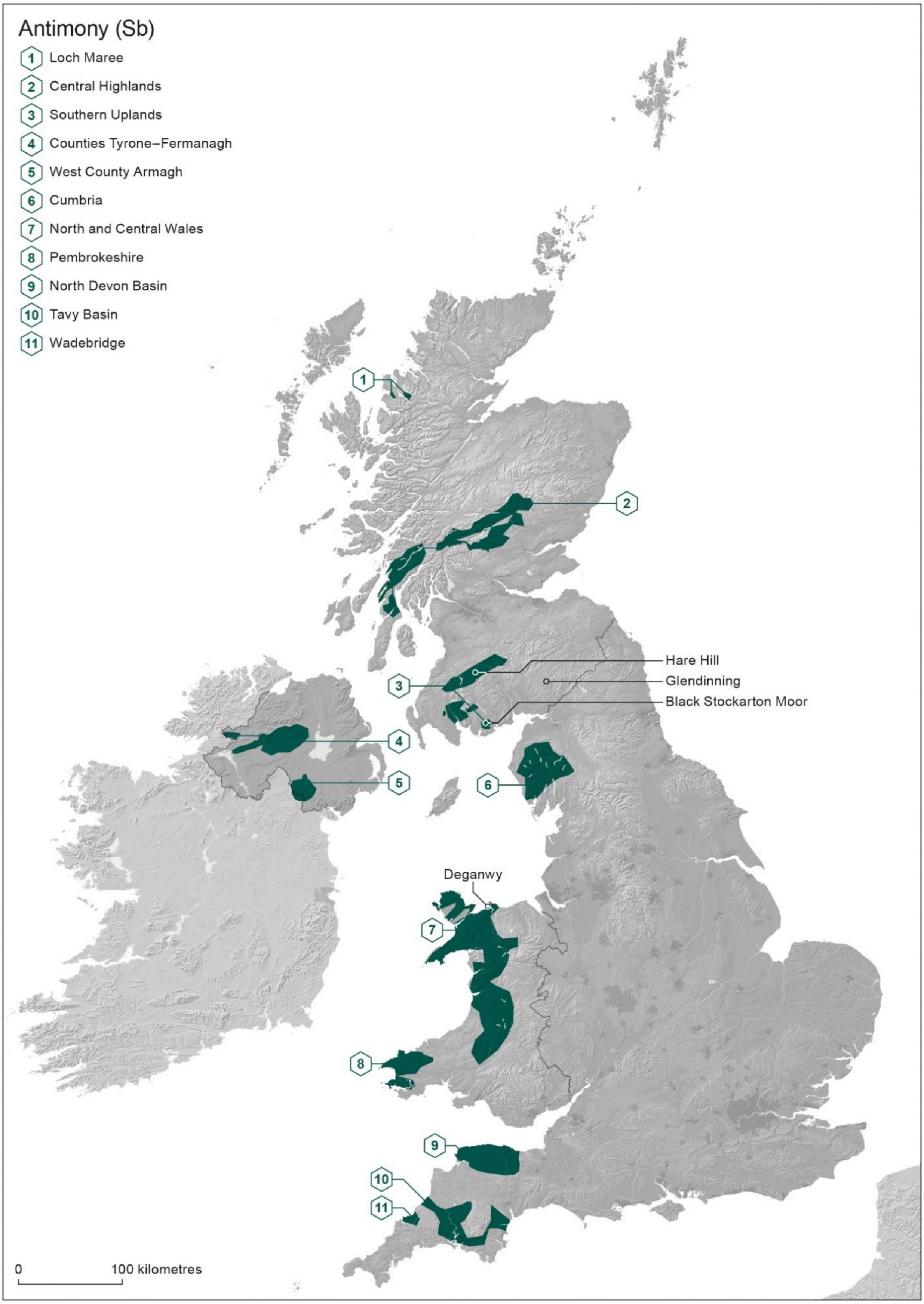

Figure 4 Areas of the UK that may be prospective for Sb. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

7.2 BISMUTH (Bi), MOLYBDENUM (Mo) AND TELLURIUM (Te)

Bismuth (Bi), molybdenum (Mo) and tellurium (Te) are typically by- or co-product commodities to major commodities such as copper (Cu), gold (Au), tungsten (W) and lead (Pb). Due to the range of associations, these CRMs occur in a variety of mineral systems. The main systems with which they are associated are porphyry igneous intrusions, **skarns**, orogenic gold deposits, granite-related mineralisation and polymetallic hydrothermal vein deposits.

In the UK, orogenic gold, VMS, granite-related mineralisation and polymetallic hydrothermal vein deposits are the most common of these deposit types, whilst porphyry intrusions and skarn-related mineralisation are less common. The distribution of VMS deposits has been mapped as described in section 7.1, whilst mapping of orogenic gold and polymetallic hydrothermal vein deposits is based on known occurrences. The geological information is used together with sediment geochemistry maps[13] for Cu, Au, W, Pb as well as Bi, Mo and Te, where available, as the basis for identifying the areas of prospectivity. Some areas where elevated concentrations of these elements are mapped in stream sediments do not match any known areas of prospective geology and may be related to anthropogenic contamination. In addition, certain types of polymetallic hydrothermal veins contain cobalt-nickel-bismuth-silver-arsenic with occasional uranium (Co-Ni-Bi-Ag-As ± U), and are important sources of Bi ore in the form of native bismuth (Kissin, 1992). Deposits were historically very important but typically have low tonnage and irregular deposit forms. Such veins cannot easily be delineated from geological maps and thus known vein occurrences are used to define potentially prospective areas.

Bismuth and Te have a close association with Au in some orogenic gold deposits, with a characteristic Bi-Te (±selenium (Se)) geochemical signature. Cononish Mine, in Tyndrum, Scotland is recognised as an unusually high Te-rich vein-gold deposit (Spence-Jones et al., 2018). The Central Highlands and Southern Uplands of Scotland and Northern Ireland contain prospective areas for gold (Smith et al., 2003), which are therefore also identified as prospective for Bi and Te.

Globally, porphyry mineral systems provide a significant percentage of Mo, Te, and Bi (John and Taylor, 2016), but relatively few are known to occur in the UK; those that do occur are typically related to Caledonian plutons and related shallow intrusions. Examples of such systems occur in the Kilmelford-Lagalochan area (Ellis et al., 1977); at Tomnadashan Mine, Loch Tay (Chapman et al., 2023; Pattrick, 1984); at Black Stockarton Moor, Cairngarroch, and Fore Burn in south-west Scotland (Allen et al., 1980; Allen et al., 1982; Brown et al., 1979); and at Chapel of Garioch, north-east Scotland (Colman et al., 1989). The Coed-y-Brenin Cu porphyry deposit in Wales has zones containing Bi-Te minerals (Allen et al., 1979; Miller, 1993; Rice and Sharp, 1976; Shepherd and Allen, 1985). High contents of Mo are seen in the stream sediment geochemistry mapping in a few locations associated with granitic plutons. In most cases, these have not been studied in any detail and are not considered to be prospective for economic mineralisation. A possible exception occurs close to Lairg in northern Scotland, in association with the Caledonian Grudie pluton (Appleton and Wadge, 1976; Holdsworth et al., 2015).

Bismuth mineralisation is commonly associated with granite-related tungsten mineralisation (section 7.12), where it occurs as native bismuth and other Bi-bearing minerals in veins with the tungsten minerals. In the UK, Bi was historically produced at Carrock Fell, Cumbria, and Castle-an Dinas in south-west England (Deady et al., 2022). Bi mineralisation is recorded at the Mourne Mountains in Northern Ireland (Moles and Tindle, 2012). Some vein tin (Sn) deposits in Cornwall are also Bi-rich, notably Wheal Jane (Kettaneh and Badham, 1978; Rayment, 1974). Examples of relevant polymetallic hydrothermal veins in the UK include Scar Crag (Solferino et al., 2021) in Cumbria, and numerous veins in the St Stephen area of St Austell, Cornwall in south-west England (Dines, 1956).

