



## RAW MATERIALS FOR DECARBONISATION

# The potential for platinum-group metals and nickel in the UK

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### Introduction

The six chemical elements referred to as the platinum-group metals (PGM) or platinum-group elements (PGE) are platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os). They are considered here with nickel because they commonly occur together in nature and PGM and nickel are extracted from the same ores in many deposits.

Platinum and palladium are of greatest commercial importance, followed by rhodium, although rhodium consumption is an order of magnitude less than that of platinum and palladium. The chief use of platinum, palladium and rhodium is in autocatalysts, but they are also used in the production of chemicals, pharmaceuticals and glass. They also have important applications in the electronics industry and for dental and medical purposes. In addition a significant amount of platinum is used in jewellery and for investment in the form of coins, bars and exchange-traded funds (Johnson Matthey, 2019). PGM are traded in a range of forms with widely varying metal contents: as metal in unwrought or powder form; in semi-

manufactured and intermediate forms; and in waste and scrap. In terms of volume, the largest share of UK trade in PGM is waste and scrap, but, by value, unwrought and partly-worked forms are much more significant with an import value of about £2.5 billion in 2017 and an export value of about £4 billion (Bide et al., 2019).

*This profile provides an overview of the geological potential for platinum-group metals and nickel 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.*

Global PGM production in 2017 amounted to approximately 446 tonnes, of which about 47 per cent was palladium and 41 per cent platinum (Brown et al., 2019). South Africa is the leading producer with a share of 58 per cent of the total in 2017, with Russia contributing 23 per cent. Other significant producers include Zimbabwe (7%), Canada (6%) and USA (4%).

PGM occur in two principal deposit classes associated with mafic and ultramafic igneous rocks: PGM-dominant deposits and magmatic nickel-copper sulfide deposits. In the former the PGM are the main economic products, while in the latter the PGM are generally a by-product of nickel extraction. The most important PGM-dominant deposits are found in South Africa, while magmatic nickel sulfide deposits are best developed in Russia and Canada. PGM may also be enriched in a range of other geological settings including ophiolites, Alaskan-Ural type complexes, hydrothermal veins and breccias, laterites, porphyry deposits, unconformity-related deposits, carbonatites and alkaline igneous rocks, and shales (Gunn, 2014). Deposits in these settings have generally supported only limited PGM production, although rich alluvial placer PGM deposits have been worked in several countries, notably Russia, Colombia, USA and New Zealand.

The PGM occur in a wide range of minerals, most commonly bonded with sulfur, arsenic, antimony, tellurium, bismuth and selenium. They also form alloys with one another and with other metals, most notably with iron. In addition the PGM are found as minor constituents of base-metal sulfides, such as pyrrhotite ( $\text{Fe}_7\text{S}_8$ ), chalcopyrite ( $\text{CuFeS}_2$ ) and pentlandite ( $(\text{Fe,Ni})_9\text{S}_8$ ).

More than two thirds of global nickel production is used to produce stainless steel (Nickel Institute, 2018). Nickel is also used in other forms of steel and non-ferrous alloys, and in plating, catalysts and magnets. Nickel in lithium-ion batteries is another important, rapidly growing application, although currently less than five per cent of global nickel production is used in batteries. Nickel is traded in a variety of forms. The most important for UK trade are mattes and sinters, scrap, ferro-nickel, unwrought metal and unwrought alloys. UK imports of nickel in all forms were valued at £545 million in 2017, with a corresponding export value of £523 million (Bide et al., 2019).

Global nickel production in 2017 amounted to nearly 2.1 million tonnes (Brown et al., 2019). The leading producers are Indonesia (16% of total), the Philippines (15%), Russia (11%), New Caledonia (10%) and Canada (ten per cent). Approximately 61 per cent of world nickel production was derived from laterite deposits in 2017, with the remainder from magmatic sulfide deposits. Numerous nickel-bearing minerals are found in nickel ore deposits. In magmatic sulfide deposits the most important nickel-bearing minerals are pentlandite and pyrrhotite, while others such as millerite (NiS), niccolite (NiAs) and siegenite ( $\text{CoNi}_2\text{S}_4$ ) are of local significance. In laterite deposits garnierite (nickel-rich serpentine), nickeliferous limonite and nickeliferous goethite are the most important hosts of nickel.

## UK production and resources

Nickel has been produced in very small quantities at a few localities in the UK. In the mid nineteenth century about 400 tonnes of nickel ore were extracted from two former copper mines near Inverary in the south-west Highlands of Scotland (Wilson and Flett, 1921). In addition, about 100 tonnes of ore were raised on a trial basis at Talnotry in south-west Scotland at the end of the nineteenth century (Wilson and Flett, 1921) (Figure 1). Small amounts of nickel-bearing ore were also extracted at a number of mines in Cornwall, commonly associated with the production of a range of other metals including cobalt, bismuth, lead, zinc, silver, iron, antimony and uranium (Dines, 1956). There has never been any commercial PGM production in the UK.

Prompted by the booming nickel market and the discovery of large economic deposits in Western Australia, Rio Tinto Zinc and Consolidated Goldfields undertook major programmes of exploration for nickel mineralisation in the Caledonian layered mafic intrusive complexes of north-east Scotland between 1967 and 1973. From 1969 onwards they formed a joint venture partnership known as Exploration Ventures Limited (EVL). EVL carried out extensive multidisciplinary surveys (geology, geophysics and geochemistry) and associated diamond drilling of some targets. They did not produce any resource or reserve estimates for nickel compliant with modern reporting standards. However, they did report 'geological reserves' for their two principal

discoveries: at Knock, near Huntly, they estimated 3 million tonnes at 0.52% Ni and 0.27% Cu; and at Arthrath, near Ellon, about 30 kilometres north of Aberdeen, they reported 17 million tonnes of ore grading 0.21% Ni and 0.14% Cu (Fletcher et al., 1997). The basis for these estimates and their equivalence to modern reporting standards are not known. In the late 1970s Amax Exploration UK Ltd followed up the EVL nickel-copper exploration programme in north-east Scotland. Records of this work are sparse although it is known to have included extensive shallow drilling in the Huntly-Knock and Arthrath areas, and limited diamond drilling at Belhelvie and Arthrath. The Amax investigations did not lead to the publication of any new resource data.

