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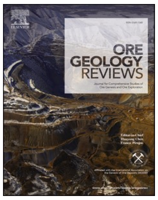

Cobalt resources in Europe and the potential for new discoveries

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ABSTRACT

Global demand for cobalt is increasing rapidly as we transition to a low-carbon economy. In order to ensure secure and sustainable supplies of this critical metal there is considerable interest in Europe in understanding the availability of cobalt from indigenous resources. This study reviews information on cobalt resources in Europe and evaluates the potential for additional discoveries.

Based on published information and a survey of national mineral resource agencies, 509 cobalt-bearing deposits and occurrences have been identified in 25 countries in Europe. Harmonised cobalt resources, classified using the United Nations Framework Classification (UNFC), have been estimated for 151 deposits in 12 countries where data are available. The calculated total resource comprises 1 342 649 tonnes of contained cobalt metal. This includes: 114 638 tonnes in commercial projects with current cobalt extraction; 370 409 tonnes in potentially commercial projects; 111 107 tonnes in historic estimates compliant with modern reporting; and 746 495 tonnes in non-compliant historic estimates. Analysis of these data reveals that cobalt resources are widely distributed across Europe in deposits of several different types.

Global mine production of cobalt is dominated by stratiform sediment-hosted copper deposits, magmatic nickel-copper deposits and nickel laterite deposits, but other deposit types may also be significantly enriched in cobalt. In Europe, current cobalt production is derived from three mines in Finland: the magmatic sulfide deposit at Kevitsa; the Kylylahti deposit of volcanogenic massive sulfide (VMS) affinity; and the black shale-hosted deposit at Sotkamo (Talvivaara).

This study has identified 104 deposits in Europe that are currently being explored for cobalt, of which 79 are located in Finland, Norway and Sweden. The Fennoscandian Shield and the Caledonian Belt in these countries are high priority exploration terrains for a variety of cobalt-bearing deposits, notably magmatic Ni-Cu-Co deposits. The Svecofennian, Sveconorwegian and the Caledonian orogenies in Fennoscandia also resulted in the formation of several other cobalt-enriched deposit types. These include chiefly metasediment- and metavolcanic-hosted Co-Cu-Au, VMS, skarn and polymetallic vein deposits.

The Kupferschiefer deposits in Poland and Germany are stratiform sediment-hosted Cu deposits with some similarities to the Central African Copperbelt, which is the predominant global producer. However, the cobalt grade in the Kupferschiefer deposits is relatively low (0.005–0.008% Co) and not currently economic to exploit without significant improvement in extraction technology.

In the Balkans and Turkey cobalt grades and tonnages are known in 27 nickel laterite deposits, with several containing more than 10 000 tonnes of cobalt metal. Only nickel is currently recovered from these deposits, but new processing technologies such as high-pressure acid leaching could enable cobalt recovery in the future.

Small polymetallic cobalt-bearing vein deposits in several European countries have been historic producers of cobalt. Today most are uneconomic, but new technologies and the drive towards locally-sourced raw materials could make them viable future sources of cobalt.

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Our analysis suggests that geological availability in Europe is not a problem. However, many economic, technological, environmental and social challenges will have to be overcome for exploration projects to become commercial.

1. Introduction

Cobalt has a range of physical and chemical properties that make it useful in numerous metallurgical and chemical applications. Prior to 2006 its main use was in superalloys in jet engines and gas turbines, although the largest application is now in cathode materials for rechargeable lithium-ion batteries (LIBs) (Harper et al., 2012; Slack et al., 2017). In 2017 about 46% of global consumption of cobalt was in LIBs, with about 17% used in superalloys (Petavratzi et al., 2019). Other important applications include catalysts, pigments, hard metals, magnets and special steels.

Global mine production of cobalt in 2018 amounted to nearly 168 000 tonnes (Brown et al., 2020). About 65% of the total came from the Democratic Republic of Congo (DRC) where it is a co-product of copper extraction from stratiform sediment-hosted deposits (SSHC) (Petavratzi et al., 2019; Brown et al., 2020). Other important producers include New Caledonia, China, Canada and Australia where cobalt is produced chiefly as a by-product of nickel extraction. In contrast, global production of refined cobalt is dominated by China, which accounted for more than 60% of the world total in 2018. Europe is also a major producer of refined cobalt with Finland (10%) and Belgium (5%) having the largest share of the world's production after China (Brown et al., 2020). The strong geographical concentration of cobalt mining and refining is considered a potentially serious risk to future cobalt supply and contributes to cobalt's designation as a critical metal for the European Union (EU) (Blengini et al., 2020).

Given the global transition towards a low-carbon economy and, in particular, the rapid growth in the deployment of electric vehicles (EV), there will inevitably be a significant increase in demand for a range of raw materials, including cobalt, for use in LIBs in EVs (Alves Dias et al., 2018; IEA, 2020). The number of EV models, including battery electric (BEV), plug-in hybrid (PHEV) and fuel cell (FCEV), produced in the EU is expected to increase from about 60 in 2018 to 333 in 2025, which equates to more than 4 million cars and vans (Transport & Environment, 2019). This is over one fifth of the current EU car production volume. The cobalt content of LIBs in electric cars and vans produced in the EU in 2025, based on a range of battery classes and an average 60 kWh battery pack, is estimated at 52 000 tonnes of cobalt metal (Table 1) (Transport & Environment, 2019). This is close to 50% of the current total global refined cobalt production. In addition, Europe is presently developing a battery manufacturing capability, which is expected to provide products for markets both within and outside the EU. Consequently, European demand for cobalt is likely to exceed this estimate. At the same time consumption of cobalt in other countries is also rising rapidly, contributing to increasing global demand.

The European Union has adopted a suite of policy and research measures as part of its strategy to reduce emissions and support sustainable mobility in the future. The European Battery Alliance was launched in 2017 to facilitate and support a battery manufacturing industry in Europe for EVs (EC, 2018). It is planned to have a 7–25% share of global battery cell manufacturing in Europe by 2028 (EC, 2019). In order to meet this target there is considerable interest in evaluating potential resources of battery raw materials in Europe (EC, 2018, 2019).

Table 1
Projected cobalt demand for EVs produced in EU-28 in 2025, based on an average 60 kWh battery pack using lithium-ion batteries of various chemistries. Calculations are based on Transport & Environment (2019) and CRM4EV (2019). NCA, lithium nickel cobalt aluminium oxide; NMC, lithium nickel manganese cobalt oxide (numbers indicate ratio of Ni, Co, and Mn on a mole fraction basis).

Battery class	Battery class contribution (%)	Cobalt (tonnes)
NMC 532	33.5	15 856
NMC 622	33.5	17 206
NMC 811	16.5	7 558
NCA	16.5	11 497
Total (tonnes Co)		52 116

This study aims to compile geoscientific information on known cobalt deposits and to harmonise available cobalt resource data in Europe using the United Nation Framework Classification scheme (UNFC) (UNECE, 2019). The quality and completeness of that data is also assessed and the potential for the discovery of additional cobalt resources reviewed.

Cobalt resources are known to be widespread on the seafloor (Hein et al., 2013; Lusty and Murton, 2018; Petersen et al., 2018). However, the quantities present are poorly known and many uncertainties remain about the technical feasibility of recovering these resources and the environmental impact of seafloor mining (Jones et al., 2018). They are, therefore, not included in this study. In addition, there is considerable interest in Europe in recovering cobalt from secondary resources such as mine waste and end-of-life products (Aquilino et al., 2019; Lebedeva et al., 2016; Petavratzi et al., 2019). However, little information exists on potential cobalt availability from secondary resources and they have not been considered in this study. Distant overseas territories of European countries are also out of scope.

2. Principal cobalt-bearing ore deposit types

Three deposit classes together account for approximately 85% of global cobalt resources, excluding past production (Mudd et al., 2013): magmatic Ni-Cu-Co-(±PGE), SSHC deposits, and Ni-Co laterite deposits. However, there are several other deposit types which may contain significant amounts of cobalt, some of which currently produce cobalt or have produced it in the past. The key features of these deposits are summarised in Table 2 and the chemical formulae of the most important cobalt-bearing minerals are given in Table 3. Unless otherwise stated, quantitative estimates of resources in the following text are the total of the measured, indicated and inferred resource categories. Resources also include any available reserve data. Metal grades are given in weight percent throughout the text.

2.1. Magmatic Ni-Cu-Co-(±PGE) deposits

Magmatic deposits are a major global source of nickel, accounting for nearly 40% of world production in 2017, as well as copper (Petavratzi et al., 2019). Cobalt is one of several by-products extracted from these deposits, which also include platinum-group elements (PGE) and other precious and minor metals (Naldrett, 2005). Economic deposits of this type vary widely in size, from about 5 to more than 500 million tonnes of ore (Mudd et al., 2013), with cobalt grades typically in the range 0.05–0.1% Co.

