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RAW MATERIALS FOR DECARBONISATION

The potential for graphite in the UK

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Introduction

Graphite is a form of carbon that occurs as black to steel grey, lustrous flaky aggregates, disseminated in metamorphic rocks or as veins with a fibrous or foliated texture (Taylor, 1994). Natural graphite has a number of special properties, such as high electrical conductivity, a high melting point, resistance to corrosion and lubricity. Consequently it has varied industrial applications, including in electronics, lubrication, metallurgy and steel production (Robinson et al., 2017). In the UK graphite is used in aerospace applications, nuclear power generation and associated industries, in the petrochemical and automotive sectors, and for glass and steel manufacturing. Global natural graphite production in 2017 amounted to an estimated 1.2 million tonnes.

China is the largest global producer of graphite, accounting for 75 per cent of the total in 2017. The largest other producers are Brazil, India, Canada, Russia and Austria (Brown et al., 2019). The UK is a small net importer of natural graphite, with total graphite imports of about 3800 tonnes, worth £3.4 million in 2017 (Bide et al., 2019). Natural graphite is considered by the European Union to be a 'critical raw material' (European Commission, 2017). In common with some other industrial minerals, natural graphite has an industrially

This profile provides an overview of the geological potential for graphite in the UK. It forms part of a series on raw materials used in decarbonisation technologies that may occur in the UK, and is based on publically available data and information.

important synthetic equivalent, which is produced in electric furnaces from petroleum coke (Harben and Bates, 1990; Taylor, 1994).

For commercial purposes, natural graphite is classified into three types, based on its morphology, grain size and crystallinity: amorphous (massive, but microscopically microcrystalline); disseminated flake; and crystalline vein (Taylor, 1994). Graphite is a common component of metasedimentary rocks and all graphite deposits are formed from metamorphism, with geological conditions affecting the type of ore. Amorphous graphite deposits result from the thermal metamorphism (typically at >300°C) of coal, petroleum or carbon-rich sedimentary rocks (Robinson et al., 2017). The purity of amorphous graphite is dependent on the original source rock, but a minimum of about 80 per cent graphite is considered to be of economic interest (Harben and Kužvart, 1997). Mexico and Russia are the main producers of amorphous graphite (Robinson et al., 2017).

Disseminated flake graphite forms when organic-rich sedimentary rocks that typically accumulate in sediment-starved basins with anoxic conditions undergo regional metamorphism at or above amphibolite facies conditions. This results in the pre-existing carbon-rich material being converted to flat, plate-like grains of graphite, which are disseminated through the metamorphosed host rock. Common host rocks include quartz-mica schist, quartzite, gneiss and marble, and the graphite content of these occurrences may vary from occasional streaks to more than 90 per cent of the rock (Harben and Kužvart, 1997; Robinson et al., 2017). The main sources of crystalline flake graphite are Brazil, Canada, China, India and Madagascar.

Crystalline vein graphite (also termed lump or high-crystalline graphite) typically occurs as well-defined veins or pockets, containing more than 75 per cent graphitic carbon (Taylor, 1994; Harben and Kužvart, 1997). Graphite vein deposits form during high-grade regional metamorphism, in similar geological settings to disseminated crystalline flake deposits. They most commonly occur in crystalline metamorphic basement rocks and the carbon is introduced into the veins by metamorphic or other fluids. The veins either cut the metamorphic host rocks or form along intrusive contacts. The only economically important deposits of this type are in Sri Lanka (Robinson et al., 2017).