[13] https://www.ukcmic.org/index.html#interactive-map

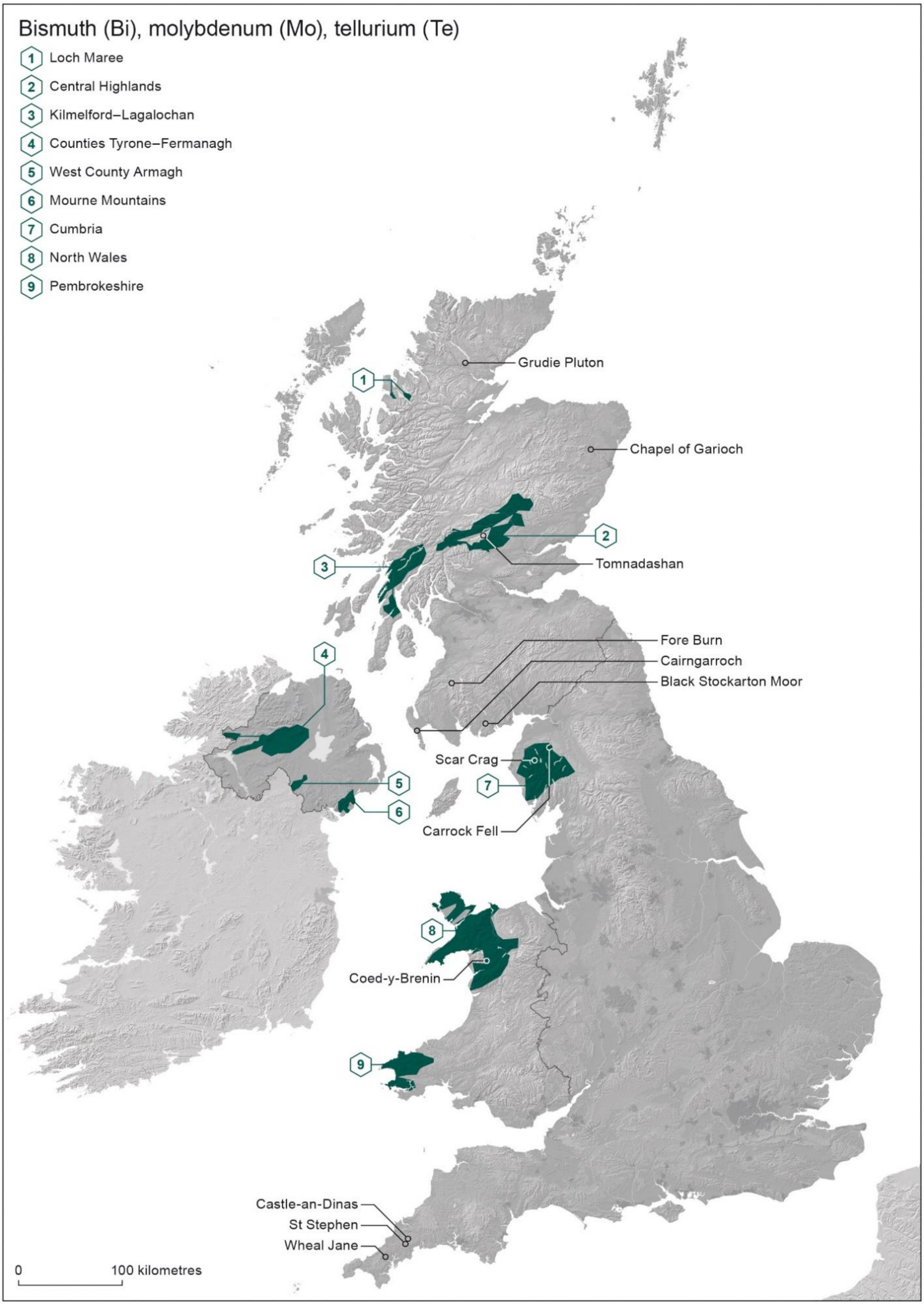

Figure 5 Areas of the UK that may be prospective for Bi, Mo and Te. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

7.3 COBALT (Co)

Cobalt (Co) is concentrated in a variety of geological settings, but economic deposits are of three principal types: magmatic nickel-copper (-cobalt-platinum-group element (PGE)) sulfide deposits in mafic-ultramafic intrusions, nickel-cobalt laterite deposits and **stratiform** sediment-hosted copper-cobalt deposits (Petavratzi et al., 2019). Other systems that contain notable concentrations of Co and are of relevance to the UK include some types of polymetallic hydrothermal veins, VMS deposits and ophiolites. In all of these deposit types, Co would most likely be produced as a co-product of Cu or Ni mining. Potentially prospective areas in the UK are identified to exist where the lithological criteria described above coincide with areas where significantly elevated concentrations of Co are mapped in the stream sediment geochemistry maps, as well as those highlighted by detailed academic (Gunn, 2007) and commercial investigation. Analogous cobalt-enriched systems outside the UK serve as additional supporting criteria in the selection of potentially prospective areas (e.g. Voisey's Bay deposit, Canada).

Caledonian mafic-ultramafic intrusions in Aberdeenshire, for example at Arthrath and Littlemill, meet the prospectivity criteria for Co associated with previously investigated magmatic Ni-Cu sulfide mineralisation (Gunn, 2007; Gunn and Styles, 2002; McKervey et al., 2007). Notably high Co concentrations measured in stream sediments are associated with the Palaeogene **intrusive** rocks on the island of Rum, in the Scottish Inner Hebrides, indicating that other Palaeogene mafic-ultramafic intrusions may be potentially prospective, including those on Skye, Mull and Ardnamurchan.

Polymetallic hydrothermal vein deposits that contain cobalt-nickel-bismuth-silver-arsenic with occasional uranium were historically important sources of Co, but these deposits are typically small and have irregular forms. Examples of these deposits in the UK include Scar Crag (Solferino et al., 2021) in Cumbria, Tynebottom in the North Pennine Orefield (Ixer and Stanley, 1987), and numerous veins in the St Stephen area of St Austell, Cornwall in south-west England (Dines, 1956). Other Co-bearing vein style mineralisation was documented from mines at Silver Glen in Perthshire and Hilderston in West Lothian, Scotland and at Wheal Sparnon, Redruth in Cornwall (Gunn and Deady, 2022a). Notably elevated Co concentrations in stream sediments collected within the Central Wales Orefield area can be related to the previously mined Pb-Zn-Cu-Ag polymetallic vein mineralisation with known occurrences of Co minerals (Mason, 1997). A sediment-hosted copper deposit at Alderley Edge in Cheshire which was previously worked primarily for Cu also produced Co as a by-product (Warrington, 2012).

VMS deposits are typically formed by hydrothermal activity on the seafloor, and some are known to be enriched in Co, with cobalt most typically contained in minerals such as pyrite. Mappable prospective geology in the UK includes Ordovician volcanic rocks in Wales and Cumbria, volcanic layers within the Dalradian Supergroup of the Central Highlands, and the rocks of the Loch Maree Group near Gairloch. These areas may be prospective for Cu, with Co as a co-product.

There are four main ophiolite complexes in the UK, including areas in the Tyrone Igneous Complex of Northern Ireland, in northern Shetland, close to Ballantrae, in south-west Scotland and on the Lizard Peninsula in Cornwall. Amongst these, only the Shetland ophiolite complex is associated with elevated Co concentrations in stream sediments. This may indicate localised Co enrichment, similar to that observed for PGE distribution in Shetland (O'Driscoll et al., 2018), thus warranting further investigation of this and other ophiolite complexes. Co-bearing veins are reported from the Tyrone Igneous Complex.

Stream sediment geochemistry maps[14] for Co display some cryptic local enrichment patterns which are not readily relatable to a known geological influence. For example, the origins of a notable Co enrichment pattern that fringes the outcrop of the Loch Doon granite pluton in the Southern Uplands of Scotland are unclear and require further investigation.

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[14] https://www.ukcmic.org/index.html#interactive-map

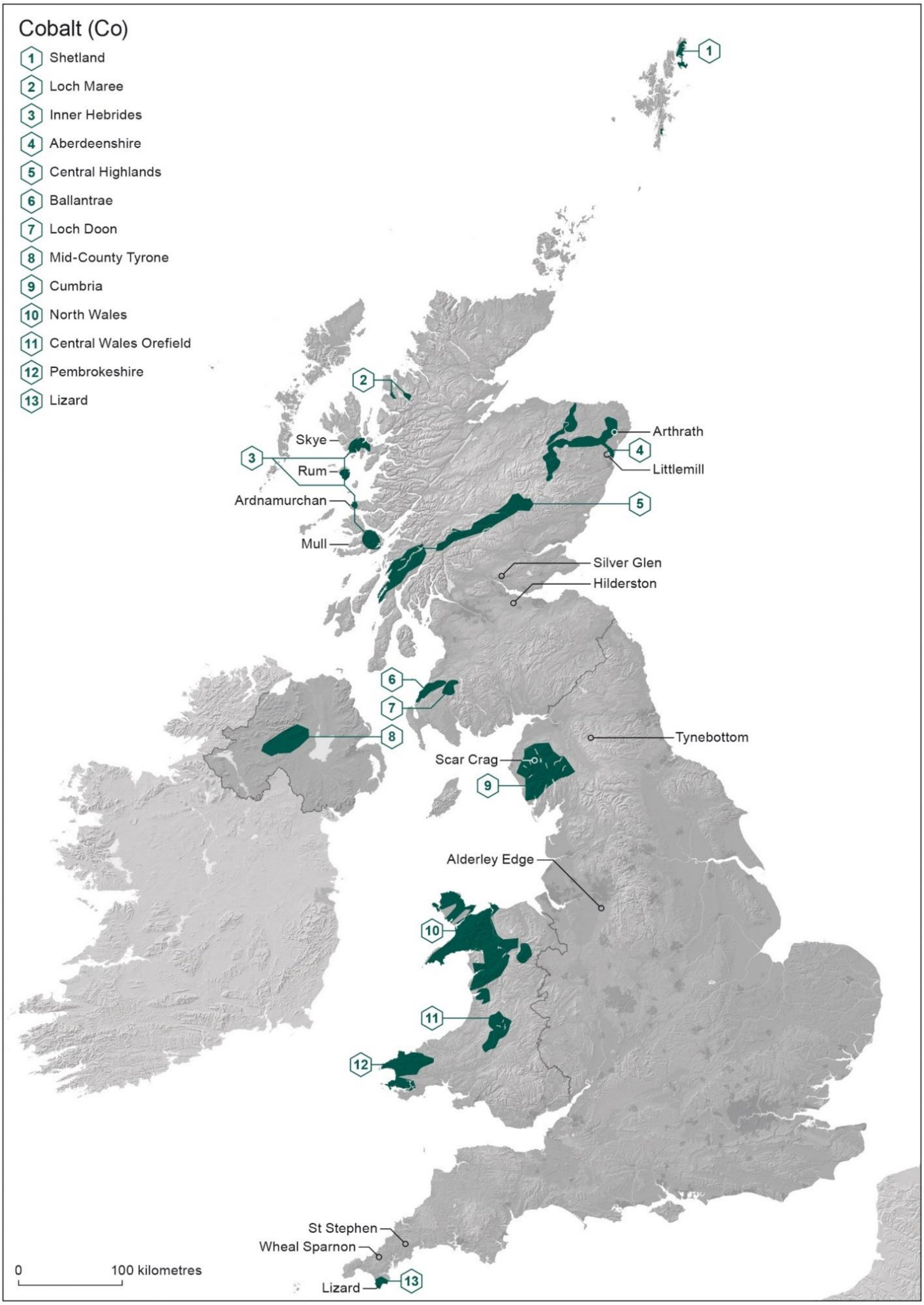

Figure 6 Areas of the UK that may be prospective for Co. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

7.4 GALLIUM (Ga), GERMANIUM (Ge) AND INDIUM (In)

Gallium is typically produced as a by-product of aluminium mining, whilst Ge and In are typically by-products of zinc. Gallium is almost exclusively extracted from bauxite and clays though minor amounts can be extracted from zinc-bearing ores or from fly ash generated from burning coal (Moskalyk, 2003). Mining of lead-zinc deposits is thought to make the largest contribution to current supply potential of Ga and Ge (Frenzel et al., 2016). Indium is primarily hosted by sphalerite in VMS deposits and is produced as a by-product of zinc **concentrates** from several VMS deposits globally (Schwarz-Schampera and Herzig, 2002). Indium can also be found associated with tin mineralisation but previously has not been considered to occur in amounts sufficient to constitute a resource (Cook et al., 2011) However, this perspective was not taken in the context of the demand for CRMs, and so areas that are prospective for tin have been included in this assessment.