These deposits are associated with mafic to ultramafic rocks originating from the upper mantle (Naldrett, 2005; Eckstrand and Hulbert, 2007). The deposits form when the magma becomes saturated with sulfur, commonly as a result of interaction with continental crustal rocks. This leads to the separation of an immiscible sulfide melt into which chalcophile elements (nickel, copper, cobalt and others) are strongly partitioned. If the sulfides are concentrated in a restricted physical space they may form an economic deposit. This can happen in embayments in the lower part of dykes, sills or flows, and at the base of a large intrusion (Schulz et al., 2014). In recent decades the importance of magma dynamics has become increasingly appreciated as being a significant factor in the formation of some of these deposits. The host intrusions are considered to be magma conduits in which unmixed sulfide melts are separated from the magma, rather than by static, gravity-driven settling (Eckstrand and Hulbert, 2007; Schulz et al., 2014).

The most important ore minerals in these deposits are pyrrhotite, pentlandite and chalcopyrite, with pentlandite being the major host for cobalt (Roberts and Gunn, 2014; Schulz et al., 2014). Magmatic sulfide deposits with globally significant cobalt production and/or resources are located in the Norilsk-Talnakh district of Russia with an average grade of 0.061% Co, as well as in Canada at Voisey's Bay in Labrador (0.09% Co) and in the Sudbury district of Ontario (0.038% Co) (Naldrett, 2004). These magmatic bodies vary in their origin and composition. Norilsk-Talnakh is related to rift- and continental flood-basalt-associated mafic sill and dyke-like bodies (Eckstrand and Hulbert, 2007). The Voisey's Bay deposits are hosted in high-aluminium basaltic rocks (Schulz et al., 2014). The Sudbury district is unique with numerous magmatic sulfide deposits related to a melt formed by a large meteorite impact (Eckstrand and Hulbert, 2007). Other examples are related to komatiitic volcanic flows and related sills such as Kambalda and Mount Keith in Australia, containing 0.207% and 0.014% Co, respectively (Naldrett, 2004; Eckstrand and Hulbert, 2007). Komatiites are Mg-rich ultramafic volcanic rocks, mainly of Archaean to Paleoproterozoic age,

Table 3

Formulae of cobalt-bearing minerals mentioned in the text; some nickel minerals which may contain minor amounts of cobalt are also included.

Mineral name	Chemical formula
Asbolane	$(Ni,Co)_{2-x}Mn\ (O,OH)_4 \cdot nH_2O$
Bravoite	$(Fe,Ni)S_2$
Carrollite	$Cu(Co,Ni)_2S_4$
Cattierite	CoS_2
Cobaltite	$CoAsS$
Cobaltpentlandite	$(Co,Ni,Fe)_9S_8$
Erythrite	$Co_3(AsO_4)_2 \cdot 8H_2O$
'Garnierite'	Collective term for Ni-bearing layer silicates
Gersdorffite	$NiAsS$
Glaucodot	$(Co,Fe)AsS$
Heazlewoodite	Ni_3S_2
Heterogenite	$CoOOH$
Kolwezite	$(Cu,Co)_2(CO_3)(OH)_2$
Linnaeite	$Co^{2+}Co_2^{3+}S_4$
Rammelsbergite	$NiAs_2$
Safflorite	$(Co,Ni,Fe)As_2$
Siegenite	$CoNi_2S_4$
Skutterudite	$(Co,Ni)As_{3-x}$
Sphaerocobaltite	$CoCO_3$
Villamaninite	$(Cu,Ni,Co,Fe)S_2$
Willyamite	$(Co,Ni)SbS$

Table 2

Key features of cobalt-bearing deposit types. (N.B. according to Mudd et al. (2013) the first three types listed account for about 85% of terrestrial global cobalt resources).

Deposit type	Description	Typical deposit size [million tonnes ore]	Co-bearing minerals	Notable examples (with cobalt grade of ore)	References
Magmatic Ni-Cu-(Co-PGE)	Massive to disseminated sulfides hosted in mafic to ultramafic igneous rocks	5–>500	pentlandite, pyrrhotite, millerite, carrollite-linnaeite	Norilsk-Talnakh, Russia (0.061% Co); Voisey's Bay, Canada (0.13% Co); Kambalda, Australia (0.21% Co)	Naldrett, 2004; Eckstrand and Hulbert, 2007; Schulz et al., 2014
Stratiform sediment-hosted Cu-Co	Hydrothermal sulfide deposits loosely bound to a siliciclastic or carbonaceous unit(s)	10–500	carrollite-linnaeite, cobaltite, cattierite, (heterogenite, sphaerocobaltite in weathered zones)	Tenke Fungurume, DRC (0.245% Co); Kisanfu, DRC (1.08%); Nchanga, Zambia (0.026% Co)	Annels & Simmonds 1984;. Hitzman et al., 2005, 2010, 2017; Taylor et al., 2013
Ni-Co laterite	Supergene weathering products of mafic to ultramafic rocks	10–800	erythrite, heterogenite, asbolane, 'garnierite', Co-rich clays	Moa, Cuba (0.13% Co); Goro, New Caledonia (0.11% Co); Murrin Murrin, Australia (0.078% Co)	Berger et al., 2011; Butt & Cluzel, 2013; Thorne et al., 2012a
Black shale-hosted	Disseminated sulfides in, dominantly, sulfur-rich black shales	Mineable deposits very large (1525 Mt at Sotkamo)	Co-bearing pyrite, pentlandite, pyrrhotite	Sotkamo, Finland (0.02% Co)	Loukola-Ruskeeniemi & Lahtinen, 2013; Kontinen & Hanski, 2015
Metasediment-hosted Co-Cu-Au	Massive to disseminated sulfides in stratabound zones, lenses, veins, breccias; mainly in rift-related environments	<1–31	Co-arsenides, sulfides, sulfarsenides	Blackbird, USA (0.42% Co); Modum district, Norway (0.26% Co)	Slack, 2013; Jervois Mining Ltd, 2020
Polymetallic Co-rich veins	Hydrothermal sulfide veins; Some known as 'five element vein' deposits (Ni-Co-As-Ag-Bi)	< 20	Co-arsenides, sulfides, sulfarsenides	Bou Azzer, Morocco (1% Co)	Kissin, 1992; Markl et al., 2016; Bouabdellah et al., 2016
Iron-oxide Cu-Au (Ag-U-REE-Co-Ni) (IOCG)	Magmatic (?)-hydrothermal, structurally-controlled replacement deposits; usually in an intracratonic setting	5–>9 000	Co-bearing pyrite, cobaltite, glaucodot	Olympic Dam, Australia (0.02% Co)	Williams & Pollard, 2001; Williams et al., 2005; BHP Group Ltd., 2019
Volcanogenic massive sulfide (VMS)	Massive sulfides formed in a submarine volcanic environment; Cobalt concentrations may be high where hosted in ultramafic–mafic rocks	<10–300	cobaltite, cobaltpentlandite,	Windy Craggy, Canada (0.066% Co); Kylylahti, Finland (0.15% Co)	Peter and Scott, 1997; Galley et al., 2007; Boliden, 2018
Mississippi Valley-type (MVT)	Epigenetic hydrothermal deposits hosted typically in dolostone or limestone. Cobalt is rarely enriched.	7 (median deposit size)*	siegenite, bravoite, gersdorffite, pyrite	Higdon, USA (0.14% Co)	Leach et al., 2010a, 2010b; Taylor et al., 2009; Seeger, 2008; Parra Avila and Alejandro, 2009
Skarn and replacement deposits	Sulfides associated with calc-silicate minerals	100–500	cobaltite, carrollite-linnaeite, pyrite, safflorite	Cornwall, USA (0.03% Co); Goroblagodat, Russia (0.02% Co)	Meinert, 1992; Slack et al., 2017

*based on 113 deposits documented by Taylor et al. (2009).

which may host ores with high nickel contents and low Cu/Ni ratios (Naldrett, 2004). In general the cobalt grades in magmatic Ni-Cu-Co-PGE deposits are relatively low compared to the SSHC class although many deposits are large and, therefore, contain significant amounts of cobalt (Slack et al., 2017).