With increased global interest in 'strategic' metals in the early 1980s the BGS, as part of its government-funded Mineral Reconnaissance Programme (MRP), undertook systematic reconnaissance exploration for PGM over several prospective areas in the UK between 1985 and 1989. The main targets investigated were: layered mafic-ultramafic intrusions of Caledonian age in north-east Scotland, including some areas previously investigated for nickel; Caledonian alkaline intrusions in north-west Scotland; and ophiolite complexes in Shetland, Cornwall and south-west Scotland. There are no estimates of resources of PGM anywhere in the UK.

## UK occurrences

The most important occurrences of magmatic nickel-copper mineralisation in the UK are associated with a suite of Caledonian syntectonic layered mafic-ultramafic intrusions in north-east Scotland, commonly referred to as the 'Younger Basics'. Magmatic nickel-copper sulfide deposits were discovered at two locations, Knock and Arthrath, in these rocks by EVL. Subsequently research focussed on PGM in these deposits and elsewhere in the region. This was undertaken at Aberdeen University (Fletcher, 1989; Fletcher et al., 1997) and by the BGS MRP (Gunn and Styles, 2002). At Arthrath EVL drilled 36 boreholes for 6850 metres, which led to the identification of sulfide mineralisation over a strike length of about four kilometres in a wide range of contaminated and xenolithic igneous rocks associated with mafic-ultramafic cumulates and hornfelsed Dalradian metasedimentary rocks. Nickel-copper

mineralisation is concentrated in five zones where disseminated and net-textured sulfides, up to 40 per cent by volume, occur in thick sections locally exceeding 100 metres in thickness. Pyrrhotite is the predominant sulfide mineral, with subordinate chalcopyrite and pentlandite. Limited drilling by Alba Mineral Resources plc in 2005 verified the EVL results in one zone and suggested that the mineralised body in that area might extend down-dip to 350 metres below surface (Alba Mineral Resources, 2005 and 2006). During 2006 Alba, in conjunction with its joint venture partner Inco Europe Ltd, conducted ground electromagnetic surveys and partial-leach shallow soil sampling over the seven kilometre length of the Arthrath intrusion. No follow up of these surveys is known to have been carried out as the joint venture ended in early 2007 (Alba Mineral Resources, 2008).

The other important nickel discovery made by EVL is located on the south-eastern margin of the Knock intrusion about seven kilometres north of Huntly. Here EVL drilled 59 boreholes for a total of 9224 metres (Gunn and Styles, 2002). The 'resource' noted above is located in two sub-parallel zones on the farms of Littlemill and Auchencrieve. Nickel and copper ores comprise massive and submassive discontinuous lenticular bodies in a structurally complex contact zone between the igneous rocks and the Dalradian country rocks. The sulfide zone is up to 20 metres thick at Littlemill and is roughly conformable with the enclosing olivine cumulates, contaminated gabbros and metasedimentary rocks. Textures vary over short distances with disseminated and net texture sulfides of magmatic origin passing into banded, brecciated and vein textures indicating the importance of deformation and/or the injection of sulfide liquids (Fletcher, 1989).

Laboratory studies of PGM in archived drillcore from the Littlemill-Auchencrieve ores were undertaken by Fletcher (1989), Fletcher and Rice (1989) and by BGS (Gunn and Styles, 2002). Values up to about 500 ppb Pt+Pd were reported with highly variable Pd/Pt ratios. It was suggested that the sulfide mineralisation was magmatic in origin with sulfide immiscibility triggered by country rock contamination. Subsequent hydrothermal reworking in ductile shear zones under amphibolite facies conditions produced the geochemical patterns and ore textures preserved along this