Overall, the potential for Ga, Ge, and In in the UK will be as by-products of either zinc, copper or tin mining, largely in polymetallic hydrothermal veins. The UK has very limited bauxite, which forms due to tropical weathering resulting in an aluminium and Ga-rich residue. Minor bauxitic layers occur as inter-**lava** layers in the Paleogene lavas in Northern Ireland but are not substantial enough to be considered as a potential mineral deposit. Stream sediment geochemical mapping[15] and known prospective areas of zinc, copper and tin mineralisation based on the BritPits[16] dataset are thus used as the main mappable criteria for these CRMs and the associated major commodities (Figure 2).

Known areas of zinc mineralisation in polymetallic hydrothermal veins include Strontian in northern Scotland; the area around Tyndrum in the Central Highlands of Scotland (Coats et al., 1978; Smith et al., 1988); Leadhills-Wanlockhead, in the Southern Uplands of Scotland (Samson and Banks, 1988); at Newton Stewart in south-west Scotland (Braithwaite and Knight, 1990); in west County Armagh, Northern Ireland; several parts of Wales; Shropshire; and the North and South Pennine Orefields (Bouch et al., 2006; Dempsey et al., 2021; Ford and Worley, 2016).

The potential for VMS-related Zn and Cu mineralisation occurs in the Tyrone Igneous Complex of Northern Ireland (Hollis et al., 2016; Hollis et al., 2014); at Loch Maree in north-west Scotland (Drummond et al., 2020); in north and south Wales (Colman et al., 1995; Cooper et al., 1983); and Cumbria (Stanley and Vaughan, 1982). Zinc mineralisation associated with stratiform deposits occurs in the North Devon Basin (Benham et al., 2004) and in many other parts of Wales and England. In the UK, a systematic review of In mineralisation has been conducted in south-west England (Andersen et al., 2016).

[15] https://www.ukcmic.org/index.html#interactive-map
[16] https://mapapps2.bgs.ac.uk/geoindex/home.html

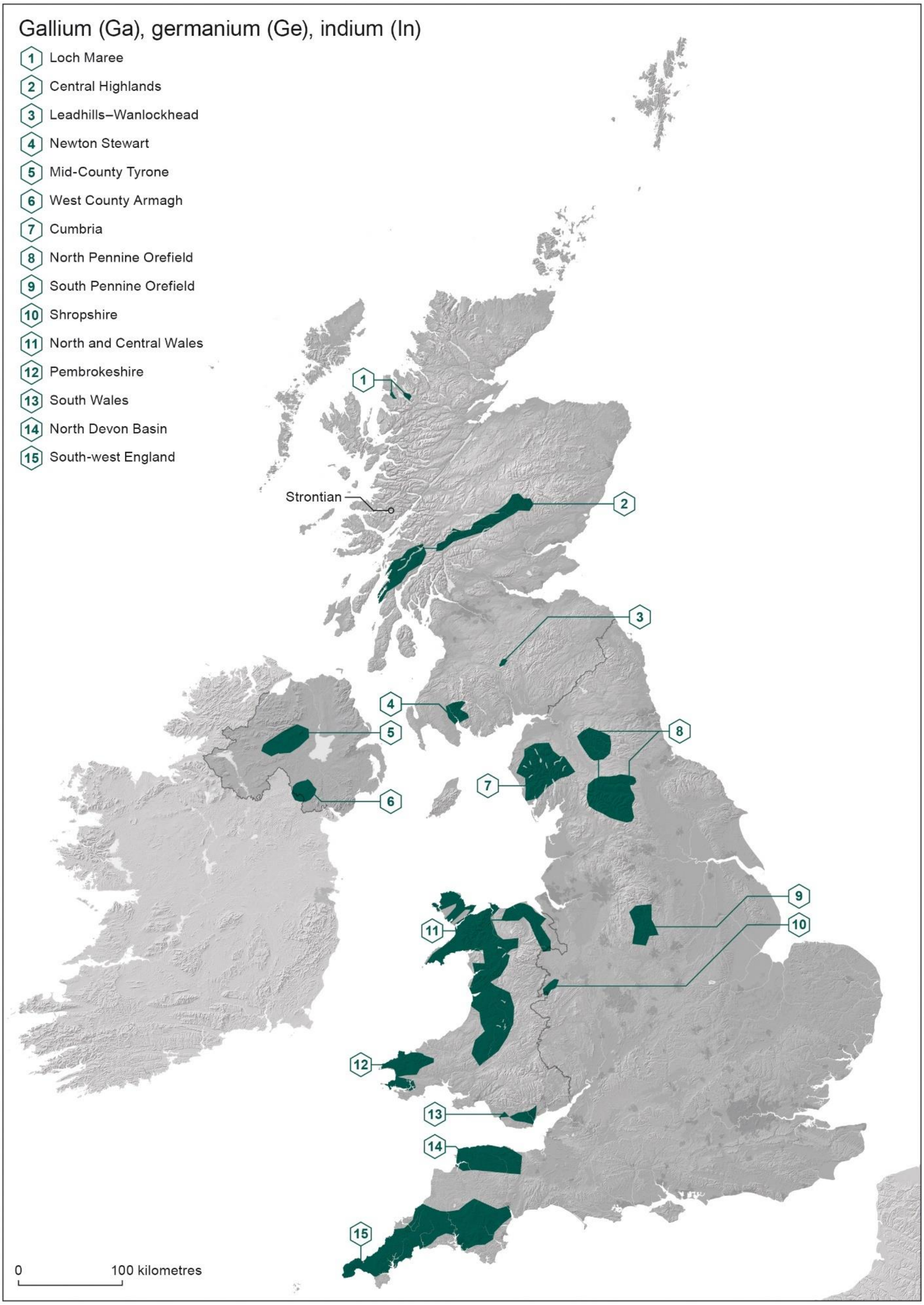

Figure 7 Areas of the UK that may be prospective for Ga, Ge and In. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

7.5 GRAPHITE (C)

Graphite is a form of carbon, and geological deposits can be classified as one of three types (amorphous, flake, and vein). Flake graphite is the main graphite type that is used as a battery raw material (Lusty and Goodenough, 2022). Graphite forms where carbon-rich sedimentary rocks have been metamorphosed, with flake graphite being restricted to areas of relatively high temperature metamorphism (**amphibolite facies** and above). Areas of potential prospectivity for flake graphite are thus those where there is evidence of amphibolite facies metamorphism and where carbon-rich metamorphosed sedimentary rocks are mapped. In Scotland, these criteria are met in parts of the Dalradian Supergroup in Argyll, the Central Highlands and Aberdeenshire, in the Loch Maree Group, near Gairloch, and in areas north of the Great Glen Fault that contain metamorphosed limestones, such as in Glen Urquhart. In the Sperrin Mountains of Northern Ireland, these criteria are met in small areas of the Dalradian Supergroup.

Vein graphite has previously been mined at the Wad mine in Borrowdale in Cumbria. The extent of this mineralisation at depth, or the potential for further occurrences in the area, has not been investigated in detail. In this area, carbon-rich sedimentary rocks of the Skiddaw Group interacted with high-temperature magmas during volcanic activity, leading to the precipitation of graphite (Ortega et al., 2010). The area of volcanic rocks in Cumbria is thus indicated on the map as being potentially prospective for vein graphite, although no other significant deposits are currently known. Vein graphite has also been mined in Glen Strathfarrar, in the Scottish Highlands, close to an area where metamorphosed carbon-rich sedimentary rocks are present.

Carbon-rich metamorphosed sedimentary rocks also exist in the Southern Uplands of Scotland, and on Anglesey and in west Wales, but these rocks have not typically been metamorphosed at high enough temperatures for the formation of flake graphite. Locally, close to igneous intrusions, higher temperatures of metamorphism may have been achieved and so small concentrations of graphite may exist in these areas which are not shown on the map. Similarly, localised concentrations of graphite may occur where igneous intrusions have been emplaced into coal seams (e.g., in Ayrshire).