2.2. Stratiform sediment-hosted Cu-Co deposits (SSHC)

Stratiform sediment-hosted Cu-Co deposits are the most important global source of cobalt accounting for 63% of cobalt mine production in 2017 (Petavratzi et al., 2019). The size and cobalt grade of these deposits vary considerably: in the Central African Copperbelt several deposits contain more than 100 million tonnes of ore with cobalt grades ranging from below 0.001% to up to 1.08% (Slack et al., 2017; Petavratzi et al., 2019). The SSHC deposits comprise hydrothermal sulfide mineralisation occurring mainly in intracontinental rifted basins or sub-basins (Hitzman et al., 2005). They typically consist of thin (commonly less than three metres thick, but up to 20 m in the Central African Copperbelt) sulfide-rich zones that are stratiform to the lithological layering in the host siliciclastic or dolomitic sedimentary rocks (Hitzman et al., 2005, 2012). The main copper minerals are chalcocite, bornite and chalcopyrite, with carrollite being the most important cobalt-bearing sulfide mineral (Annels and Simmonds, 1984). These deposits are commonly associated with three lithological groupings: (1) a syn-rift oxidized red-bed sequence typically comprising coarse-grained siliciclastic rocks; (2) an overlying reduced, commonly organic-rich layer, composed of shallow marine or large-scale lacustrine origin; and (3) sulfate- and halite-bearing evaporites. However, the latter are easily dissolved and may no longer be present. They may be replaced by much thinner silicified, albitised and/or collapse breccia units (Hitzman et al., 2005). In simple terms, these deposits are considered to be derived from hydrothermal fluids which leached and transported metals upwards from the basement, the red beds and, in many cases, underlying bimodal volcanic rocks. Precipitation was triggered by the interaction of the oxidised fluid with the reduced lithological units (Hitzman et al., 2005). There is no consensus on whether this fluid flow occurred during early basin evolution, during basin inversion and fault reactivation, or during both (Cailteux et al., 2005; McGowan et al., 2006; Borg et al., 2012; Selley et al., 2018). There are indications that cobalt-rich deposits in the Central African Copperbelt are related to mafic intrusions in the basement that were the source of a cobalt-enriched mineralising fluid (Hitzman et al., 2017).

SSHC deposits have been identified in several countries, but the most important examples occur in the Neoproterozoic Central African Copperbelt, in the Mesozoic Kupferschiefer Basin in central Europe and the Paleoproterozoic Udokan Basin in Russia. The Central African Copperbelt, located in the Katanga province in southern DRC and in north-west Zambia, contains the largest share of global cobalt resources with 6.5 million tonnes of contained cobalt metal, including past production (Taylor et al., 2013). These authors report median cobalt concentrations of 0.3% in 170 sediment-hosted stratiform deposits worldwide. Deposits in the DRC have generally higher cobalt grades than those in Zambia: for example, 1.1% Co at Kisanfu and 0.7% at Mukondo in the DRC (Slack et al., 2017). In contrast the giant Nchanga deposit in Zambia has a cobalt grade of only 0.026%, but the cobalt endowment is substantial on account of its large size (Taylor et al., 2013; Slack et al., 2017). In several locations (e.g. at Tenke Fungurume), primary sulfides have been oxidised due to surface weathering down to about 100 m, which resulted in significant cobalt enrichment and transformation to oxidic ore minerals such as heterogenite and sphaerocobaltite, referred to as a ‘cobalt cap’.

2.3. Ni-Co laterite deposits

Laterites are regoliths that typically develop through weathering of various lithologies in humid tropical to subtropical climates (Butt and Cluzel, 2013). Where they form on ultramafic rocks, they may contain significant concentrations of nickel and cobalt. Laterite deposits mined for nickel generally contain more than 1% Ni and some may be accompanied by cobalt concentrations of up to 0.22% (Berger et al., 2011; Slack et al., 2017). The ore zone is commonly 10–40 m thick and comprises weathered ultramafic bedrock, known as saprock, overlain by a sequence (from base to top) comprising saprolite, a clay-rich (plasmic) zone, a mottled zone and a lateritic duricrust (Butt and Cluzel, 2013; Slack et al., 2017). The most important ore constituents include serpentine, talc, chlorite, clays, erythrite, heterogenite, asbolane, heazlewoodite, millerite, goethite, limonite and lithiophorite (Slack et al., 2017).

Metal concentration in laterites involves various supergene processes and depends on several geological variables including protolith composition, topography and structural features. Climate history is also a major control on nickel laterite formation as relatively high temperatures accompanied by high rainfall facilitate intense weathering of ultramafic protoliths. Recent data indicate that the majority of peridotites presently weathering to form nickel–cobalt laterites experience distinct climatic conditions characterised by limited seasonality and annual precipitation of more than 1000 mm (Thorne et al., 2012b). Another important factor in forming nickel–cobalt-enriched laterite deposits is the degree of permeability of the parent material (Pelletier, 1996; Brand, 1998). Faults, fractures, joints and cleavage play a key role in the metal remobilisation process by increasing the permeability of the protolith (Butt and Cluzel, 2013).

Most nickel–cobalt laterite deposits are mid-Tertiary to Holocene in age, although there is considerable variation in their composition and mineralogy. Three sub-types are recognised: oxide; hydrous magnesium silicate; and clay silicate (Brand, 1998; Freyssinet et al., 2005). Most oxide deposits comprise chiefly limonitic ore in the upper part of the saprolite. These are dominated by Fe-oxyhydroxides as the main nickel carriers, with Mn-oxides commonly being also enriched in cobalt and nickel. The Moa Bay deposit in Cuba is a notable example of this type, with a total resource of 191 million tonnes grading 0.13% Co and 0.98% Ni (Sheritt International Corporation, 2019). In hydrous magnesium silicate deposits nickel and cobalt are enriched in the lower part of the saprolite, where nickel is hosted by nickel-bearing layer-silicates, often referred to as ‘garnierite’ (Butt and Cluzel, 2013). The best known example of this sub-type is the Goro deposit in New Caledonia, which has a resource of 323 million tonnes grading 0.11% Co and 1.48% Ni (Berger et al., 2011). In the third sub-type nickel and cobalt are enriched in clay minerals such as saponite and smectite in the mid to upper saprolite. This sub-type forms in cratonic terranes, where the ore-bearing regolith is developed over a prolonged period of weathering. The ore zone is preserved due to the low relief and the stability of the craton (Butt and Cluzel, 2013). Murrin Murrin in Western Australia is a good example of a large nickel–cobalt deposit of this type. It has a combined resource of 231 million tonnes grading 1.01% Ni and 0.078% Co (Glencore, 2018).

2.4. Other deposit types

Significant cobalt enrichment may also be found in a wide range of other geological settings. Cobalt has been extracted from some of these, commonly as a by-product of mining copper, nickel, silver, lead or zinc. Key features of these deposits are summarised in Table 2 and have been described by Slack et al. (2017) and Petavratzi et al. (2019).

The most important types include:

(1) Black-shale hosted deposits
(2) Iron-oxide Cu-Au deposits (IOCG)
(3) Metasediment-hosted Co-Cu-Au deposits
(4) Mississippi-Valley type deposits (MVT)
(5) Polymetallic and other cobalt-rich vein deposits
(6) Skarn and replacement deposits
(7) Volcanogenic massive sulfides (VMS)

Perhaps the most well-known amongst these are the cobalt-rich vein deposits because they have been important past producers of cobalt in several countries. Many of these vein deposits have also been referred to as 'five-element vein deposits' and multiple stages of mineralisation are generally recognised beginning with (1) a sub-economic sulfide stage. This is followed in turn by stages containing dominantly (2) native elements, (3) arsenides and antimonides, (4) sulfarsenides and sulfides, and finally (5) by a gangue mineral-dominated stage (Markl et al., 2016). Cobalt is typically hosted in arsenides and sulfarsenides (Kissin, 1992; Markl et al., 2016). Notable examples include the Cobalt district of northern Ontario and various mining districts in Europe, such as the Erzgebirge in the Czech Republic and Germany (Kissin, 1992; Markl et al., 2016). Another important example is Bou Azzer in Morocco, which is the only mining district in the world that is currently producing cobalt as the main commodity. Average annual production from Bou Azzer is about 100,000 tonnes of ore grading about 1% Co (Bouabdellah et al., 2016).

Metasediment-hosted Co-Cu-Au deposits are a diverse group found in several countries. Deposits of this type were mined in the past for cobalt, copper and gold and a range of other by-product metals. Notable examples include deposits of the Blackbird district in Idaho, USA (Slack, 2013) and the Modum district of Norway (Sandstad et al., 2012). There is no consensus on the origin of these deposits: some have been previously compared with IOCG deposits whereas others are described as polymetallic variants of orogenic gold systems (Slack, 2013). Polymetallic vein and metasediment-hosted deposits were relatively attractive in the past because of their high grades and the availability of valuable by-products, such as gold and silver (Sandstad et al., 2012; Slack, 2012, 2013). Although generally of little recent interest on account of their small size, they are now the focus of renewed exploration on account of their cobalt potential. For example, advanced exploration and deposit evaluation are currently underway at Blackbird and the Idaho Cobalt Belt, which was an important cobalt producer in the first half of the twentieth century (Jervois Mining Ltd, 2020).