UK production and resources

Graphite is a widespread constituent of metamorphic rocks in the UK, particularly in Scotland. Graphite has been mined in north-west England, but not in Wales or Northern Ireland. The best-known graphite deposit in the UK is located at Seathwaite, in the Borrowdale valley of the English Lake District, in Cumbria. Mining at Seathwaite began at least as early as the late 16th century, continuing intermittently until it was abandoned in the late 19th century (Symes and Young, 2008). Production data is scarce, but, operating for nearly 300 years, it must have produced a significant quantity of very pure lump graphite. The deposit was exhausted by the mid-1800s. In Scotland, graphite has been worked in several counties on a small scale. Production data is scarce, and even the relatively important mines in the Highlands only appear to have produced a few tonnes of graphite annually. For example, the Glen Strathfarrar deposit is reported to have produced five tons of graphite in 1818 (Heddle, 1923), and a vein at Invergarry produced about two tons of graphite in 1825. It is reported that more than 100 tons of graphite was raised from the Craigman coalmine near New Cumnock, in the Strathclyde region. However, this mine operated for about 100 years and the period over which this production took place is unclear (Strahan et al., 1917).

There has been no systematic or modern exploration for graphite in the UK. There is currently no mine production of graphite in the UK and there are no deposits in which graphite reserves or resources have been reported.

UK occurrences

Minor graphite is widespread in metamorphosed carbon-rich sedimentary rocks in the UK, particularly in the Lower Palaeozoic sedimentary rocks of Wales, and in the Cambrian and Precambrian rocks of the Northern Highland and Grampian terranes of Scotland (Bevins, 1994; Strachan et al., 2002).