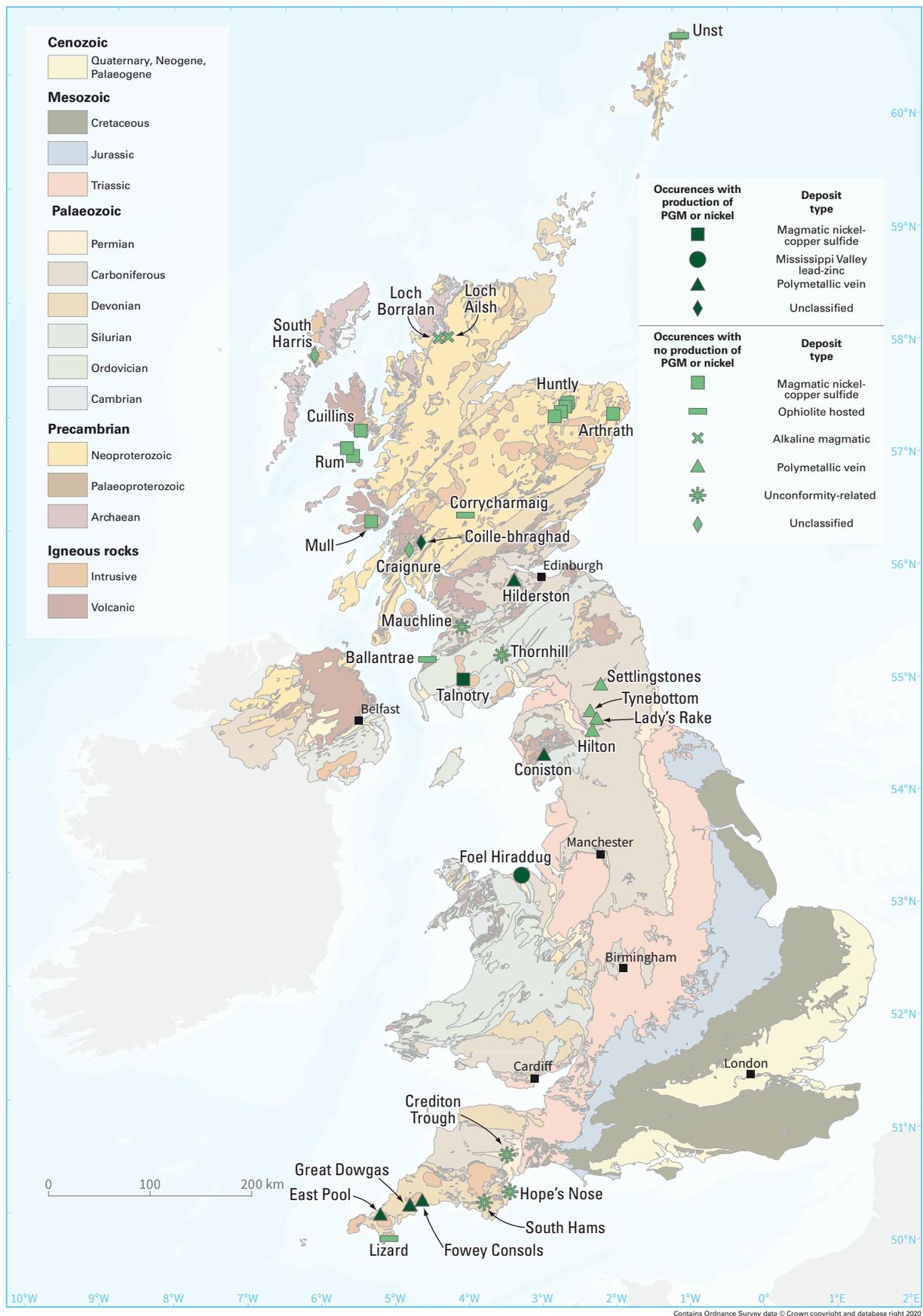


Figure 1 Location of principal occurrences of nickel and platinum-group metals in the United Kingdom.

margin of the Knock intrusion. In contrast, there was less deformation and remobilisation at Arthrath leading to the preservation of more extensive zones of sulfide mineralisation. Re-examination of drillcore samples from Arthrath and Littlemill confirmed sporadic PGM enrichment in massive and submassive copper-nickel-iron sulfide ores, with maxima of 456 ppb Pd and 418 ppb Pt (McKervey et al., 2007). Detailed mineralogical studies led to the development of a new genetic model involving the mixing and mingling of relatively late, primitive magma with earlier magmas that had already differentiated to more evolved compositions (McKervey et al., 2007). The nickel-copper-PGM distribution at Arthrath is considered to be predominantly of magmatic origin, while in the Knock intrusion there has been substantial modification by later hydrothermal activity.

BGS also carried out exploration for stratiform magmatic PGM mineralisation over the Huntly intrusion in north-east Scotland. Despite the widespread occurrence of disseminated magmatic sulfide mineralisation no values above 50 ppb Pt or Pd were reported. A different style of PGM mineralisation was identified in an area underlain by olivine cumulate rocks in the western part of the Huntly intrusion (Gunn and Shaw, 1992). High precious metal contents, up to about 700 ppb Pt+Pd+Au, were reported in irregular discordant bodies, up to a few metres wide, of graphite- and sulfide-bearing orthopyroxene-rich pegmatites. However, diamond drilling of these bodies failed to identify any significant continuity at depth.

The distribution of PGM in a group of pre-tectonic 'Older Basic' rocks in north-east Scotland was also investigated by BGS (Gunn and Styles, 2002). These rocks occur as discontinuous, concordant sheets and pods in an elongate belt, known as the Portsoy Lineament, running towards the south-south-west from the coast at Portsoy over a distance of more than 100 kilometres. Low tenor PGM enrichment up to about 170 ppb Pt+Pd has been reported at several localities in the upper Deveron valley section of the lineament (Gunn et al., 1990; Gunn and Styles, 2002). At some localities, notably in the Succoth-Brown Hill intrusion and at Kelman Hill, higher PGM values up to 280 ppb Pt+Pd, with increased Pd/Pt ratios and locally accompanied by gold enrichment (up to 370 ppb Au), were identified. Mineralogical studies

suggest an origin related to late, low temperature processes associated with serpentinisation of the altered and sheared ultramafic host lithologies (Gunn et al., 1990; Gunn et al., 1996). The highest PGM values are found in pyroxene-rich rocks.

PGM mineralisation has also been recorded in the Siluro-Ordovician Loch Borralan and Loch Ailsh alkaline pyroxenite-syenite complexes along the north-western margin of the Scottish Caledonides in north-west Scotland, about 25 kilometres north-east of Ullapool (Shaw et al., 1992 and 1994; Styles et al., 2004). Analysis of rocks and drillcore revealed elevated platinum and palladium in pyroxenites and syenites in both complexes. The highest values, up to about 900 ppb Pt+Pd, occur in pyroxenites in the Loch Borralan Complex. Mineralogical studies identified a few platinum-group mineral grains of magmatic origin but many more grains are associated with carbonate, barite and sulfides in veins and fractures, indicating the importance of low temperature hydrothermal remobilisation of the PGM (Styles et al., 2004).

BGS studies in the Lower Proterozoic intrusive complex in South Harris, Outer Hebrides revealed no significant PGM values in the main mafic and ultramafic sections of the body, but minor palladium enrichment, up to 210 ppb, was reported in the Langavat Metamorphic Belt on the eastern margin of the igneous complex (Shaw et al., 1993).

Minor PGM occurrences have been documented in layered mafic-ultramafic rocks in the Tertiary igneous centres on Rum, Mull and Skye in north-west Scotland. On Rum platinum-group minerals have been identified in layered cumulates and in late intrusive plugs in the Rum Central Complex. Elevated PGM concentrations, exceeding 2500 ppb PGM+Au, have been reported in the Eastern Layered Series associated with thin (millimetre-scale) chrome spinel layers and minor interstitial sulfides. A wide variety of platinum-group minerals has been identified in this part of the Rum complex and a magmatic origin for the mineralisation proposed (Power et al., 2000). PGM mineralisation is also present in association with disseminated sulfides (>400 ppb total PGM+Au) and in late-stage sulfide-rich dykes (>2000 ppb total PGM+Au) within the West Sgaorishal plug on Rum (Power et al., 2003). This mineralisation is considered to be essentially magmatic in origin

with contamination by a sedimentary source causing sulfur saturation of the magma.

Local concentrations of abundant and diverse platinum-group minerals have also been reported in the Ben Buie intrusion on Mull and in the Outer Layered Series of the Cuillin Complex on Skye. These occurrences differ in mineralogy and style from those reported on Rum leading to the development of a combined orthomagmatic-hydromagmatic model for their origin (Pirrie et al., 2000).