In contrast, economically viable black-shale hosted deposits are rare, and, although they may be large, their metal grades tend to be low. The Sotkamo deposit, also known as Talvivaara, in Finland is probably the best example of this type, grading 0.019% Co and 0.25% Ni, with a known resource 1 525 million tonnes of ore (Terrafame Ltd, 2018; Garcia-Balbuena, pers. comm., 2020).

Volcanogenic massive sulfide (VMS) deposits, which are major global sources of copper, lead, zinc, gold and silver, may also be enriched in cobalt when associated with mafic or ultramafic volcanic rocks. Notable examples include deposits at Windy Craggy in British Columbia, Canada and at Derni in the Qinghai Province, China. Cobalt resides dominantly in pyrite and pyrrhotite in these deposits (Peter and Scott, 1997; Wang et al., 2000), but cobaltpentlandite can be an important host, as well (Peltonen et al., 2008). In Europe, the Kylylahti mine in the Outokumpu VMS district of eastern Finland is currently producing cobalt from ores grading 0.16% Co (New Boliden, 2019).

Reliable data on cobalt resources and current cobalt production associated with IOCG deposits are sparse (Mudd et al., 2013). However, IOCG deposits tend to be large and enriched in a range of commodities including cobalt, iron, copper, gold, silver, uranium, rare earth elements (REE) and phosphorus. Mudd et al. (2013) estimated a global resource of 6.75 million tonnes contained cobalt in only 27 deposits, but a large proportion of this total is considered by these authors to be highly speculative. Olympic Dam in South Australia is the largest known IOCG deposit with a total resource of 10 727 million tonnes ore (BHP Group Ltd., 2019). However, the cobalt grade has only been reported for 605 million tonnes of ore at 0.02% Co (Williams and Pollard, 2001).

3. Data sources and methodology

This study encompasses all 30 countries in the European Economic Area (EEA), as well as EU candidate countries (Albania, Montenegro, North Macedonia, Serbia and Turkey), potential candidate countries (Bosnia-Herzegovina and Kosovo), as well as the United Kingdom and Greenland. Information on cobalt-rich deposits from these countries has been compiled from various sources including published research, company websites and reports; and from databases provided by geological survey organisations and research institutions. In addition, for the purposes of this study a survey was carried out across 27 European geological surveys, ministries of mines and academic institutes to acquire additional data on cobalt resources. Replies were received from sixteen of these institutions providing information on individual deposits. This result enabled the construction of a Co resource database for 25 European countries including information on the operational status, previous activities, resource estimates and deposit type.

Fig. 1 shows the distribution of known cobalt resources in Europe, classified by 'deposit', 'prospect' and 'occurrence'. Deposits (Fig. 1A) are here defined as localities where cobalt resource data are available and the cobalt grade exceeds 0.01% Co. However, it is important to note that these resource estimates are of variable quality. Some deposits are well explored and have associated resource estimates compliant with the standards of the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) (CRIRSCO, 2019). In other cases the resource estimates are not compliant with international or national standards and are consequently potentially less reliable. If the tonnage of cobalt metal contained in the deposit was not provided by the survey respondents, then it was calculated by multiplying the total resource tonnage (measured, indicated and inferred) by the cobalt grade. Any reported mineral reserve is included in the total resource in our calculations. It is also important to note that in many deposits where other metals, such as copper or nickel, are the main commodities of interest, cobalt grades and/or tonnages are commonly not reported. In some instances, cobalt concentrations are only available for a small number of samples and are, therefore, not representative of the entire deposit. In these cases, a cobalt resource cannot be estimated and localities are classified here as 'prospects' or 'occurrences' (Fig. 1B). The term 'prospect' is used to refer to exploration projects where cobalt is of potential economic interest, but where quantitative geochemical data are limited to surface samples and a small number of sub-surface samples from trenching or drilling. In 'prospects' there has generally been no systematic evaluation of the distribution and abundance of cobalt. Information about cobalt in an 'occurrence' is generally more limited with geochemical data available for only a few samples, typically derived from the surface or near-surface. Occurrences have been included in this study when they have cobalt concentrations greater than 0.01%, following guidelines from FRAME (2019). However, the continuity of these concentrations within the mineralised body or zone may not be known. In addition a locality is classified as an 'occurrence' if cobalt has been extracted there in the past, but no information on the cobalt grade is available.

4. Harmonised European cobalt resource estimates

It is difficult to obtain a pan-European cobalt resource estimate because available data are sparse. Even operating mines that produce nickel or copper typically do not report cobalt grades in their statistics. This is because cobalt is a by-product of copper or nickel extraction, or it is not recoverable, or it only makes a small financial contribution, if any, to the operation. In general, estimates of resource and reserve for by-products are difficult to acquire and likely to be imprecise. It is, therefore, crucial to consider the data quality and uncertainty associated with cobalt resource figures. Another important factor is that the available data may be based on a range of reporting codes and standards which may not directly map to international reporting templates, such as CRIRSCO or the United Nations resource classification framework (UNECE, 2019). However, even when systems of reporting are nominally aligned, some degree of subjective interpretation is inevitable, especially when dealing with historic figures. Consequently, the calculation of a reliable total European cobalt resource is very challenging.