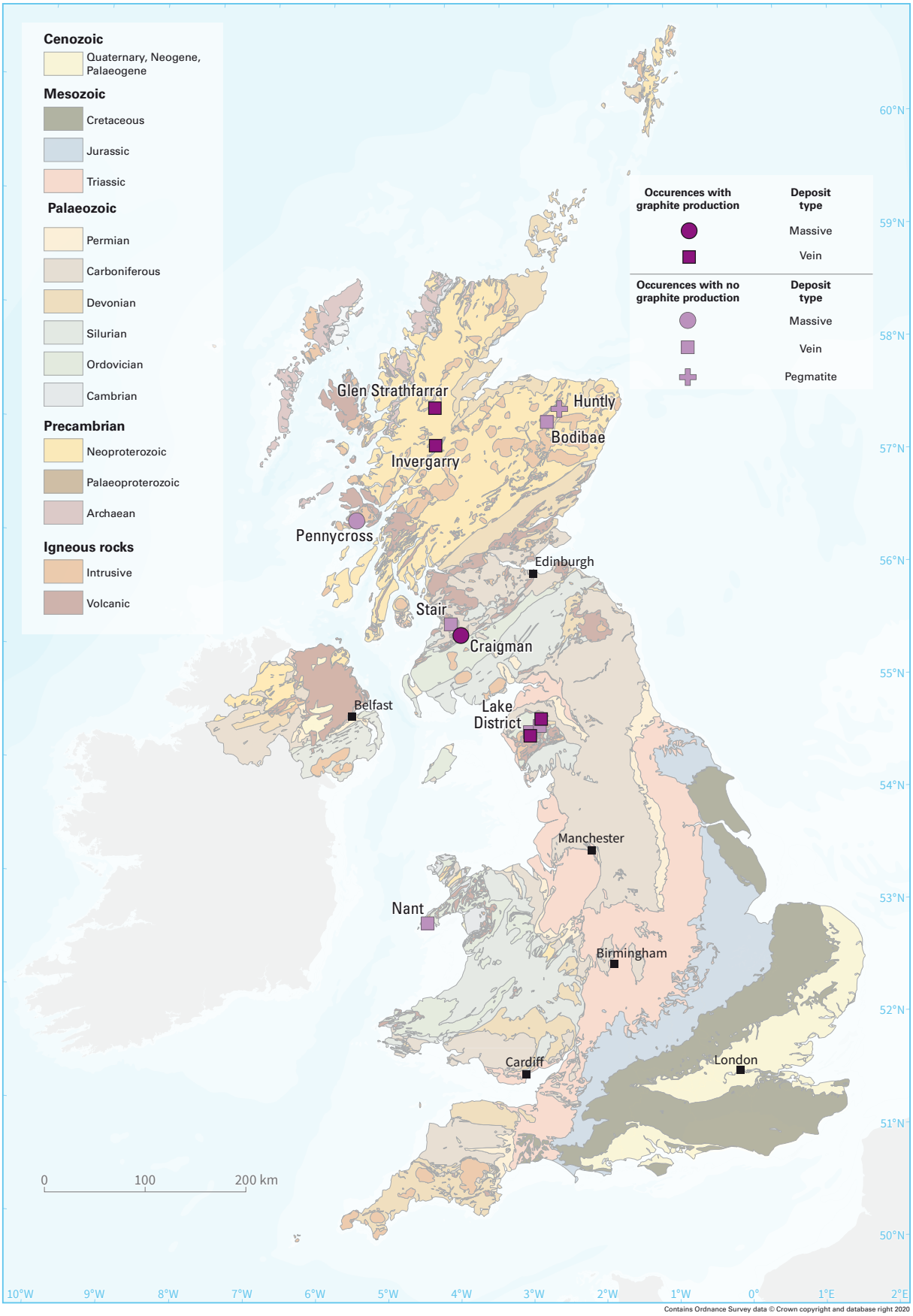

Figure 1 Location of principal graphite occurrences in the United Kingdom.

The long-abandoned Seathwaite deposit is famous for its remarkably pure graphite, which was at first used for marking sheep, but its main use for many years was in moulds for the casting of coins and cannonballs. In the 19th century, it formed the basis of the renowned pencil industry in Keswick (Symes and Young, 2008; Ortega et al., 2010; British Geological Survey, 2019). The extensive dumps surrounding the mine are reported to contain some impure graphite (Strahan et al., 1917). This occurrence is unique in the UK and it is one of only two large graphite deposits hosted by volcanic rocks worldwide. The Seathwaite deposit is hosted by andesite lavas and sills that form part of the Upper Ordovician Borrowdale Volcanic Group (Ortega et al., 2010). The deposit comprises eight fault-controlled veins of varying orientation. Graphite is restricted to a 400 m length section of the vein complex, which is associated with a broad alteration zone (Strens, 1965). The faults are filled with narrow veins and stringer mineralisation composed of massive graphite, chlorite and quartz. The most significant graphite concentrations occur at the intersections of the faults, where pipe-like bodies, up to three metres in cross-section and extending for up to 100 m in length, are developed. Graphite in these pipe-like zones comprises nodules, irregular patches or small veins within the altered volcanic rocks. Graphite in the Seathwaite deposit has a spectrum of morphologies, but mainly occurs as flakes in both the pipes and veins. The origin of the deposit is controversial. The most recent research concluded that it formed because of an unusual combination of geological factors, including the incorporation of carbonaceous matter from the underlying sedimentary sequence by andesitic magmas, and a major active deep-seated fault system that focussed the rapid upward transport of C–O–H-rich fluids (Ortega et al., 2010). Graphite has also been found on the neighbouring hills e.g. at Grisedale Pike. However, it is suspected that this material was derived from Seathwaite, and may have become scattered by historical smuggling activity (Strens, 1965; Young, 1987).

There are also reports of a 'graphite mine' in Bannerdale, near Mungrisdale, close to Keswick in Cumbria (Ziemba, 1975). Although some authors suggest the graphite was a minor by-product of the lead-bearing veins being worked, Young (1987) indicates that graphite was obtained from a separate working at Bannerdale. The graphite-bearing vein trends east–west and is steeply dipping. Clots of graphite up to 2.5 cm size, in association with chlorite, muscovite, manganite and iron sulfides, are concentrated along the margins of a quartz vein (Ziemba, 1975; Young, 1987). Elsewhere in Cumbria minor graphite has been identified in the country rock and associated with sulfide mineralisation, for example, at the Dale Head Mine, Newlands Valley (Stanley and Vaughan, 1980) and the Wanthwaite Mine, St Johns in the Vale (Kingsbury and Hartley, 1958). Minor graphite has also been identified at Bowscale Tarn in the Caldew Valley, at Shap Granite Quarry at Shap and at the Greenside Mine near Glenridding (Young, 1987).