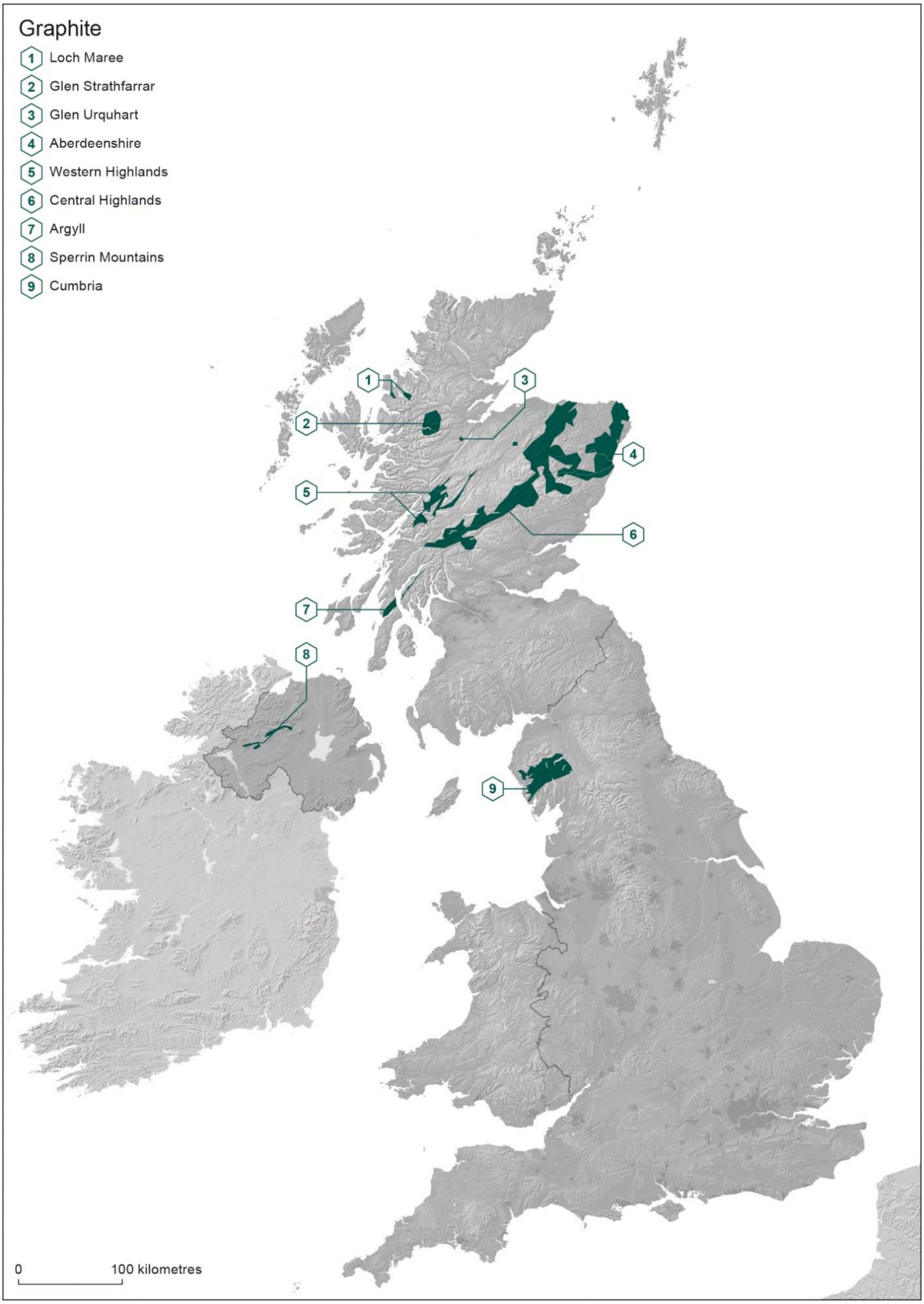

Figure 8 Areas of the UK that may be prospective for graphite. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

7.6 MAGNESIUM (Mg)

Magnesium can be sourced from both sea water and hard rock sources; in this assessment only the prospectivity for hard rock sources of magnesium is considered. The main hard rock resource occurs in sedimentary rocks including magnesium-rich carbonate and **evaporite sequences**. The prospectivity of these rocks will vary depending on the end-use of the ore, as different magnesium contents are required for different end-products (Highley et al., 2006).

The magnesium-bearing minerals of economic importance are dolomite, carnallite, magnesite, brucite, and olivine. Dolomite is a magnesium-rich limestone, which occurs in the UK within Cambrian to Ordovician rocks of the Durness Group in north-west Scotland; in Neoproterozoic rocks in the Central Highlands and on Islay, where the limestones of the Appin Group have been recorded as being dolomitised; in Permian rocks including the Raisby, Ford, Cadeby and Brotherton Formations in north-east England; and in Carboniferous rocks including the Monsal Dale Limestone in Derbyshire, the Pembroke Limestone Group in south Wales and the Black Rock limestone group in the south Wales-Bristol area (Frazer et al., 2014, Highley et al., 2006). Carnallite is an evaporite mineral, and is typically associated with Permian-aged, Zechstein evaporite sequences that occur at depth in east Yorkshire and continue offshore.

Magnesite, or other variably hydrated Mg-carbonates, occur along with brucite in ultramafic lithologies and **serpentinite**. The irregular distribution of the minerals in these lithologies is such that they are not considered in this assessment. Magnesium is also contained in the mineral olivine, a common rock-forming mineral that typically occurs in mafic and ultramafic lithologies. Olivine occurs in Cenozoic igneous rocks in western Scotland and in Northern Ireland and is variably altered such that it would not represent a potential resource and is not considered further in this assessment.

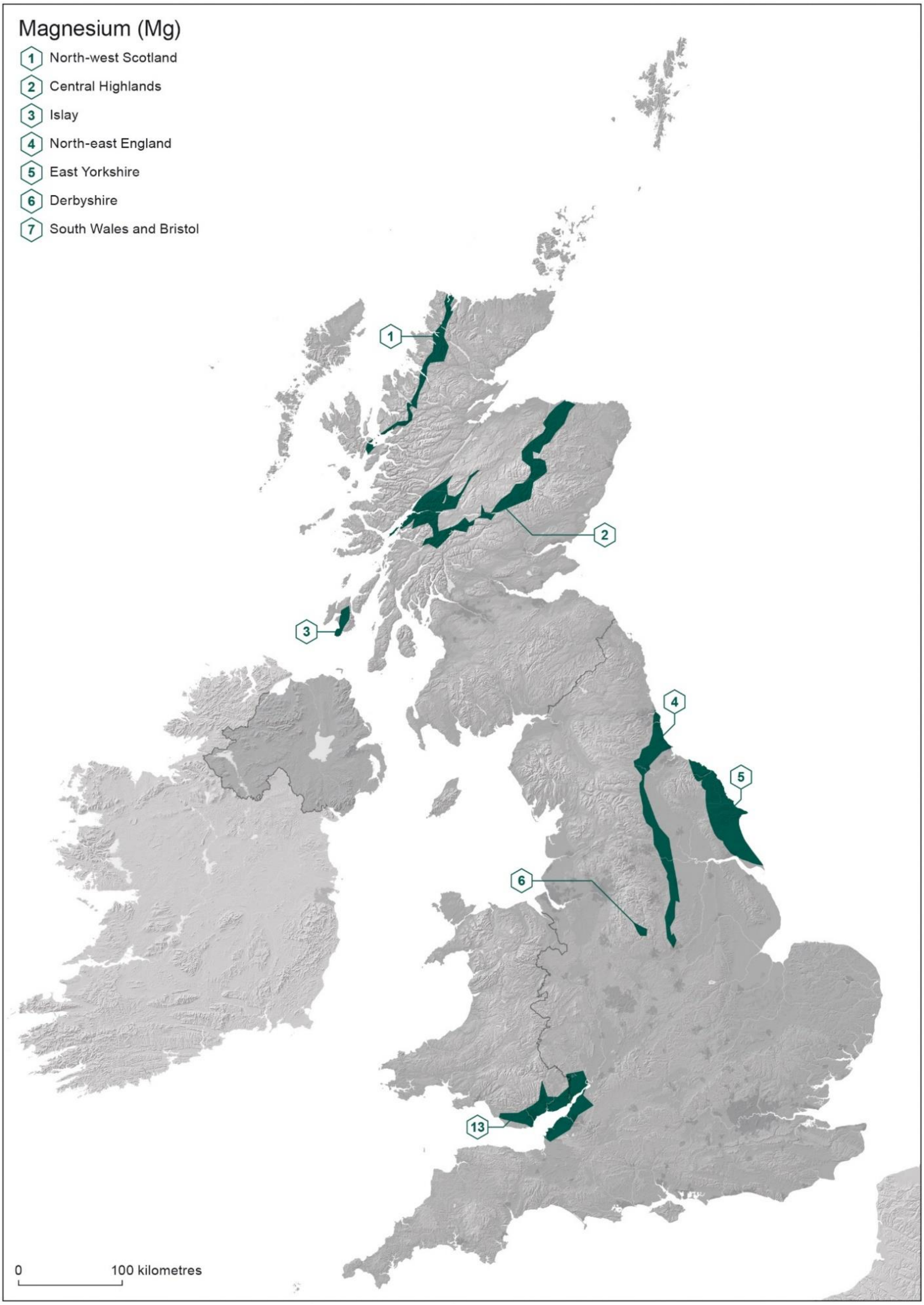

Figure 9 Areas of the UK that may be prospective for Mg. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

7.7 MANGANESE (Mn)

Manganese is a highly mobile element that can be transported and concentrated in a large range of terrestrial and marine environments. This results in an array of manganese mineralisation types, diverse in occurrence, origin, mineralogy, and geochemistry (Harben and Kužvart, 1997; Nicholson et al., 1997). Manganese deposits are associated with hydrothermal, sedimentary, volcanogenic, metamorphic, and surficial **supergene** processes (Harben and Bates, 1990; Roy, 1997). The largest deposits of Mn are related to world-scale deglaciation events during the Palaeoproterozoic and Neoproterozoic, whereby influx of highly oxygenated melt water in the ocean leads to the precipitation of Mn previously dissolved in anoxic marine environments (Roy, 1997). Depending on depth of precipitation, these events lead to the formation of shallow Mn-rich carbonate platforms or deep metalliferous **black shales**. In the Dalradian rocks of the Argyll Group across Scotland and Northern Ireland, the geological setting is potentially prospective for manganese and so this Group is indicated on the map as potentially prospective.

Localised deposits related to hydrothermal **exhalative** systems or magmatic-hydrothermal systems are commonly encountered in the UK. In north-west Wales, the Hafotty formation of the Harlech Dome comprises a series of distal hydrothermal Mn-rich strata dispersed within a thick succession of Cambrian sandstone that can be tracked over 190 km^2 (Waldron et al., 2011). In the Llyn Peninsula in north Wales, Mn mineralisation occurs as a series of **stratabound lenticular** bodies hosted by Lower Ordovician mudstones associated with high-level mafic intrusions (Gibbons et al., 1993), and was historically mined at the Benallt and Nant mines. In the south-west of England, Mn-rich mineralisation occurs in the Tavy and North Devon basins (Benham et al., 2004; Dines, 1956). Stratiform-related Mn mineralisation has also been exploited at Laverock Braes near Bridge of Don, Aberdeen. Other forms of Mn mineralisation have been exploited near Inverness where the Mn ore is commonly found overlying hematite beds within sandstone of Devonian age (Nicholson, 1990). At the Lecht mine in north-east Scotland, Mn mineralisation formed as a result of seepage from overlying Mn-rich bog.