A small body of arsenic-rich nickel-copper ore occurs at Talnotry located about nine kilometres north-east of Newton Stewart in the Southern Uplands of Scotland. The mineralisation is located near the base of a sheet-like diorite intrusion emplaced in Ordovician metasedimentary rocks in the aureole of the Cairnsmore of Fleet granite (Stanley et al., 1987). Geophysical surveys by BGS indicated that the deposit is small, 20 metres in length and up to 4 metres wide (Parker, 1977). The mineralisation was discovered in about 1885 and trial working continued until 1890. About 100 tons of ore were raised but none ever left the site (Wilson and Flett, 1921). Stanley et al. (1987) undertook detailed mineralogical studies, which identified niccolite, gersdorffite (NiAsS), pyrrhotite, pentlandite and chalcopyrite as the main ore minerals. They reported up to 7.3% Ni and 49 ppm Pt in representative specimens of niccolite-gersdorffite ore. Power et al. (2004) distinguished three main phases of mineralisation in the Talnotry body with platinum-group minerals concentrated in a lower pyrrhotite-chalcopyrite-dominant assemblage. The mineralisation at Talnotry is probably magmatic in origin, although why this very small body contains such high PGM grades remains unclear. However, it should be noted that in the mid 1980s the analytical methodology for the determination of PGM in rocks and ores was not necessarily reliable. Accordingly, without detailed knowledge of the sampling and analytical procedures utilised, the accuracy of the reported platinum content cannot be guaranteed.

Platinum-group minerals have also been reported from a small (500 metres x 200 metres) body of metamorphosed and altered ultramafic rocks at Corrycharmaig near Killin in Perthshire (Power and Pirrie, 2000). Although no bulk geochemical data

have been published for these rocks, a suite of platinum-group minerals, dominated by ruthenium, iridium and osmium species, was identified in small podiform chromitite bodies. Low tenor nickel-bearing mineralisation (mainly heazlewoodite, niccolite and Ni-Fe alloy), comparable with serpentinised ultramafic lithologies elsewhere, also occurs within the chromite-rich lithologies at Corrycharmaig. On account of the chemistry of the chromite, its mode of occurrence and the nature of the PGM assemblage, an ophiolitic origin has been suggested for the Corrycharmaig body (Power and Pirrie, 2000).

Extensive academic research and limited commercial exploration have been undertaken to investigate the potential for PGM mineralisation in ophiolite complexes on Unst, Shetland, at Ballantrae, Ayrshire and on the Lizard in Cornwall.

During the 1980s high PGM concentrations were reported in the Unst ophiolite in Shetland associated with podiform chromite ores, which were worked between 1820 and 1945 (Gunn et al., 1985; Gunn 1989). Four major units of mafic and ultramafic rocks, with an aggregate thickness of about seven kilometres, are present. These have been interpreted as the lower part of an incomplete ophiolite complex obducted at about 498 Ma (Flinn et al., 1991). Low tenor nickel-iron sulfide mineralisation, up to 1 to 2 per cent by volume, is widespread in both the chromitites and silicate rocks. Significant PGM enrichment has been identified at several levels within the Unst ophiolite. The highest values, exceeding 100 ppm of both platinum and palladium, accompanied by ppm levels of gold and the other PGM, occur in spoil heaps at a locality known as Cliff. Cliff is situated close to the basal thrust of the ophiolite in a zone of talc-carbonate alteration at the margin of a chromitite pod. Sperrylite and stibiopalladinite, the most abundant platinum-group minerals, occur in chlorite haloes around chromite grains, commonly associated with nickel, iron and cobalt sulfides and arsenides. There is no consensus on the genesis of this mineralisation: BGS proposed a hydrothermal origin related to serpentinisation (Gunn et al., 1985; Gunn, 1989), while Prichard and co-workers favoured a genetic model involving predominantly magmatic processes (Prichard et al., 1996). Lower grade Pt-Pd-dominant mineralisation has also been reported locally in the cumulate sequence of the

complex. Elsewhere on Unst PGM mineralisation more typical of ophiolites, dominated by osmium, iridium and ruthenium, occurs in association with chromitites. The most notable example of this type is found at Harold's Grave where ppm levels of ruthenium and iridium were reported, accompanied by relatively low palladium and platinum contents. Three small programmes of shallow drilling were undertaken by commercial companies between 1984 and 1999 to investigate the most promising PGM targets in the Unst ophiolite (Gunn and Styles, 2002). At Cliff, which was the main focus of two of these programmes, no significant high-grade PGM mineralisation was identified in situ.

The occurrence of platinum in the Lizard complex in Cornwall was first documented by McPherson and Lamb (1921). This has never been substantiated by modern investigations and drainage surveys by BGS failed to identify PGM values exceeding background levels (Gunn and Styles, 2002). However, Hutchinson (2001) described the occurrence of a suite of platinum-group minerals associated with altered pentlandite and chalcopyrite and secondary magnetite near Carrick Luz in the eastern part of the Lizard complex. This mineral assemblage is interpreted to be magmatic in origin with local hydrothermal redistribution. Geochemical analysis of these samples did not reveal platinum or palladium values exceeding 10 ppb.

BGS also investigated small occurrences of chromite mineralisation at two localities (Poundland Burn and Pinbain Bridge) in the Ballantrae ophiolite, near Girvan in Ayrshire (Stone et al., 1986). Geochemical data on chromite samples and heavy mineral concentrates collected from a wide area underlain by ultramafic rocks provided no evidence of PGM enrichment. However, it is important to note that the analytical methodology used to determine the PGM abundance in chromite-rich samples provided poor precision and high analytical detection limits (Gunn and Styles, 2002). Later mineralogical studies by Power and Pirrie (2004) identified a diverse, but not abundant, suite of platinum-group minerals dominated by iridium-, osmium- and ruthenium-bearing phases associated with the Pinbain chromite. This assemblage is typical of ophiolitic chromitite-hosted PGM mineralisation.