Elsewhere in England most graphite occurrences comprise observations of minor amounts of graphite and are rarely described in detail. In these occurrences graphite typically occurs as a rock-forming mineral or minor accessory phase in association with igneous intrusions and other types of mineralisation, or as inclusions in other minerals (e.g. in parts of Cornwall and at the Millclose Mine, Derbyshire) (Tindle, 2008). Graphite is a common fine-grained constituent of marine sedimentary rocks in Wales. However, the only notable occurrence is the Nant manganese mine, on the Llŷn, in Gwynedd. Graphite specimens from this locality are held in the National Museum of Wales, but no information about the nature and abundance of the graphite use is available (Bevins, 1994).

Graphitic rocks are widespread in Scotland, with the mineral recorded in schist, gneiss, marble, granite and pegmatites (Strahan et al., 1917; Tindle, 1998). It is reported that the Royal Scottish Museum in Edinburgh holds specimens of graphite from about twenty localities in Scotland (Strahan et al., 1917). However, it is unclear how many of these samples represent rock specimens in which graphite is a major rock-forming constituent.

One of the most significant graphite deposits in Scotland is Glen Strathfarrar, west of Loch Beannacharan, where vein-graphite occurs in fractures in folded Proterozoic metasedimentary rocks (Horne and Hinxman, 1914; Wright et al., 2012). Another historically worked graphite

occurrence in the Highland region is at Invergarry, near the head of Loch Lochy, on the west side of Leacann Doire Bannear. The graphite vein is reported to vary from 30–90 cm in width, and be "of fairly good quality" (Strahan et al., 1917).

Graphite occurs at a number of locations in Ayrshire, including at Stair where it is associated with antimony and copper mineralisation (Heddle, 1923). At the Craigman coal mine massive and columnar graphite occurs in 'pockets' of variable shape and size (up to 90 cm wide), which are irregularly distributed within a dolerite intrusion. One of these pockets produced about 15 tons of graphite (Strahan et al., 1917). Massive granular lumps of graphite have been found near Pennycross on the Isle of Mull. Thin graphite-bearing veins are reported from near to Oban (Heddle, 1923).

Thin veins containing graphite occur at a number of locations in the Grampian region. There are reports of historical "graphite mines" near Huntly and at Portsoy (Read, 1923; Heddle, 1923). Partially melted metasedimentary rocks that form the contact facies to the Huntly and Knock intrusions are frequently graphitic (Fletcher and Rice, 1989). Platinum-group element exploration in the district led to the discovery of irregular discordant bodies of graphite- and sulphide-bearing orthopyroxene-rich pegmatites, in the cumulate rocks of the Huntly pluton. These bodies, up to 3.5 m wide, are exposed in the Bin Quarry, about 4.5 km north-east of Huntly. They were investigated by drilling, but no significant continuity at depth was identified. The graphite and sulfide contents of the bodies are highly variable, each locally comprising up to 50 per cent of the rock. The graphite occurs as fine to coarse patches, laths and networks, and is commonly intergrown with, and replaces, sulfide. Similar rocks have also been recorded from the River Deveron near Huntly Castle (Gunn and Shaw, 1992; Gunn et al., 2015).

Resource potential

Graphite is a widespread constituent of many metamorphosed carbonaceous sedimentary rocks in the UK and minor graphite-bearing veins are common in Scotland. However, there are no domestic resources or reserves. There are very few significant graphite occurrences in the UK, and even the historically important deposits, are unlikely to be of current economic interest due to their small size and accessibility or depletion of the graphite resource. Graphite is very unlikely to be mined on a commercial scale in the UK.

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