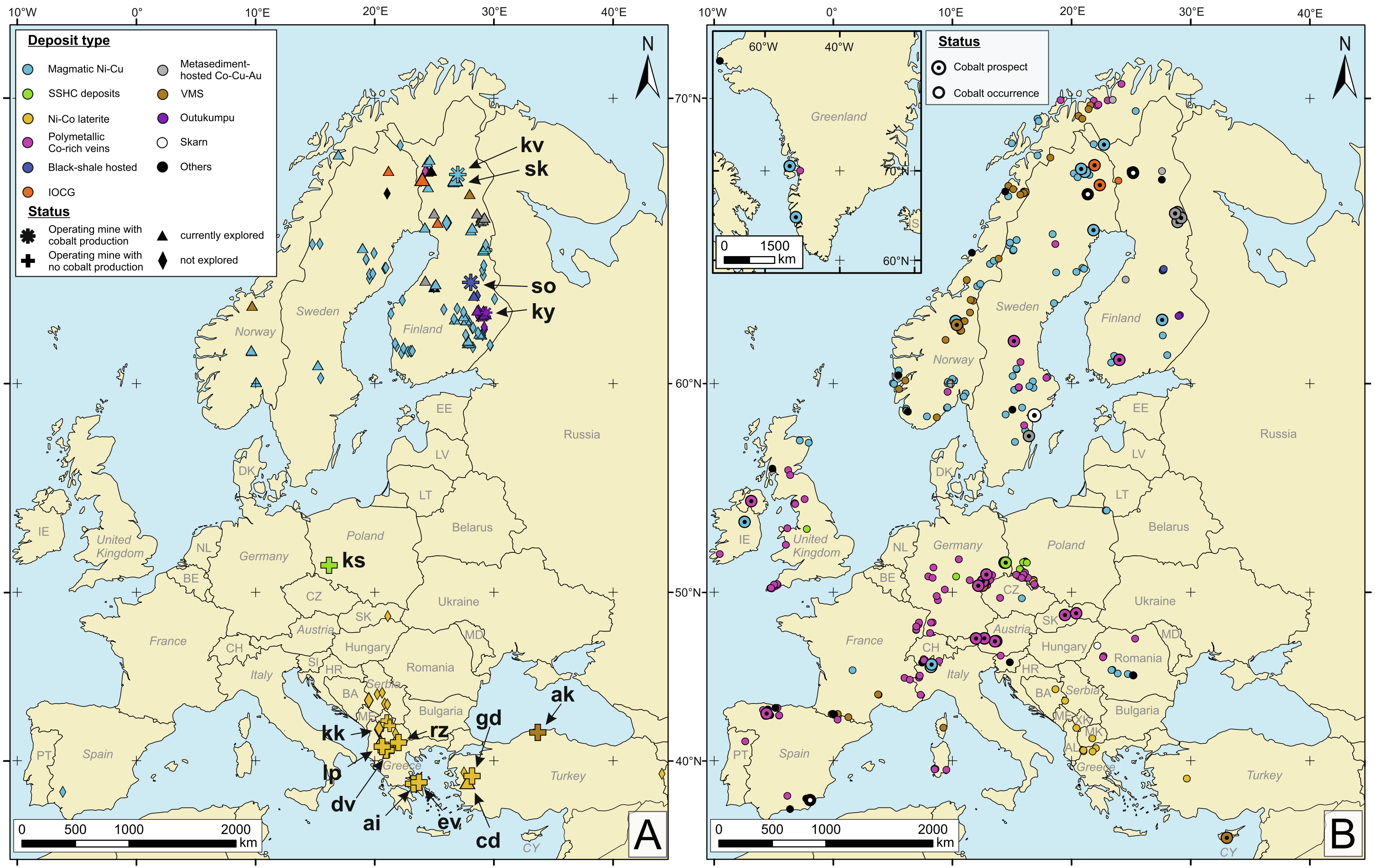

Fig. 1. **A** Distribution of cobalt-bearing deposits with cobalt resource estimates in Europe classified by deposit type and status. Deposits designated 'not explored' include abandoned mines or previous exploration. Deposits or districts with more than 10,000 tonnes cobalt metal content: ai, Agios Ioannis; ak, Asikoy; cd, Caldag; dv, Devolli; ev, Evia; gd, Gördes; kk, Kukes; ks, Kupferschiefer; kv, Kevitsa; ky, Kylylahti; lp, Librazhd-Pogradec; rz, Ržanovo; sk, Sakatti; so, Sotkamo. **1B:** Distribution of cobalt 'prospects' and 'occurrences' in Europe, with no current cobalt resource estimates. Explanation of abbreviated country names: AL, Albania; BA, Bosnia and Herzegovina; BE, Belgium; CH, Switzerland; CZ, Czech Republic; CY, Cyprus; DK, Denmark; EE, Estonia; HR, Croatia; IE, Ireland; IS, Iceland; LT, Lithuania; LV, Latvia; ME; Macedonia; MD; Moldova; MK, North Macedonia; NL, The Netherlands; PT, Portugal; SI, Slovenia; SK, Slovakia; XK, Kosovo.

The United Nations Framework Classification (UNFC) for resources has been used in this study to classify and harmonise cobalt-bearing deposits in terms of their stage of development and the reliability of reported resource figures. The UNFC was developed by the United Nations Economic Commission for Europe (UNECE) to harmonise existing standards and reporting codes. It is designed as a universal framework for minerals, hydrocarbons, water and renewable energy resource classification. The UNFC framework uses three criteria to classify resources: (1) economic and social viability (E-category); (2) field project status and feasibility (F-category); and (3) degree of confidence in the estimate (G-category) (UNECE, 2019). The G-categories can be directly translated to widely used CRIRSCO terms: G1 is either a proven reserve or a measured resource, G2 is either a probable reserve or an indicated resource and G3 is an inferred resource. The UNFC categories, classes and associated quantities of cobalt contained in European resources are shown in Table 4, which also shows how the classification scheme has been used in this study. It is important to note that data from only a few deposits collected for this study were previously classified using the UNFC framework.

Cobalt resource estimates represent commercial projects (classes E1 F1 G1, 111; E1 F1 G2, 112) when reserve figures (proven and probable classes) are published in line with the CRIRSCO-reporting template. Potentially commercial projects (classes 221, 222, 223) represent those that have cobalt resource estimates (measured, indicated and inferred classes) recently published under one of the reporting codes and standards aligned with the CRIRSCO-reporting template (Table 4). When a compliant resource has been reported in the past, but the project has subsequently been abandoned, resources are classified in G- and F-categories 3 (classes 331, 332, 333) (Table 4). Such estimates would need revising and updating to ensure their current economic, social and technical feasibility. Non-compliant historic estimates have been reported without following the CRIRSCO-reporting template and may be of variable quality. These can be divided into two groups: (1) class 334, representing early exploration projects for cobalt, but where further data are required to confirm the resource and project feasibility; and (2) class 344, any additional quantities with known cobalt grades, but currently of no economic interest (Table 4). All reported resource estimates represent the resource that is still in place. Where data are available any mined resources have been subtracted from the original resource.

For this study the UNFC criteria have been applied to the available cobalt resource data only, rather than to the main commodity in a deposit. For example, an operational mine producing nickel with resource and reserve data based on an international standard would report in the highest category for nickel (proven reserves, class 111). However, the available cobalt grades may not be reported to a compliant resource code and cobalt tonnages are, therefore, allocated to a lower class. If the mine plans to extract cobalt in the future, further resource estimates based on measured cobalt concentrations would be required to upgrade the G-category and metallurgical testing for the extraction of cobalt would be necessary to prove technical feasibility (F-category).

Table 4
UNFC-2009 classification scheme, modified after UNECE 2013, Figure III.2 and UNECE 2019 and cobalt resource estimates based on data collected for this study. Mineral reserves and resources are CRIRSCO-compliant categories. Abbr.: Abbreviated UNFC-class as used in the text.

	Resource estimates		**UNFC-2009 categories**			**Abbr.**	**Cobalt contained [tonnes]**	**UNFC-2009 Class**	**Contained cobalt metal [tonnes]**	**Comment**	
Increasing uncertainty	Mineral Reserve	Proven	E1	F1	G1	111	**6950**	Commercial projects	**144 638**	Cobalt resources, which are very likely to be extracted in the near future	
		Probable	E1	F1	G2	112	**107 688**				
	Mineral Resource	Measured	E2	F2	G1	221	**455 715**	Potentially commercial projects	**370 409**	Cobalt resources in development for extraction	
		Indicated	E2	F2	G2	222	**95 091**				
		Inferred	E2	F2	G3	223	**219 603**				
	Compliant historic estimates		E3	F3	G1	331	**9203**	Previously potentially commercial projects	**111 107**	Previously estimated resources, which require revisions and adaptations to ensure feasibility	Total cobalt content: **1 342 649 tonnes**
			E3	F3	G2	332	**13 852**				
			E3	F3	G3	333	**88 052**				
	Historical estimates or non-compliant cobalt grade		E3	F3	G4	334	**29 674**	Exploration projects	**746 495**	Early cobalt exploration, but further data required to confirm resource and feasibility	
			E3	F4	G4	344	**716 821**	Additional quantities in place associated with known deposits		Currently not explored for cobalt as a target commodity	

4.1. Results

The total cobalt resource in all UNFC classes from this study is 1 342 649 tonnes (Fig. 2, Table 4). This figure has been derived by aggregating the available resource estimates for each deposit. The inherent uncertainty in each of these estimates is rarely published so it is not possible to quantify the accuracy of the total calculated resource or of that in each resource class.

Cobalt resources in classes 111 and 112 (114 638 tonnes contained cobalt), representing commercial projects, account for only about 8% of the total. In commercial projects most of the resource (107 688 tonnes) is allocated to class 112, with only 6 950 tonnes in class 111. The cobalt reserves (class 112) at Sotkamo mine are by far the largest at 99 788 tonnes, accounting for 87% of the total in all commercial projects. Potentially commercial projects (classes 221, 222, 223) represent about a quarter of the total cobalt resources with 370 409 tonnes. They comprise chiefly inferred resources with a share of nearly 17% (class 223), with approximately 7% indicated resources (class 222) and about 4% measured resources (class 221). Approximately eight percent of the cobalt resources (111 107 tonnes) are classified as 331, 332 or 333, where the majority are inferred resources (class 333). The majority of cobalt resources are in non-compliant historic estimates, constituting nearly 56% of the total resources (746 495 tonnes). Of the historic estimates, 96% are additional quantities with no current economic interest for cobalt; only 4% are in early exploration projects for cobalt.

It is notable that commercial projects (classes 111 and 112) constitute only three deposits (Sotkamo, Kevitsa and Kylylahti, all in Finland), while historic estimates (classes 334 and 344) are derived from 109 different deposits. Those 109 deposits have an average cobalt content of 6 768 tonnes, several orders of magnitude smaller than the cobalt content at Sotkamo. It should be noted that the estimate presented in this study is based on only those deposits with available data, that is 151 deposits from twelve countries. Given the absence of data from many countries it is not currently possible to derive a comprehensive and up to date estimate for Europe as a whole.

5. Cobalt-bearing deposits in Europe

5.1. Size and grade of deposits

Cobalt-bearing deposits are found in several countries in Europe, but many of these are small or have low cobalt grades, and consequently only a few deposits have been exploited commercially. In Fig. 3 the size and grade of cobalt-bearing deposits in Europe are shown together with representative examples of similar deposits found elsewhere. A full dataset for the European deposits is given in the Electronic Supplementary Material to this paper.