Geochemical surveys and allied mineralogical studies conducted by BGS between the 1970s and 1990s identified an association between gold and PGM related to the boundary between Permian red-bed basins, related igneous rocks and underlying more reduced strata. Based on work carried out in the South Hams district of Devon Leake et al. (1991) developed a model in which gold and PGM are leached in oxidising fluids from dispersed sources within the red bed environment. They are transported as chloride complexes from which they are precipitated at unconformable or faulted contacts with unoxidised strata, or as a result of mixing with fluids derived from such beds. In South Hams gold grains recovered from alluvium and overburden were found to have a complex internal structure and a distinctive chemical signature (enriched in palladium, copper, mercury, platinum and silver). They also contained a suite of inclusions dominated by selenide minerals and some palladium-species (Leake et al., 1991 and 1992). These grains are similar in many respects to the precious and base metal selenide mineralisation that is found in carbonate veins at Hope's Nose, near Torquay (Stanley and Criddle, 1990). Mineral grains with similar morphology and chemistry were subsequently identified at several other localities on Permo-Triassic rocks in Britain, notably in the Crediton Trough, north of Dartmoor, in Devon (Leake et al., 1994), and in the Mauchline Basin and Thornhill Basin in Ayrshire (Leake and Cameron, 1996; Leake et al., 1997). More detailed mineralogical and fluid inclusion studies of unconformity-related gold-palladium occurrences in and around the Permo-Triassic basins of south-west England refined this genetic model and identified several criteria for their further exploration (Shepherd et al., 2005). Limited commercial exploration of some of these unconformity-related targets was conducted in the 1990s and early 2000s, but no unequivocal bedrock sources for the gold or PGM were identified.

Two former copper mines near Inverary in the south-west Highlands of Scotland produced small quantities of nickel between 1854 and 1867 (Wilson and Flett, 1921). At the Coille-bhraghad mine more than 400 tonnes of nickel ore, comprising pyrrhotite, chalcopyrite, pyrite and pentlandite, were produced from a small open pit following renewal of mining activities when the ore was found to be nickeliferous. At

Craignure, about 10 kilometres along strike to the south-west, small quantities of nickel ores were removed from dumps of material discarded during earlier copper extraction, but mining was not re-started. No modern studies of these ores have been undertaken but they were reported as being replacements of quartzitic bands within the predominantly pelitic Dalradian metasedimentary sequence. There is no information on the extent of the nickel-bearing mineralisation, but as the deposits occur at similar structural levels in proximity to a suite of metabasic intrusive rocks, potential may exist for further deposits along strike between the two bodies (Coats et al., 1982).

Silver, lead and nickel were extracted at various times between 1607 and 1898 from the Hilderston mine, near Linlithgow in West Lothian, central Scotland (Wilson and Flett, 1921; Stephenson et al., 1983). The mineralisation comprises Late Carboniferous hydrothermal veins in Lower Carboniferous sedimentary rocks where they are cut by east-west faults and quartz dolerite dykes. Two distinct mineralisation assemblages have been identified: a barium-silver-nickel-cobalt suite extracted during early shallow working; and a barium-lead-zinc suite found in later, deeper workings. In the former the mineral assemblage comprises barite, calcite, dolomite, pyrite, chalcocopyrite, niccolite, bravoite ((Fe,Ni)S<sub>2</sub>), annabergite (Ni<sub>3</sub>(AsO<sub>4</sub>)<sub>2</sub>·8H<sub>2</sub>O), erythrite (Co<sub>3</sub>(AsO<sub>4</sub>)<sub>2</sub>·8H<sub>2</sub>O) and native silver. This ore was found entirely within 18 metres of the surface. The main silver vein was up to 5 cm thick and contained up to 1.34% Ag. The nickel ore was reported to contain about 30% Ni and 2% Cu (Wilson and Flett, 1921).

In south-west England small quantities of nickel ore have been recorded in several old mines commonly associated with cobalt and bismuth in late-stage, low temperature, discordant veins known as crosscourses. Dines (1956) notes production of small tonnages (<10 tonnes) of nickel ore in the St Austell district at St Austell Consols, Fowey Consols and East Pool Mine. Small quantities of nickeliferous ores were also recorded in the St Ives district, the Carn Brea area and the Helford-Falmouth area (Dines, 1956). In addition mixed nickel and cobalt ores were reported to have been produced in the St Austell district at St Austell Consols and Dowgas Mine.

Small amounts of nickel-cobalt mineralisation comprising niccolite accompanied by 'smaltite'

(CoAs<sub>3,x</sub>) (possibly skutterudite or cobaltite) have been recorded with copper ores in the Bonser vein and in the Paddy End section of the mines near Coniston in the Lake District (Young, 1987). Russell (1925) reported the production of three tons of nickel and cobalt ore in 1855 and further sales of smaller quantities of nickel ore in 1873.

Minor occurrences of niccolite and several other nickel-bearing minerals have been recorded at three disused mines in the North Pennine orefield (Young et al., 1985; Ixer, 1986). At the Lady's Rake lead mine near Harwood in Upper Teesdale a magnetite-rich ore containing niccolite with chalcocopyrite, galena, gersdorffite, pyrite, pyrrhotite, sphalerite and ullmannite (NiSbS) has been described. At the Settlingstones lead mine near Hexham a varied suite of nickel-bearing minerals (including niccolite, millerite, rammelsbergite (NiAs<sub>2</sub>) and ullmannite) has been found, together with minor amounts of cobalt minerals (skutterudite and gersdorffite), in association with the galena and witherite ores (Young et al., 1985; Ixer, 1986). At the Hilton mine, near Appleby, the lead mineralisation is accompanied by niccolite and gersdorffite, with a final phase comprising fluorite, galena and millerite (Bridges, 1982; Ixer, 1986). Young et al., (1985) concluded that the nickel-bearing assemblages at Settlingstones, Lady's Rake and Hilton may have been produced by skarn-type alteration accompanying the emplacement of the Whin Sill which itself may have been the source of the nickel.