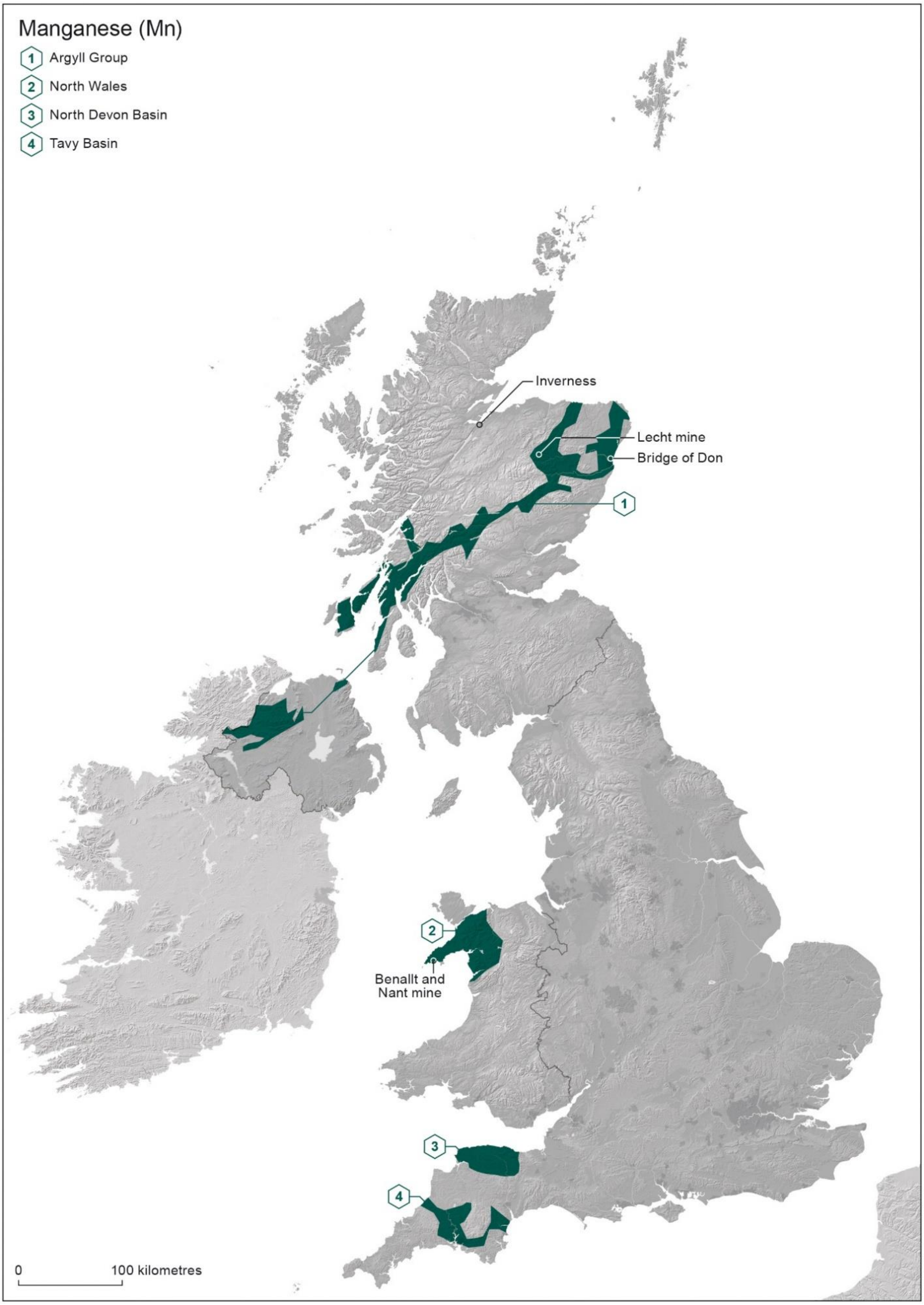

Figure 10 Areas of the UK that may be prospective for Mn. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

7.8 NICKEL (Ni), PLATINUM GROUP ELEMENTS (PGEs), AND VANADIUM (V)

Nickel (Ni) and platinum group element (PGE) mineralisation can be hosted in several different mineral systems. These include layered mafic-ultramafic intrusions, ophiolites, laterites and polymetallic hydrothermal vein deposits, which typically contain nickel-cobalt-arsenic-silver-bismuth with occasional uranium (Aiglsperger et al., 2016; Barnes et al., 2010; Burisch et al., 2017; Naldrett et al., 2000). Vanadium (V) is included in this section due to its association with magmatic accumulations of magnetite and ilmenite in mafic-ultramafic intrusions which are a major source of this metal (Cawthorn et al., 2005). Some sedimentary systems may also host these elements, e.g. minor amounts of V have been produced from the sediment-hosted Cu deposit at Alderley Edge in Cheshire (Braithwaite, 1994; Colman and Cooper, 2000). The mappable criteria used here are based on stream sediment geochemical maps[17] for Ni and V and geological mapping of mafic-ultramafic intrusions and ophiolite complexes. The G-BASE dataset does not include PGE data that is suitable for this assessment, so prospectivity for PGEs in the UK is entirely based on their known geochemical and mineralogical affinity with ultramafic rocks, and also informed by review of academic research (Gunn and Styles, 2002; O'Driscoll et al., 2018; Prichard et al., 1981) and commercial investigations.

Extensive lava fields and mafic-ultramafic intrusions of Palaeogene age occur in Northern Ireland and in the Scottish Inner Hebrides. The lavas, as well as their underlying feeder zones, and the mafic-ultramafic intrusions (Slieve Gullion in Northern Ireland and Skye, Rum, Mull and Ardnamurchan in Scotland) are considered to have potential for magmatic Ni-Co-PGE-V deposits (Andersen et al., 2002; Barnes et al., 2016; Lusty, 2016; Power et al., 2000). The Antrim Lava Group in Northern Ireland contains localised laterite horizons that serve as foci of relative enrichment in Ni, Cr and V (Hill et al., 2001). These are potentially prospective, but the mineral system requires further investigation. Other major mafic-ultramafic intrusions include the suite of Caledonian intrusions in Aberdeenshire. Important Ni deposits are known to occur in the Arthrath intrusion and on the southeast flank of the Knock intrusion, where they were identified based on geological mapping and drilling (Gunn and Styles, 2002). Localised enrichment in PGE, Ni, V and Cr is also noted from the nearby mafic-ultramafic intrusions belonging to the Portsoy Lineament. In north-west Scotland, high concentrations of Ni in stream sediment are associated with mafic-ultramafic intrusions within the Lewisian Gneiss Complex that are known to contain Fe-Ni-Cu sulfides (Guice et al., 2018) but have not been investigated as potential mineral deposits. At Talnotry, in the Southern Uplands, there is a small Ni-bearing orebody associated with a mafic intrusion that was worked in the past (Gunn and Deady, 2022a).

The ophiolites of Shetland, Ballantrae, the Lizard, and the Tyrone Igneous Complex are all associated with high concentrations of Ni and Cr in stream sediment samples. PGE enrichment has been reported in the Shetland ophiolite and some PGE-rich rock samples also contain copper (Cu), arsenic (As) and Ni mineralisation. MRP studies in the Lizard ophiolite showed that the gabbroic rocks contain a notable amount of vanadium-bearing ilmenite (Leake et al., 1992).

Polymetallic hydrothermal vein deposits were historically important sources of Ni but typically have low tonnage and irregular deposit forms. Examples of these deposits include Scar Crag (Solferino et al., 2021) in Cumbria, Tynebottom in the North Pennine Orefield (Ixer and Stanley, 1987) and veins in the St Stephen area of St Austell in south-west England (Dines, 1956; Gunn and Deady, 2022b). The North Pennine Orefield also hosts Ni mineralisation at Lady's Rake, Settlingstones and Hilton, likely formed by skarn-type alteration (Young et al., 1985). Ni has been produced in small quantities in the past at Hilderston and Coille-Bhràghad in Scotland (Colman and Cooper, 2000). Small amounts of Ni-Co mineralisation are known from Cu mines near Coniston in the Lake District (Russell, 1925). In the Central Wales Orefield, Ni occurs in Pb-Zn-Cu-Ag polymetallic vein mineralisation, and was mined near Tal-y-Bont. Nickel was also produced from the Foel Hiraddug mine, near Llandudno (Gunn and Deady 2022b).

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[17] https://www.ukcmic.org/index.html#interactive-map