In Europe the largest magmatic deposits are Kevitsa and Sakatti in Finland, containing 29 750 tonnes and 20 210 tonnes of cobalt metal, respectively (Anglo American, 2019; New Boliden, 2019) (Fig. 1A). However, these are relatively small in comparison with renowned magmatic deposits worldwide such as Pechenga in Russia and Voisey's Bay in Canada, which contain 169 500 tonnes and 123 300 tonnes of

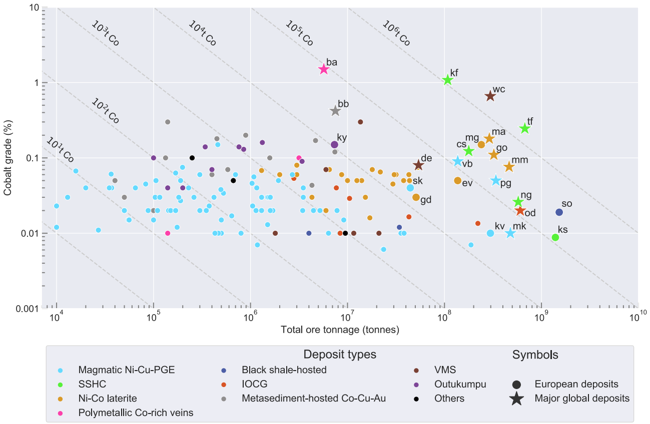

Fig. 3. Size, grade and cobalt content of European cobalt deposits compared with those of some major global deposits. The quality of the grade and tonnage data are variable: some data are from resource estimates compliant with the CRIRSCO-reporting template, while others are historic estimates or from codes not compliant with current reporting standards. Data for global deposits are from Taylor et al. (2013), Slack et al. (2017), Petavratzi et al., (2019) and Jervois Mining Ltd (2020). Named deposits: ba, Bou Azzer, Morrocco; bb, Blackbird, USA; cs, Chambishi Southeast, Zambia; de, Deeni, China; ev, Evia, Greece; gd, Gördes, Turkey; go, Goro, New Caledonia; kf, Kisanfu, DRC; ks, Kupferschiefer district, Poland; kv, Kevitsa, Finland; ky, Kylylahti, Finland; ma, Moa, Cuba; mg, Mokra Gora, Serbia; mk, Mount Keith, Australia; mm, Murrin Murrin, Australia; ng, Nchanga, Zambia; od, Olympic Dam, Australia; pg, Pechenga, Russia; sk, Sakatti, Finland; so, Sotkamo (Talvivaara), Finland; tf, Tenke Fungurume; vb, Voisey's Bay, Canada, wc, Windy Craggy, Canada.

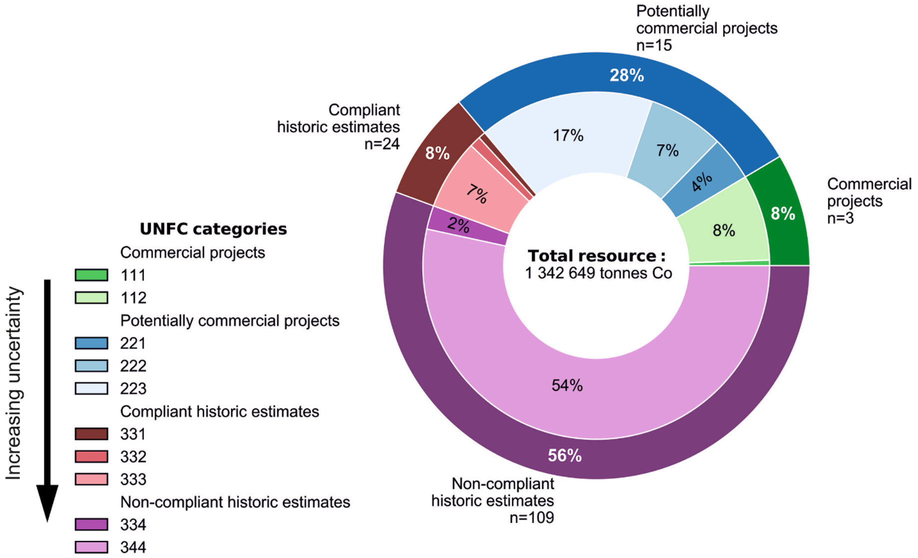

Fig. 2. Cobalt resources in Europe classified using the UN Framework Classification (UNFC) categories and classes (n = number of deposits). Segments with no label have a share of one percent or less.

cobalt metal, respectively (Naldrett, 2004; Slack et al., 2017). Mount Keith in Australia is of a similar order of magnitude to Kevitsa and Sakatti, containing 47 800 tonnes of cobalt metal (Fig. 3).

SSHC deposits in Europe are restricted to the Kupferschiefer district in south-west Poland and eastern Germany. Based on limited published data, the Polish deposits are estimated to contain a total of about 122 360 tonnes of cobalt metal (Szamalek et al., 2017) (Fig. 1A), quite similar to Voisey's Bay. However, the estimated cobalt grade in the Kupferschiefer is very low, 0.005–0.008% Co, which makes cobalt recovery from these ores economically less attractive and there is no current cobalt extraction (Pazik et al., 2016). These grades are also markedly lower than in SSHC deposits of the Central African Copperbelt, which contain between 0.03 and 1.08% Co (Slack et al., 2017) (Fig. 3).

Lateritic nickel deposits are widespread in the Balkans where several mines are currently in operation (Herrington et al., 2016). The grades here range between 0.02 and 0.15% Co, which are generally lower than in world-class examples such as Goro in New Caledonia, Murrin Murrin in Australia and Moa in Cuba (Petavratzi et al., 2019) (Fig. 3). The sizes of these deposits vary considerably, from 0.3 million tonnes of ore up to about 1 000 million tonnes, although cobalt grades are commonly not reported. Known cobalt tonnages in European examples of laterite deposits exceed 10 000 tonnes in 13 deposits, including Agios Ioannis and Evia in Greece with JORC-compliant resources of 21 800 tonnes and 68 500 tonnes of cobalt metal, respectively (Apostolikas, pers. comm., 2019). The Gördes mine in Turkey currently produces a mixed nickel–cobalt hydroxide and plans to produce cobalt in the near future. The mine reports proven reserves of 15 280 tonnes cobalt metal (Zorlu, 2019). The largest lateritic nickel deposit in Europe is at Mokra Gora in Serbia (1 000 million tonnes ore) (Herrington et al., 2016). Although the cobalt grade (0.15% Co) is reported only for a resource of 240 million tonnes of ore, this deposit has a potentially very large cobalt endowment (Apostolikas, 2009).

The black shale deposit at Sotkamo is conspicuous on account of its low cobalt grade but very large size. It is the largest known black-shale deposit in the world with a resource tonnage of 1 525 million tonnes grading 0.019% Co, which equates to 289 750 tonnes contained cobalt (Lukkaroinen, 2018; Terrafame Ltd, 2018).

In addition to the deposits highlighted above potential cobalt resources are also known in other deposit types distributed widely in Europe. Fig. 1 shows clearly that Fennoscandia is well endowed with dominantly magmatic Ni-Cu-Co deposits, but examples of several other deposit types are also present. These include metasediment-hosted Co-Cu-Au (possibly comparable with orogenic gold deposits), IOCG, polymetallic cobalt-rich vein, skarn, VMS, and Outokumpu-type deposits. Outokumpu-type deposits are restricted to the Outokumpu district in Finland, often ascribed to the VMS class, but here allocated to their own deposit class. In this district the Kylylahti mine is currently producing cobalt with about 820 tonnes of cobalt metal remaining and mine closure is planned for autumn 2020 (New Boliden, 2019) (Figs. 1 and 3). Elsewhere in Europe many occurrences are small and there is little information on their cobalt endowment.

5.2. Archaean to Palaeoproterozoic deposits in the Fennoscandian Shield

The Fennoscandian Shield comprises the largest mass of Precambrian rocks in Europe and shows many similarities to Proterozoic shields in Canada, Australia and South Africa, all well known for their abundance of large metal deposits. The Fennoscandian Shield is part of the East European craton, extending from the Kola Peninsula in north-west Russia across Finland and most of Sweden and Norway. Archaean crust is mainly exposed in eastern and northern Finland, north-western Russia and north-east Norway, encompassing the oldest rocks (3.5–2.5 Ga) in Europe. The shield experienced several intraplate rifting events before major orogenies occurred. Rock units of the Svecofennian orogeny (1.90–1.87 Ga), also known as the Svecokarelian orogeny, dominate in the central part of the shield, whereas Mesoproterozoic rocks, dominantly related to the Sveconorwegian orogeny, are located in the south-west (Lahtinen et al., 2011) (Fig. 4). Key features of the most important cobaltiferous deposits in the Fennoscandian Shield are shown in Table 5.