In the Central Wales Orefield nickel occurs in a variety of minerals, commonly with cobalt, as a minor component of polymetallic vein mineralisation, which was previously mined for lead, zinc, copper and silver (Mason, 1997). Nickel occurs most commonly in pentlandite, siegenite and millerite, which have been recorded at several mines associated with base metal sulfide ores. Most of these are located near Tal-y-bont in Ceredigion (National Museum Wales, 2019a, 2019b and 2019c). Niccolite and siegenite are also found as trace constituents of the copper ores at the Great Orme mine near Llandudno (National Museum Wales, 2019d and 2019b). Cobalt-nickel-bearing mineralisation occurs at the Foel Hiraddug mine (also known as Moel Hiraddug) near Dyserth, located about 30 kilometres east of Llandudno. . The occurrence comprises asbolane associated with manganese oxides and hematite in a clay-filled fissure hosted in limestone of Carboniferous

age. In addition to working for hematite and pyrite, cobalt and nickel were also produced at this site. Mine production of cobalt ore is estimated to have been 264 tons between 1878 and 1880 (Foster, 1882; North, 1962). The orebody had a length of about 23 metres and an average width of about 0.3 metres (with a maximum of 3 metres). It was worked to a depth of about 73 metres and a second 'vein' was trialled to about 30 metres. Foster (1882) reported assays of ore parcels containing 1.0 to 1.8% Co and 0.4 to 1.1% Ni.

In the Upper Carboniferous Coal Measures of South Wales claystone-ironstone nodules are widespread in mudstones adjacent to the coal seams (Bevins and Mason, 2010). Within these concretionary nodules, which range in size from a few centimetres to over one metre, a suite of sulfide minerals is commonly developed along septarian cracks lined with siderite. The sulfide suite comprises millerite, galena, chalcopyrite, sphalerite, pyrite, marcasite and siegenite. Most notable are the acicular groups of millerite crystals, which may attain a length of several centimetres. There is no consensus on the origin of these nodules or the included sulfides.

## Resource potential

A considerable amount of research has identified high concentrations of PGM and nickel, and the occurrence of a wide range of nickel- and PGM-bearing minerals, in several areas of the UK. However, it should be noted that in many cases these metals are minor constituents of polymetallic ores and are unlikely to constitute anything more than a minor by-product of the extraction of another metal. Nevertheless, further research into the abundance and distribution of nickel (and cobalt) in some of the polymetallic ores worked in historic mining districts in Wales, Cornwall, the Lake District and the north Pennines is warranted as few modern systematic studies have been undertaken in these areas.

The most attractive targets for nickel exploration, with possible by-product PGM and cobalt, are located in the Caledonian layered mafic-ultramafic intrusions in north-east Scotland. Available data from commercial surveys and academic research underline this potential and highlight a number of targets favourable for magmatic nickel sulfide mineralisation, with possible associated PGM and cobalt. Although the geology of the north-east

Grampians is complex and bedrock exposure is sparse, experience from past commercial exploration has demonstrated the efficacy of soil geochemistry and electromagnetic surveys for locating deposits of this type in the region. The application of these or similar techniques based on modern conceptual models for deposits of this type provide a sound basis for undertaking further exploration.

In Northern Ireland there is potential for the occurrence of PGM mineralisation associated with the Palaeogene Antrim Lava Group (Andersen et al., 2002). Although there is little published information on PGM in these rocks, their geological setting and the presence of elevated PGM concentrations in regional geochemical data suggest that there is potential for magmatic nickel-copper-PGM deposits associated with the Antrim Lava Group and their underlying feeder zones (Lusty, 2016).

While the occurrence of precious metal grains with distinctive chemistry and inclusion suites suggest the possibility of the widespread occurrence of unconformity related mineralisation, no bedrock sources for these grains have been identified. Further systematic exploration to identify bedrock sources is warranted in some areas, notably in the South Hams and Crediton Trough districts of Devon and in the Mauchline and Thornhill Basins in Ayrshire.

The nickel-bearing claystone-ironstone nodules in south Wales are a potential target for further research. Although the nodules have a significant lateral extent no assessment of their potential as a source of metals appears to have been undertaken. Geochemical studies to elucidate their metal contents are recommended, followed by an investigation of the controls on their distribution and abundance.

## References

- ALBA MINERAL RESOURCES PLC. 2005. Drilling Results. 29 November 2005. [https://www.albamineralresources.com/ul/Alba%20Press%20Release%20\(Nov%2029th\).pdf](https://www.albamineralresources.com/ul/Alba%20Press%20Release%20(Nov%2029th).pdf)
- ALBA MINERAL RESOURCES PLC. 2006. Drilling Results. [https://www.albamineralresources.com/ul/Alba%20RNS%20-%20Drilling%20Results%20\\_23rd%20Jan%202006\\_.pdf](https://www.albamineralresources.com/ul/Alba%20RNS%20-%20Drilling%20Results%20_23rd%20Jan%202006_.pdf)