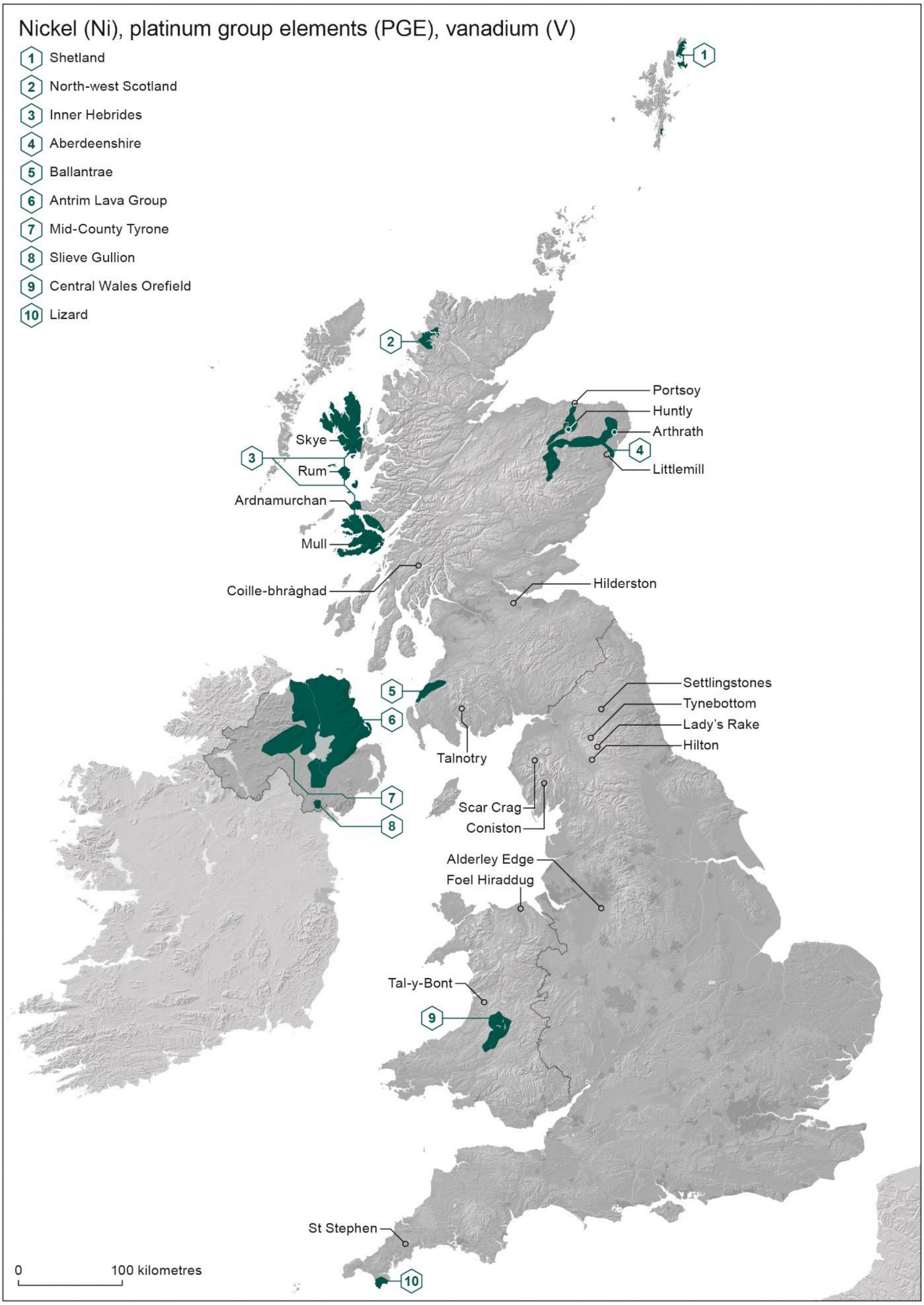

Figure 11 Areas of the UK that may be prospective for Ni, PGE and V. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

7.9 RARE EARTH ELEMENTS (REE)

The rare earth elements (REE) are a group of 17 geochemically similar elements which include the lanthanides (lanthanum through to lutetium), scandium (Sc), and yttrium (Y). The UK has limited prospectivity for the REE, which are typically exploited from carbonatites and **alkaline** igneous rocks (Beard et al., 2023; Goodenough et al., 2016). The only significant area of such rocks in the UK occurs in the NW Highlands of Scotland, in the Loch Borralan, Loch Ailsh and Loch Loyal igneous complexes (Goodenough et al., 2021). Close to Loch Loyal, alteration veins that host REE-bearing minerals (allanite and apatite) represent the most REE-enriched lithologies known in the UK (total rare earth oxides up to 2 wt.%) (Walters et al., 2013). However, these veins are small and typically discontinuous. Further work is required to fully assess the extent and REE potential of these veins.

Figure 12 Areas of the UK that may be prospective for REE. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

7.10 SILICON (Si)

Feedstock material for metallurgical grade silicon, also referred to as ‘silicon metal’ for its lustrous appearance, requires pure silica or quartz (over 99.5% SiO_2) with a low **fines** content. Although there are several deposits in the UK of high purity quartz sands and poorly consolidated sandstones, they are too fine-grained to be a suitable feedstock for standard processing techniques for silicon metal and, as such, are not considered here. This limits potential sources to **quartzites** (metamorphosed sandstones), which are rarely of sufficient purity and vein quartz.

Vein quartz is common throughout the UK but no deposits of sufficient size to merit consideration as a silica source for silicon metal have been identified. There is one deposit which has been worked in the past for industrial applications near Dalwhinnie in the Grampian Highlands, Scotland, although resources are thought to be small (Highley, 1977). Quartzites are common in the UK, but they mainly have low silica content and high aluminium content which is a significant impurity in the manufacture of silicon metal. Limited exploration has shown three quartzite formations (Scaraben and Loch Treig in Scotland and Holyhead in Wales) to have potential for high grade silica applications, although in all cases limited analyses show SiO_2 grades to be between 98–99% SiO_2 and, as such their resource potential is uncertain.

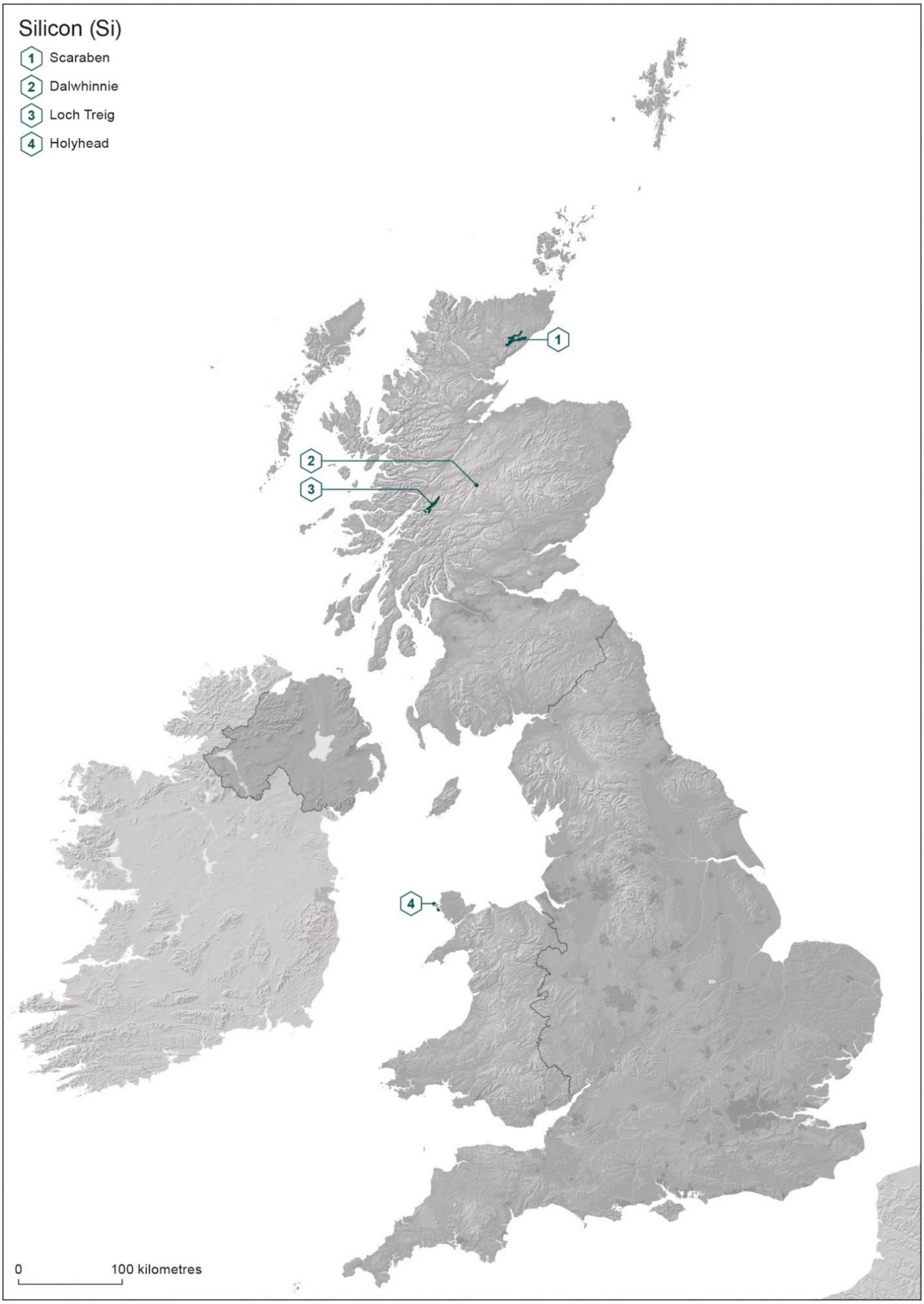

Figure 13 Areas of the UK that may be prospective for Si. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

7.11 STRONTIUM (Sr)

Strontium (Sr) mineralisation typically occurs in Sr-rich evaporites which form in shallow basins under certain evaporitic conditions, and which contain the mineral celestine, the main ore of Sr (Dill et al., 2009; Martin et al., 1984). There is also evidence that celestine-bearing **nodules** can form in certain geological environments where sea sponges are rapidly buried in **chalk**-forming seas (Madsen and Stemmerik, 2009).

In the UK, historic extraction (between 1880 and 1970) of Sr occurred from celestine-rich nodules and veins in the Triassic Mercia Mudstone Formation around Bristol, SW England (Thomas 1973; Nickless et al., 1976). The distribution of Sr in the evaporite-rich Triassic Mercia Mudstone Formation is not well understood due to the heterogenous nature of the formation. Therefore, the geographic extent of the evaporite-bearing bed, together with the Sr geochemistry maps, was used to constrain the prospective areas in the Somerset-Gloucester-Monmouth region. The Cambridge-Luton area, where high concentrations of Sr were measured in stream sediment samples collected over the Grey Chalk subgroup, is also highlighted as potentially prospective. Some areas where higher concentrations of Sr are depicted in the stream sediment geochemistry maps do not coincide with prospective geology. These elevated concentrations may instead be related to anthropogenic contamination, caused by activities such as gypsum mining. High Sr concentrations in several places in the north west of Scotland are associated with Sr-enriched granites but are unlikely to host Sr mineralisation.

Strontium can also be hosted as the mineral strontianite in polymetallic vein deposits, such as in Pb-Zn veins at Strontian, the type locality for the mineral strontianite and for where the element is named.