5.2.1. Komatiite-hosted deposits (3.5–2.06 Ga)

The oldest Ni deposits are Archaean to Palaeoproterozoic magmatic Ni-Cu-Co-PGE deposits hosted by komatiitic rocks in greenstone belts (Makkonen et al., 2017). Cobalt grades have been reported for eleven komatiite-hosted deposits. The Kuhmo-Suomussalmi Greenstone Belt (seven deposits), together with the Tainiovaara deposit in eastern Finland and the Ruossakero deposit in the north-west, are likely related to a phase of komatiitic volcanism (2.9–2.8 Ga) (Fig. 4). Ruossakero is the largest deposit with 35.6 million tonnes grading 0.01% Co (Lahtinen, 2008). The Pulju Belt (ca. 2.06 Ga) is part of the Palaeoproterozoic Central Lapland Greenstone Belt, situated in northern Finland (Makkonen et al., 2017). Unlike much of the Central Lapland Greenstone Belt, the Pulju Belt includes extensive komatiitic rocks and hosts the Hotinvaara and Iso-Siettelöjoki deposits with cobalt grades of 0.03% and 0.05%, respectively (Konnunaho et al., 2015).

5.2.2. Rift-related mafic–ultramafic Ni-Cu-Co (PGE) deposits (2.5–1.95 Ga)

The Archaean continents experienced several rifting stages during the early Palaeoproterozoic (2.5–1.95 Ga), which led to the formation of many bodies of mafic–ultramafic intrusive and extrusive rocks. These are associated with sulfide-poor Cr, V-Ti-Fe and PGE deposits as well as sulfide-rich Ni-Cu-Co (PGE) deposits (Lahtinen, 2012). The Tornio-Näränkävaara Belt contains ca. 2.44 billion years old mafic–ultramafic layered intrusions with major PGE-rich Ni-Cu deposits (Lahtinen et al., 2011; Iljina et al., 2015). In this belt cobalt grades are only reported for the Niittylampi deposit (0.046% Co) in the Portimo complex and the Kaukua (0.0057% Co) and Haukiaho deposits (0.0059% Co) in the Koillismaa complex (Makkonen et al., 2017; NGU, 2020).

The Kevitsa mafic–ultramafic intrusion evolved within the Central Lapland Greenstone Belt during rifting 2.1–2.05 billion years ago, simultaneous with komatiitic volcanism in the area (Fig. 4) (Makkonen et al., 2017). The intrusion hosts a large magmatic deposit of the same name, which has been mined since 2012 and has a remaining ore tonnage of 297.5 million tonnes. Besides the production of nickel, copper, gold, platinum and palladium, cobalt is an important by-product with a grade of 0.01–0.011% Co (Santaguida et al., 2015; New Boliden, 2019). Cobalt is mostly incorporated in the main sulfide ore minerals pentlandite and pyrrhotite, rather than occurring as discrete cobalt minerals (Santaguida et al., 2015). The Sakatti deposit is a recent greenfield discovery, about 20 km south-west of the Kevitsa mine, located in the Sattasvaara Formation (2.3–2.1 Ga). It is compositionally similar to Kevitsa, being enriched in copper, but the cobalt grade is higher with 0.04% in the inferred resources and up to 0.11% in the indicated resources (Brownscombe et al., 2015; Anglo American, 2019). The deposit is often compared to the Kevitsa deposit but its origin remains unclear.

5.2.3. Black-shale hosted deposits (2.1–1.9 Ga)

In eastern Finland a few black-shale hosted deposits occur in the Palaeoproterozoic Kainuu Schist Belt, along the Archaean-Proterozoic boundary. These include the Sotkamo deposit, which currently produces nickel, copper, zinc and cobalt. The organic carbon-rich black schists that host the sulfides were deposited in a stratified marine basin 2.1–1.9 billion years ago (Loukola-Ruskeeniemi and Lahtinen, 2013). Later multi-phase deformation during the Svecofennian orogeny (ca. 1.91–1.78 Ga) led to upgrading of primary metal concentrations through redistribution and recrystallization of the local proto-ores (Loukola-Ruskeeniemi and Lahtinen, 2013; Kontinen and Hanski, 2015).

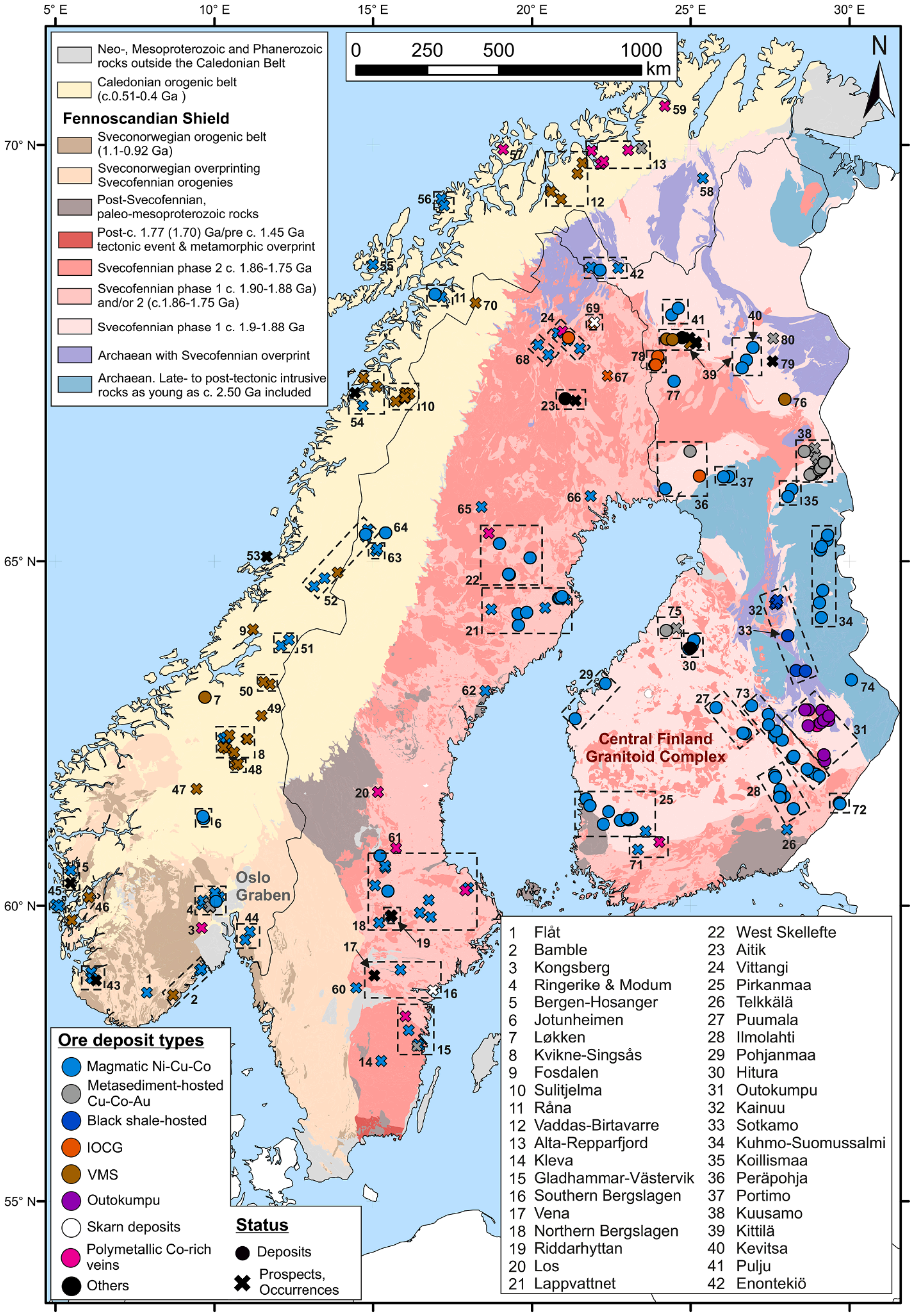

Fig. 4. Cobalt-bearing deposits in Fennoscandia (excluding the Russian part) in relation to important geotectonic events. Selected localities are named and details of other numbered deposits are given in the Electronic Supplementary Material. Districts with several deposits are outlined by dashed lines. The geotectonic basemap was supplied by the Geological Survey of Finland [Geological map of the Fennoscandian Shield, Finnish section] © Geological Survey of Finland (2001), the Geological Survey of Sweden and the Geological Survey of Norway and is based on Koistinen et al. 2001.