- ALBA MINERAL RESOURCE PLC. 2008. Annual Report 2007. <https://www.albamineralresources.com/ul/Alba%20AR07.pdf>
- ANDERSEN, J C O, POWER, M R, and MOMME, P. 2002. Platinum-group elements in the Palaeogene North Atlantic Igneous Province. In: CABRI, L. J. (ed.), *The Geology, Geochemistry, Mineralogy and Beneficiation of Platinum-Group Elements*, 637–667. CIM Special Volume 54. *Canadian Institute of Mining and Metallurgy*.
- BEVINS, R E, and MASON, J S. 2010. Upper Palaeozoic millerite-bearing ironstones of the South Wales coalfield. In: *Mineralisation of England and Wales* (eds. BEVIN, R E, et al.), 346–351. Geological Conservation Review Series, No. 36, *Joint Nature Conservation Committee*, Peterborough.
- BROWN, T J, IDOINE, N E, RAYCRAFT, E R, HOBBS, S F, SHAW, R A, EVERETT, P, KRESSE, C, DEADY, E A, and BIDE, T. 2019. World Mineral Production 2013–2017.
- BRIDGES, T F. 1982. An occurrence of nickel minerals in the Hilton mine, Scordale, Cumbria. *Journal of the Russell Society*, 1, 33–39.
- COATS, J S, TANDY, B C, and MICHIE, U. MCL. 1982. Geochemical drainage survey of central Argyll, Scotland. *Institute of Geological Sciences, Mineral Reconnaissance Programme Report*, No. 50.
- DINES, H G. 1956. The metalliferous mining region of south-west England. *Economic Memoir of the Geological Survey of Great Britain*.
- FLETCHER, T A. 1989. The Geology, Mineralisation (Ni, Cu, PGE) and Isotope Systematics of Caledonian Mafic Intrusions near Huntly, N.E. Scotland. PhD thesis, University of Aberdeen, UK.
- FLETCHER, T A, and RICE, C M. 1989. Geology, mineralisation (Ni-Cu) and precious-metal geochemistry of Caledonian mafic intrusions near Huntly, northeast Scotland. *Transactions Institution of Mining and Metallurgy (Section B, Applied Earth Science)*, 94, B185–200.
- FLETCHER, T A, BOYCE, A J, FALLICK, A E, RICE, C M, and KAY, R L F. 1997. Geology and stable isotope study of Arthrath mafic intrusion and Ni-Cu mineralisation, northeast Scotland. *Transactions Institution of Mining and Metallurgy (Section B, Applied Earth Science)*, 106, B169–178.
- FLINN, D, MILLER, J A, and RODDOM, D. 1991. The age of the Norwick hornblende schists of Unst and Fetlar and the obduction of the Shetland ophiolite. *Scottish Journal of Geology*, 27, 11–19.
- FOSTER, C, LE NEVE. 1882. On the occurrence of cobalt ore in Flintshire. *Transactions Royal Geological Society Cornwall*, 10, 107–112.
- GUNN, A G. 2014. Platinum-group elements. In: GUNN, A G. (ed) *Critical Metals Handbook*, Wiley.
- GUNN, A G. 1989. Drainage and overburden geochemistry in exploration for platinum-group element mineralisation in the Unst ophiolite, Shetland, U.K. *Journal of Geochemical Exploration*, 31, 209–236.
- GUNN, A G, LEAKE, R C, STYLES, M T, and BATESON, J H. 1985. Platinum-group element mineralisation in the Unst ophiolite, Shetland. *British Geological Survey, Mineral Reconnaissance Programme Report* 73.
- GUNN, A G, STYLES, M T, STEPHENSON, D, SHAW, M H, and ROLLIN, K E. 1990. Platinum-group elements in ultramafic rocks of the Upper Deveron Valley, near Huntly. Aberdeenshire. *British Geological Survey, Mineral Reconnaissance Programme Report* 115.
- GUNN, A G, and SHAW, M H. 1992. Platinum-group elements in the Huntly intrusion, Aberdeenshire, north-east Scotland. *British Geological Survey, Mineral Reconnaissance Programme Report* 124.
- GUNN, A G, STYLES, M T, ROLLIN, K E, and STEPHENSON, D. 1996. The geology of the Succoth-Brown Hill mafic-ultramafic intrusive complex, near Huntly, Aberdeenshire. *Scottish Journal of Geology*, 32, 33–49.
- GUNN A G, and STYLES M T. 2002. Platinum-group element occurrences in Britain: magmatic, hydrothermal and supergene. *Transactions of the Institution of Mining and Metallurgy Section B-Applied Earth Science* 111: B2–B14.
- HUTCHINSON, D. 2001. The origin and distribution of platinum-group element mineralization in the oceanic upper mantle: a comparison of samples from the Lizard and Troodos ophiolite complexes, and dredge samples from the Tonga Trench. PhD Thesis, University of Cardiff.

- IXER, R A, STANLEY, C J, and VAUGHAN, D J. 1979. Cobalt-, nickel- and iron-bearing sulpharsenides from the North of England. *Mineralogical Magazine*, 43, 389–395.
- IXER, R A. 1986. The ore mineralogy and parageneses of the lead-zinc-fluorite-baryte orefields of the English Pennine and Mendip Hills. In: *Mineral Parageneses*, eds. Craig, J R. et al., Theophrastus Publications, Athens.
- JOHNSON MATTHEY. 2019. PGM Market Report, May 2019. [http://www.platinum.matthey.com/documents/new-item/pgm%20market%20reports/pgm\\_market\\_report\\_may\\_19.pdf](http://www.platinum.matthey.com/documents/new-item/pgm%20market%20reports/pgm_market_report_may_19.pdf)
- LEAKE, R C, BLAND, D J, STYLES, M T, and CAMERON, D G. 1991. Internal structure of Au-Pd-Pt grains from south Devon, England, in relation to low-temperature transport and deposition. *Transactions Institution of Mining and Metallurgy* (section B: Applied Earth Science), 100, B159–178.
- LEAKE, R C, CAMERON, D G, BLAND, D J, STYLES, M T, and ROLLIN, K E. 1992. Exploration for gold in the South Hams district of Devon. *British Geological Survey, Mineral Reconnaissance Programme Report*, 121.
- LEAKE, R C, CAMERON, D G, SCRIVENER, R C, and BLAND, D J. 1994. Exploration for gold in the Crediton Trough, Devon. Part 2: detailed surveys. *British Geological Survey, Mineral Reconnaissance Programme Report*, 134.
- LEAKE, R C, and CAMERON, D G. 1996. Exploration for gold in the Thornhill Basin, southern Scotland. *British Geological Survey, Mineral Reconnaissance Programme Open File Report* 19.
- LEAKE, R C, CAMERON, D G, BLAND, D J, STYLES, M T, and FORTEY, N J. 1997. The potential for gold mineralisation in the British Permian and Triassic red beds and their contacts with underlying rocks. *British Geological Survey, Mineral Reconnaissance Programme Report*, 144.
- LUSTY, P. 2016. Critical metals for high-technology applications: mineral exploration potential in the north of Ireland. In: YOUNG, M E. (ed.), *Unearthed: impacts of the Tellus surveys of the north of Ireland*. Dublin. Royal Irish Academy.
- MASON, J. 1997. Regional polyphase and polymetallic vein mineralization in the Caledonides of the Central Wales Orefield. *Transactions of the Institution of Mining and Metallurgy*. Section B. Applied Earth Science 10
- McKERVEY J A, GUNN A G, Styles M T. 2007. Platinum-group elements in Ordovician magmatic Ni-Cu prospects in northeast Scotland. *Canadian Mineralogist*, 45, 2: 335–353.
- McPHERSON, G.Jnr, and LAMB, T. 1921. Platinum-bearing rocks in the Lizard district. *Geological Magazine*, 58, 512–514.
- NATIONAL MUSEUM OF WALES. 2019a. Cobalt pentlandite. <https://museum.wales/mineralogy-of-wales/database/?mineral=82&name=Cobaltpentlandite>.
- NATIONAL MUSEUM WALES. 2019b. Siegenite. <https://museum.wales/mineralogy-of-wales/database/?mineral=95&name=Siegenite>.
- NATIONAL MUSEUM WALES. 2019c. Millerite. <https://museum.wales/mineralogy-of-wales/database/?mineral=319&name=Millerite>.
- NATIONAL MUSEUM WALES. 2019d. <https://museum.wales/mineralogy-of-wales/database/?mineral=310&name=Nickeline>
- NICKEL INSTITUTE. 2018. Stainless steel: The role of nickel. <https://www.nickelinstitute.org/about-nickel/stainless-steel/>
- NORTH, F J. 1962. Mining for metals in Wales. National Museum of Wales. <https://www.aditnow.co.uk/documents/personal-album-128/mining-for-metals-in-wales.pdf>
- PARKER, M E. 1977. Geophysical surveys around the Talnotry mine, Kirkcudbrightshire. *Mineral Reconnaissance Programme Report*, Institute of Geological Sciences, 10.
- PIRRIE, D, POWER, M R, ANDERSEN, J C O, and BUTCHER, A R. 2000. Platinum-group mineralization in the Tertiary Igneous Province: new data from Mull and Skye, Scottish Inner Hebrides, UK. *Geological Magazine*, 137, 651–658.
- POWER, M R, and PIRRIE, D. 2000. Platinum-group element mineralization within ultramafic rocks at Corrycharmaig, Perthshire: implications for the origin of the complex. *Scottish Journal of Geology*, 36, 143–150.
- POWER, M R, and PIRRIE, D. 2004. Platinum-group minerals within the Ballantrae Complex, SW Scotland. *Scottish Journal of Geology*, 40, 1–5.