Figure 14 Areas of the UK that may be prospective for Sr. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

7.12 TIN (SN), TUNGSTEN (W), LITHIUM (LI), TANTALUM (TA) AND BERYLLIUM (BE)

Tin (Sn), tungsten (W), lithium (Li), tantalum (Ta) and beryllium (Be) mineralisation is typically associated with granites, **pegmatites**, and the surrounding host rocks. Mineralisation can take the form of vein-hosted (Sn, W), **placer**-hosted (Sn), pegmatite-hosted (Li, Ta, Be) and **geothermal brine**-associated (Li). A first order classification of granite types is adopted here to distinguish between **I-type** granites (formed by melting of an igneous source) and **S-type** granites (formed by melting of a sedimentary source) (Chappell and White, 1974; Chappell and White, 2001) as this clearly separates CRM affinities across the UK. I-type granites are more frequently associated with Mo, Bi, Sb, and Te, whereas S-type granites tend to be associated with Sn, W, and Li and therefore I-type granites are not considered further here. Pegmatites are very coarse-grained granitic rocks, often found close to large granitic bodies; they can be enriched in a range of critical raw materials, most particularly Li, Cs and Ta. In areas of S-type granite, Li may be enriched in geothermal brines circulating in fractures in the rocks, and may be a potential target for exploitation, typically as a by-product of heat and/or power generation.

The key mappable target criteria for Li, Sn, W, Ta and Be are thus based on geological mapping and associated research, allowing identification of areas of S-type granites. In the UK, the Caledonian and Variscan orogenies resulted in the emplacement of S-type granites from Shetland to the Isles of Scilly. These have been assessed in association with stream sediment geochemistry to constrain areas of interest for Sn, W, Li, Ta and Be, recognising that contamination from historical mining may obscure the ‘natural’ geochemical patterns. A further limitation of the stream sediment geochemistry dataset for this assessment is that limited coverage is available for these elements.

Caledonian S-type granites in Scotland predominantly occur in the north-east and south-west of Scotland (Oliver, 2001; Oliver et al., 2008). In north-east Scotland, W-Li-bearing granite has been identified at Glen Gairn, while Li-rich pegmatite has been found at Glen Buchat and also on the coast at Portsoy (Hall and Walsh, 1972; Jackson, 1982). Given that pegmatites typically occur in ‘swarms’ of multiple intrusions, it is unlikely that these are isolated occurrences, and therefore the zone extending from Glen Gairn to Portsoy is indicated as potentially prospective.

S-type granites related to the Caledonian Orogeny occur in south-west Scotland and northern England, and are termed the Trans-Suture suite (Brown et al., 2008). Little mineralisation is known from these granites, but historic W mining occurred at Carrock Fell Mine (Appleton and Wadge, 1976). In northern England, the major Weardale and Wensleydale granites are concealed beneath younger rocks at the surface but have been explored by drilling. The influence of the concealed Weardale granite on the Li potential of the North Pennine Orefield is notable and represents an ongoing area of exploration, especially for Li in geothermal brine. As the geology is concealed, the areas with potential for critical raw materials in northern England have been delineated on the basis of the available stream sediment geochemical mapping.

The Variscan S-type granites and associated mineral systems of south-west England have been mined since ancient times and represent a globally significant Sn-W resource (Romer and Kroner, 2015) with W mining having taken place recently at Hemerdon. The St Austell granite in Cornwall is known to contain Li resources, which are currently under exploration. The Palaeogene granite of the Mourne Mountains in Co. Down, Northern Ireland has known W (and Bi) mineral occurrences (Moles and Tindle, 2012), but the wider mineralisation potential for Sn, Li and Be is unknown.

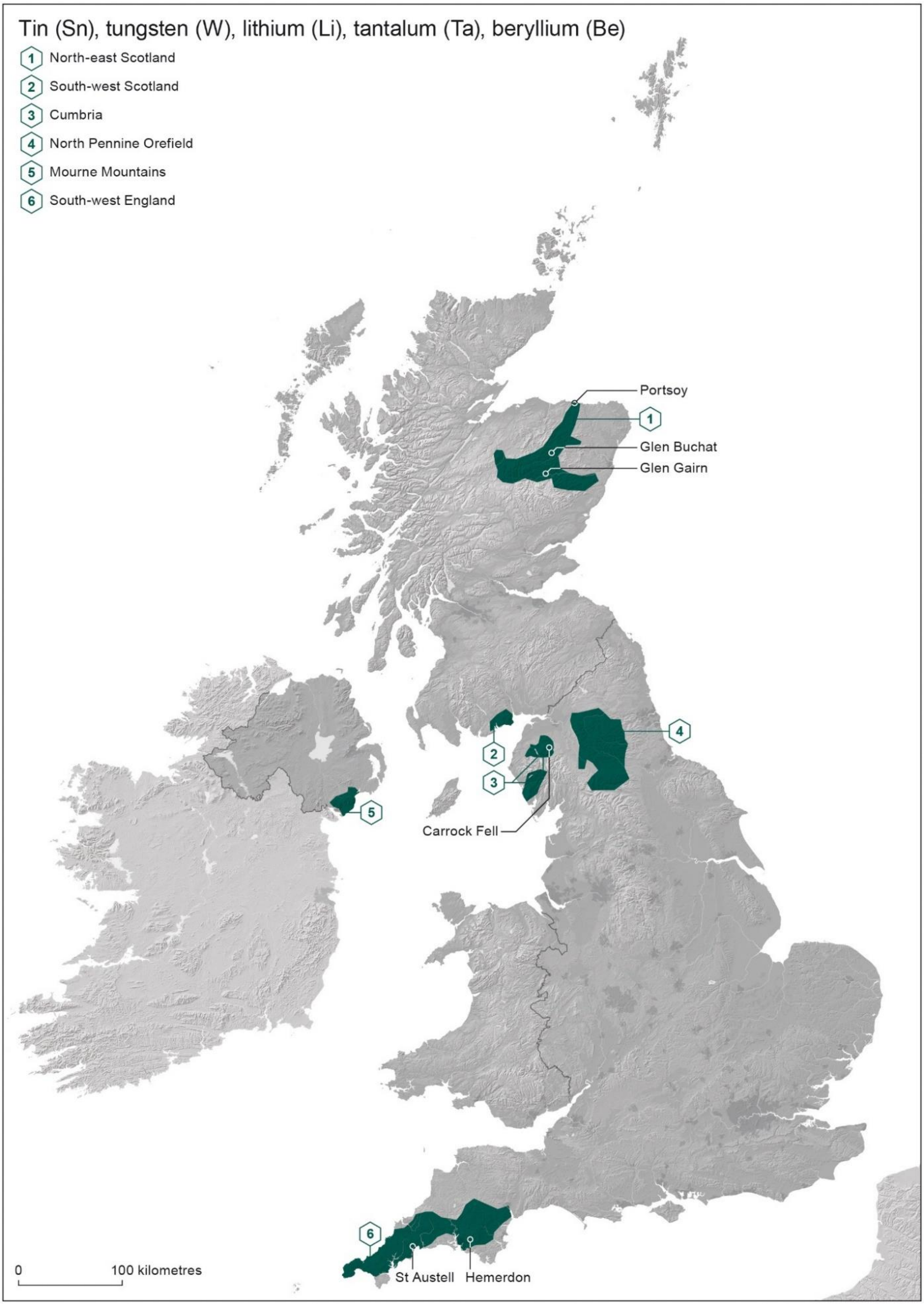

Figure 15 Areas of the UK that may be prospective for Sn, W, Li, Ta and Be. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

Conclusions

This systematic assessment of UK geology highlights the potential for many areas of the country to be prospective for CRMs. The distribution of these prospective areas is a function of the geology, and many areas have potential for more than one CRM.

The key areas that we identify as particularly worthy of further investigation (Figure 16) are, from north to south: areas of prospective geology around Loch Maree near Gairloch; parts of the central Highlands and Aberdeenshire; areas of prospective geology in mid-County Tyrone in Northern Ireland; parts of Cumbria; parts of the North Pennine Orefield; areas in north-west Wales and Pembrokeshire; and south-west England. Although these locations are key because of their potential to be prospective for several different CRMs, prospectivity for individual CRMs exists across many other parts of the country. All of the key areas have been mined historically or are currently being explored for mineralisation.

The maps presented here do not represent areas where mineral deposits containing CRMs are guaranteed to be found; they simply represent areas where the geological criteria have been met and thus there is potential for deposits to occur. It is also important to note that mineral deposits could be found beyond the identified prospective areas, where localised geological conditions are suitable. Because an area has been highlighted as having geological potential this does not mean that area will be targeted, nor that permission will be granted for exploration or mining, nor that economic discoveries will be made in an area. Where the geology is prospective, there is a need for much more detailed investigation to provide the baseline data needed to underpin exploration.

This report highlights that parts of the UK are underexplored, particularly in terms of the CRMs, and that more geoscientific data are required to enable more specific targeting of mineral deposits. Experience from other jurisdictions indicates that the availability of high-resolution geological, geochemical and geophysical data aids in the development of a strong exploration and mining sector. Additionally, the deportment of CRMs such as Ga, Ge, In, Mo, Bi and Te in many deposit types is not well understood and requires further work. Where exploration for major commodities such as copper, zinc, gold and nickel is ongoing, it will be important that consideration is given to all possible raw materials in order to achieve full value mining where possible. Due to the extensive nature of historic mining in the UK, it may be valuable to reappraise areas of mining waste as potential resources for some CRMs that historically would have been considered waste material. Thorough consideration of environmental, social, economic and legal aspects will be essential before any exploration or mining might develop in an area.

In order to provide the geological baseline required to enable domestic production of critical minerals, the next steps should include the acquisition of high-resolution geological, geochemical and geophysical datasets for the key areas (Figure 16). These regional datasets will underpin identification of specific CRM prospects suitable for further investigation. It is important that mineral exploration in these areas includes consideration of CRMs alongside precious and base metals. This work will provide the basis for ‘domestic production where it works for communities and our natural environment and increases resilience’, as stated in the UK Critical Minerals Strategy Refresh of 2023.