- POWER, M R, PIRRIE, D, ANDERSEN, J C O, and BUTCHER, A R. 2000. Stratigraphical distribution of platinum-group minerals in the Eastern Layered Series, Rum, Scotland. *Mineralium Deposita*, 35, 762–775.
- POWER, M R, PIRRIE, D, and ANDERSEN, J C O. 2003. Diversity of platinum-group element mineralisation styles in the North Atlantic Igneous Province: new evidence from Rum, UK. *Geological Magazine*, 140, 499–512.
- POWER, M R, PIRRIE, D, JEDWAB, J, and STANLEY, C J. 2004. Platinum-group element mineralisation in an As-rich magmatic sulphide system, Talnotry, southwest Scotland. *Mineralogical Magazine*, 68, 395–411.
- PRICHARD, H M, LORD, R A, and NEARY, C R. 1996. A model to explain the occurrence of platinum- and palladium-rich ophiolite complexes. *Journal Geological Society of London*, 153, 323–328.
- RUSSELL, A. 1925. A notice on the occurrence of native arsenic in Cornwall; of bismuthinite at Shap, Westmorland; and of smaltite and niccolite at Coniston, Lancashire. *Mineralogical Magazine*, 20, 299–304.
- SHAW, M H, GUNN, A G, FLETCHER, T A, STYLES, M T, and PEREZ, M. 1992. Data arising from drilling investigations in the Loch Borrallan intrusion, Sutherland, Scotland. *British Geological Survey, Mineral Reconnaissance Programme Open File Report 8* (2 vols; 340 pp).
- SHAW, M H, GUNN, A G, and MENDUM, J R. 1993. Investigations into the distribution of platinum-group elements, South Harris, Isle of Lewis, Scotland. *Mineral Reconnaissance Programme Open File Report 10*.
- SHAW, M H, GUNN, A G, ROLLIN, K E, and STYLES, M T. 1994. Platinum-group element mineralisation in the Loch Ailsh alkaline igneous complex, north-west Scotland. *British Geological Survey, Mineral Reconnaissance Programme Report 131*.
- SHEPHERD, T J, BOUCH, J E, GUNN, A G, MCKERVEY, J A, NADEN, J, SCRIVENER, R C, STYLES, M T, and LARGE, D E. 2005. Permo-Triassic unconformity-related gold-palladium mineralization, South Devon, UK: new insights and the European perspective. *Mineralium Deposita*, 40, 24–44.
- STANLEY, C J, SYMES, R F, and JONES, G C. 1987. Nickel-Copper Mineralization at Talnotry, Newton Stewart, Scotland. *Mineralogy and Petrology*, 37, 293–313.
- STANLEY, C J, and CRIDDLE, A J. 1990. Precious and base metal selenide mineralization at Hope's Nose, Torquay, Devon. *Mineralogical Magazine*, 54, 485–493.
- STEPHENSON, D, FORTEY, N, and GALLAGHER, M. 1983. Polymetallic mineralisation in Carboniferous rocks at Hilderston, near Bathgate, Central Scotland. *British Geological Survey, Mineral Reconnaissance Programme report 68*.
- STONE, P, GUNN, A G, COATS, J S, and CARRUTHERS, R M. 1986. Mineral exploration in the Ordovician Ballantrae Complex, SW Scotland. In: Galagher, M.J. (ed) *Metallogeny of basic and ultrabasic rocks. Institution of Mining and Metallurgy*, London, 263–278.
- STYLES, M T, GUNN, A G, and ROLLIN, K E. 2004. A preliminary study of PGE in the Late Caledonian Loch Borrallan and Loch Ailsh alkaline pyroxenite-syenite complexes, north-west Scotland. *Mineralium Deposita*, 39, 240–255.
- WILSON, G V, and FLETT, J S. 1921. The lead, zinc, copper and nickel ores of Scotland. *Memoirs of the Geological Survey, Scotland. Special reports on the mineral resources of Great Britain*, Vol. XVII.
- YOUNG, B, STYLES, M P, and BERRIDGE, N G. 1985. Niccolite-magnetite mineralization from Upper Teesdale, North Pennines. *Mineralogical Magazine*, 49, 555–559.
- YOUNG, B. 1987. Glossary of the minerals of the Lake District and adjoining areas. *British Geological Survey*.

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