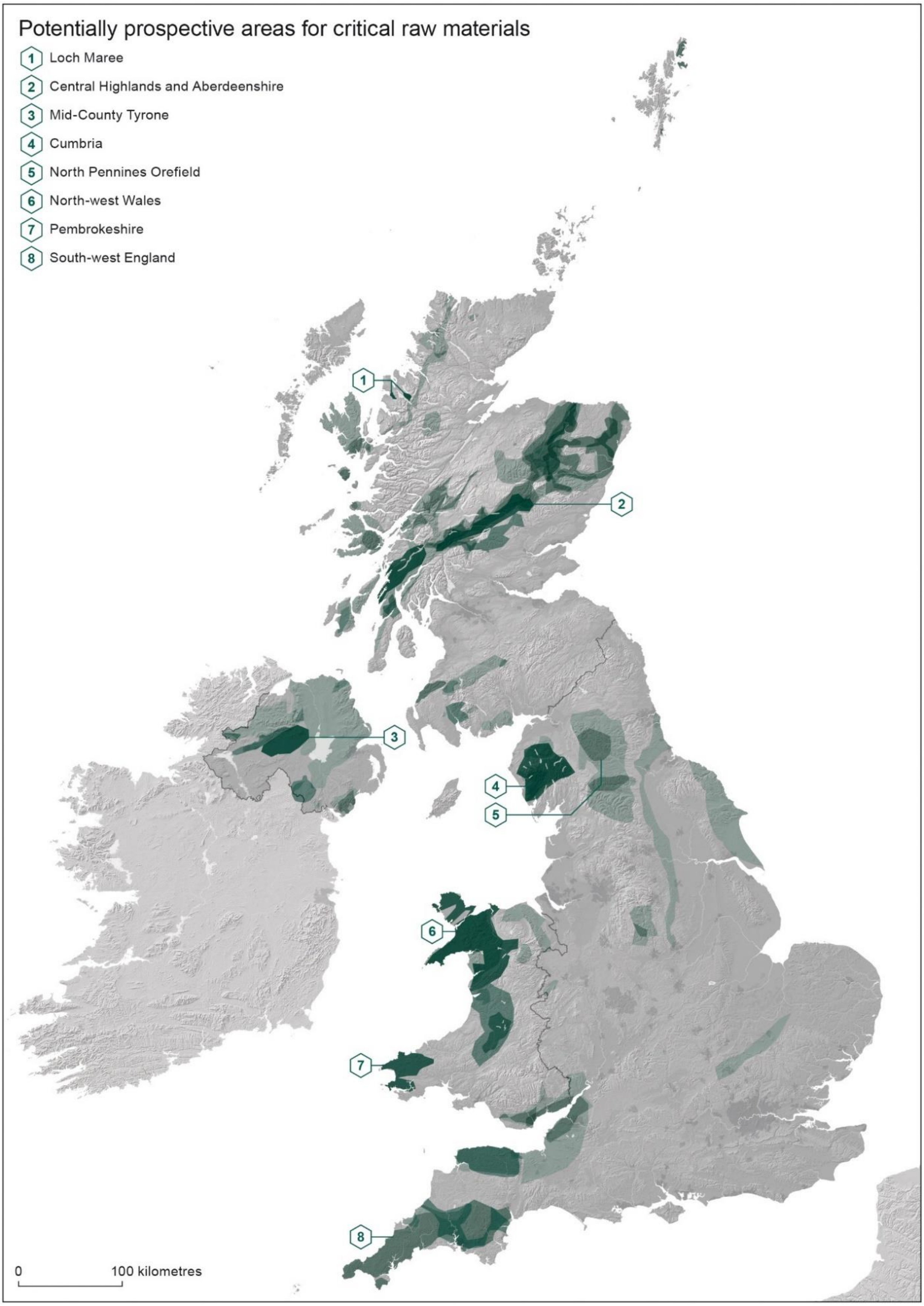

Figure 16 Areas of the UK considered potentially prospective for critical raw materials. The darker areas are those that are prospective for several CRMs. Contains Ordnance Survey data © Crown copyright and database right 2023. Contains NEXTMap Britain elevation data from Intermap Technologies.

Glossary

Alkaline enriched in the alkali elements sodium and potassium.

Alluvial/alluvium a deposit formed by the action of running water.

Amphibolite facies a distinct metamorphic mineral assemblage formed in the Earth's crust typical of regional metamorphism under moderate to high pressures (in excess of 3000 bars) and at temperatures in the range of 450-700^{o}C.

Bauxite a clay-rich rock formed by weathering, which is the main ore of aluminium.

Black shale a fine-grained sedimentary rock (shale) that contains abundant organic matter.

Brine water that is highly enriched in salts.

By-product materials that are produced incidentally to the main economic product(s) of a mining operation.

Carbonatite an unusual magmatic rock containing greater than 50% carbonate minerals.

Chalk a white porous sedimentary carbonate rock.

Concentrate the product produced after the first stage of processing of an ore.

Commodities a raw material which can be bought or sold.

CRIRSCO Committee for Mineral Reserves International Reporting Standards; a code of practice that sets the minimum requirements for reporting mineral resources and reserves.

Critical raw materials commodities that are economically important and at risk of supply interruption.

Co-product materials that occur together in nature and are, therefore, generally mined together. All co-products make an economic contribution to the project from which they are sourced.

Evaporite sequences a sedimentary rock precipitated from aqueous (water-containing) solutions and concentrated by evaporation.

Exhalative a system where hydrothermal or basin fluids are exhaled into submarine environments, meeting cold water (typically oceanic) and precipitating minerals.

Fault a fracture or a zone of fractures in bedrock, along which there has been parallel displacement of rock masses relative to one another.

Felsic gneisses a foliated rock formed by regional metamorphism (gneiss) containing abundant light-coloured minerals (felsic).

Ferrous containing or consisting of iron.

Fines referring to a specific fine (small) grain-size of quartz or impurity within a silica-sand deposit.

Geochemical the application of the tools and principles of chemistry to explain processes and changes within geological systems.

Geological potential where the geological criteria for the potential for mineralisation occurs together.

Geophysical the study of the Earth by quantitative physical methods.

Geothermal relating to or produced by the heat of the Earth.

Granite a coarse-grained crystalline intrusive igneous rock composed mostly of quartz, alkali feldspar and plagioclase.

Hydrothermal a convective process which redistributes energy and mass in response to circulating hot water in the earth's crust.

I-type granite a granite formed from magma that was generated by the melting of igneous sources.

Igneous a rock or mineral that solidified from molten or partly molten magma, or the processes leading to, related to, or resulting from the formation of these rocks.

Intrusion/intrusive a body of igneous rock that has formed from magma cooling beneath the Earth's surface.

Lacustrine a deposit or rock produced by or formed in a lake or lakes.

Laterite an iron oxide-rich rock system formed by tropical weathering of igneous protolith.

Lava molten rock (magma) that is erupted on to the Earth's surface.

Leaching loss of soluble components within a system by percolating and circulating fluids.

Lenticular resembling in shape the cross section of a lens.

Lithosphere the solid portion of the Earth including the crust and upper mantle, approximately 100 km in thickness.

Mafic-ultramafic igneous rocks with low silica content (45-55% for mafic and <45% for ultramafic), and high content of dark (mafic) minerals, such as olivine, pyroxene or amphibole.

Magma molten or semi-molten rock, from which igneous rocks are formed.

Magmatic a rock formed from magma, or the processes leading to, related to, or resulting from the formation of these rocks.

Metamorphism/metamorphic changes to rock under higher temperature and/or pressure, resulting in recrystallisation, chemical reaction, and the formation of new minerals.

Metasedimentary a metamorphosed rock of sedimentary origin.

Migmatised a rock composed of two intermingled but distinguishable components with the naked eye, typically an igneous rock (e.g., granite) within a metamorphic host rock.

Mineral deposit a natural accumulation of a particular mineral at unusually high concentration in the Earth's crust.

Mineral system all geological factors that control the generation and preservation of mineral deposits.

Mineralisation the process or processes by which a mineral or minerals are introduced into a rock.

Nodule a rounded mineral concretion (lump/aggregate) that is distinct from, and may be separated from, the formation in which it occurs.

Ophiolite a fragment of oceanic crust and mantle emplaced onto a continent during subduction.

Ore-forming minerals the minerals from which commodities (chiefly metals) can be extracted in a way that is economic.

Orogenic gold referring to gold mineralisation formed by hydrothermal processes in a zone of compressional deformation in the crust.

Orogeny a process in which a section of the earth's crust is folded and deformed by compression to form a mountain range

Pegmatite a very coarse-grained granitic rock.

Placer a surficial mineral deposit formed by mechanical concentration of mineral particles from weathered debris.

Pluton a large igneous intrusion in the earth's crust.

Polymetallic containing several metals.

Porphyry an igneous intrusion with a typical texture of large-grained crystals in a finer crystal groundmass.

Quartzite a metamorphic rock containing at least 80% quartz.

Reserve the economically mineable part of a measured and/or indicated mineral resource.

Resource a concentration or occurrence of material of economic interest in or on the Earth's crust in such form, quality, and quantity that there are reasonable prospects for eventual economic extraction.

Rifting the extension of the Earth's lithosphere, potentially leading to the splitting apart of a single tectonic plate into two or more tectonic plates separated by divergent plate boundaries.

S-type granite a granite formed from magma that was generated by the melting of sedimentary source.

Sedimentary a rock formed at the Earth's surface, either composed of fragmental material that originates from the weathering of rocks and is transported by air, water or ice, or formed by other natural processes such as chemical precipitation from solution or secretion by organisms.

Serpentinite a metamorphic rock formed by hydration of ultramafic rocks, largely composed of serpentine minerals.

Skarn a metasomatic rock that forms due to the interaction of an intrusion and (typically) a carbonate rich bedrock.

Stratabound occurrence of mineralisation contained within one or more stratigraphic unit.

Stratiform a geological formation or mineral deposit in the form of roughly parallel bands or sheets as layers, beds or strata.

Supergene a type of surface weathering which results in the enrichment of metals.

Suture zone the surface expression of a boundary where two continents have collided.

Syntectonic a geological process or event occurring during a period of orogenic (mountain-building) activity.

Terrane a fault-bounded body of rock of regional extent, characterised by a geological history different from that of adjacent terranes.

Terrestrial on or relating to the land.

Turbidite a sediment or rock with characteristic grain size sorting, deposited from a current containing suspended sediment flowing downslope in air, water or other fluid.

Vein a sheet-like of body of minerals within a rock, typically formed by hydrothermal processes.

Volcanogenic Massive Sulfide (VMS) a base- and/or precious-metal mineralisation typically hosted by, or associated with, submarine volcanic and/or volcaniclastic rocks.

Weathering the breakdown of rock on the Earth's surface.

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