5.2.4. Ophiolite-related Outokumpu deposits (1.95–1.94 Ga)

The Outokumpu ore district, located in the North Karelian Schist Belt in eastern Finland, hosts polymetallic Cu-Co-Zn-Ni-Ag-Au deposits that have a complex origin. It is thought that a late rifting event (1.95 Ga) led to the formation of VMS-type Cu-Co-Zn proto-ore by hydrothermal sulfide deposition on the ultramafic ocean floor (Peltonen et al., 2008). Subsequently, the ultramafic seafloor and the sulfide ores were obducted onto the margins of the Karelian Craton, now present as the Outokumpu Allochthon (Peltonen et al., 2008; Eilu et al., 2012a). During this period Ni-sulfide mineralisation is thought to have taken place syntectonically through alteration of nickel-rich olivine of the ultramafic seafloor rocks. This was mixed and remobilised with the VMS-type ore to produce the Cu-Co-Zn-Ni-Ag-Au deposits. The cobalt content of these ores is relatively high compared to both magmatic Ni-Cu-Co sulfide and typical VMS ores, ranging from 0.03 to 0.25% Co. Cobalt is dominantly hosted by pyrite and cobaltpentlandite, and less commonly by cobaltite in arsenic-rich units (Peltonen et al., 2008). After a long mining history in the district starting in 1913, the Kylylahti deposit is currently the only operational metal mine in the district with a remaining reserve of 500 000 tonnes. In 2018, Kylylahti produced 278 tonnes of cobalt metal (New Boliden, 2018, 2019).

5.2.5. Svecofennian magmatic and other deposits (1.9–1.75 Ga)

After 500 million years of rifting and intracratonic basin evolution, the allochthonous ophiolites at Outokumpu are the first evidence of convergence in the Fennoscandian Shield, which resulted in the accretion and subsequent collision of several microcontinents along linear belts (1.92–1.79 Ga) (Weihed et al., 2005). The resulting Svecofennian orogeny is known for many magmatic Ni-Cu-Co deposits, as well as gold deposits with elevated cobalt concentrations. The magmatic Ni-Cu-Co deposits are related to mafic–ultramafic intrusions and have a complex synorogenic origin, but likely developed at convergent plate

Table 5
Selected cobalt-bearing deposits in Fennoscandia. Cobalt resources are calculated from the cobalt grade and the total ore tonnage.

Name	Location	Deposit type	Status	Cobalt Resource (tonnes metal)	Resour-ce Code	References
Hitura	Savo Belt, central Finland	Magmatic-Ni-Cu-PGE	Abandoned mine, Co production until 2014	891	NI 43–101	Belvedere Resources, 2012; FODD, 2020
Juomasuo	Kuusamo Belt, east Finland	Metasediment-hosted Co-Cu-Au	Currently explored	8620	JORC	Slack, 2013; Dragon Mining, 2014; Latitude 66 Cobalt, 2019
Kevitsa	Kittilä, central Lapland, Finland	Magmatic-Ni-Cu-PGE	Operating mine with Ni, Cu, PGE, Au and Co production	31 144	PERC	Boliden, 2019; FODD, 2020
Kylylahti	North Karelian Schist Belt, east Finland	Outokumpu	Operating mine with Cu, Zn, Co and Au production	8436	PERC	New Boliden, 2018, 2019; FODD, 2020
Rajapalot	Peräpohja Schist Belt, west Finland	Metasediment-hosted Co-Cu-Au	Currently explored	1849	NI 43–101	Mawson Resources, 2018, 2019; FODD, 2020
Sakatti	Kittilä, central Lapland, Finland	Magmatic-Ni-Cu-PGE	Currently explored	20 210	JORC	Anglo American, 2019; FODD, 2020
Sotkamo (Talvivaara)	Kainuu Schist Belt, eastern Finland	Black-shale hosted	Operating mine with production of Ni, Zn, Co and Cu	289 750	JORC	Terrafame Ltd, 2018; Garcia-Balbuena, pers. comm., 2020
Dalen	Jotun Nappe Complex, central Norway	Magmatic-Ni-Cu-PGE	Currently explored	1560	JORC	Drake Resources, 2014; FODD, 2020
Ertelien	Ringerike, Kongsberg Com-plex, south Norway	Magmatic-Ni-Cu-PGE	Abandoned mine, currently explored	1618	NI 43–101	FODD 2020
Løkken	Trondheim Nappe Complex, central Norway	VMS (Cyprus-type)	Abandoned mine, currently explored	4200	Historic estimate	Grenne et al., 1999; FODD, 2020
Råna (Bruvann)	Narvik, central Norway	Magmatic Ni-Cu-PGE	Abandoned mine, currently explored	1373	Historic estimate	Barnes, 1987; FODD, 2020
Skuterud (Modum)	Kongsberg Com-plex, south Norway	Metasediment-hosted Co-Cu-Au	Abandoned mine, previously explored in 2018	None	None	Berkut Minerals, 2019; Eilu et al., 2012b; Slack, 2013
Gladhammar	Gladhammar-Västervik, south Sweden	Metasediment-hosted Co-Cu-Au	Abandoned mining district, Co production in the 18th and 19th centuries; currently explored	None	None	Berkut Minerals, 2019; FODD, 2020; Hallberg and Reginiussen, 2019
Lainejaur	Skellefte district, north Sweden	Magmatic-Ni-Cu-PGE	Abandoned mine, currently explored	690	JORC	Berkut Minerals, 2019; FODD, 2020
Los	central Sweden	Polymetallic cobalt-rich veins	Abandoned mine, production of Ni, Cu and Co in the 18th century	None	None	Welin, 1966; Hallberg & Reginiussen, 2019; FODD, 2020
Tunaberg	Bergslagen, south-central Sweden	Skarn	Abandoned mining district, Cu and Co production in 18th and 19th centuries; currently explored	None	None	Berkut Minerals, 2019; FODD, 2020; Hallberg and Reginiussen, 2019
Vena	Bergslagen, south central Sweden	‘fahlband’ type mineralisation hosted by felsic metavolcanic rocks	Abandoned mining district, Co production in 18th and 19th centuries	None	None	Hallberg & Reginiussen, 2019; FODD, 2020

margins (Makkonen et al., 2017). In Finland Svecofennian Ni-Cu-Co deposits occur in: the Savo Belt at Kotalahti and Hitura; the Pirkanmaa Belt at Vammala; the Pohjanmaa Belt at Oravainen; the Peräpohja Schist Belt at Kemi; and in the areas of Ilmolahti, Puumala and Telkkälä in south-east Finland. Deposits of the same origin have also been discovered in the Lappvattnet Belt in Sweden (Fig. 4) (Weihed et al., 2005; Makkonen et al., 2017). Within the Svecofennian orogen in Sweden magmatic deposits are also located in the Skellefte district and in the Bergslagen ore province. South of Bergslagen a notable deposit is found at Gladhammar where historic cobalt grades of about 6% have been reported, known to be hosted in carrollite, cobaltite and skutterudite within the metasedimentary Västervik Formation (Tegengren, 1924).

In total there are about 50 deposits in these districts that have reported cobalt resources. Most are small in size with the Hitura mine in the Savo Belt being the largest (21.19 million tonnes ore of which 4 million tonnes remain). The mine was intermittently in production from 1966 to 2014 with a formally reported Co production of about 544 tonnes. In southern and central Sweden, mines at Vena, Riddarhyttan, Tunaberg, Håkansboda and Åtvidaberg in Bergslagen, together with Gladhammar and Los, produced cobalt during the 18th and 19th centuries, following its first discovery in the Riddarhyttan ore in Bergslagen, in 1735. Gladhammar is Sweden’s largest historic producer of cobalt with an estimated 256 tonnes extracted (Tegengren, 1924; Hallberg and Reginiussen, 2019).

There are many known orogenic Au deposits related to the Svecofennian orogeny some of which are enriched in cobalt and copper. The classification of these deposits is uncertain, with some alternatively described as metasediment-hosted Co-Cu-Au deposits and others as IOCG deposits (Weihed et al., 2005; Eilu et al., 2012a; Slack, 2013). (Goldfarb et al., 2001; Slack, 2013). Cobalt-bearing deposits are located in the Central Lapland Greenstone Belt, the Peräpohja Belt and the Kuusamo Belt in Finland where they are hosted by mafic to ultramafic metavolcanic and various volcaniclastic rocks deformed during collisional compression and regional metamorphism (Vanhanen, 2001; Eilu, 2015; Molnár et al., 2017; Pohjolainen et al., 2017). The Kuusamo Belt is currently being explored, including the Juomasuo and Sivakkaharju deposits (Latitude 66 Cobalt, 2019). Another prospect, which shows many similarities to these deposits, is the Rajapalot Au-Co project in the Peräpohja Belt considered to be of Palaeoproterozoic age with late tectonic hydrothermal mineralisation (Ranta et al., 2018). The current inferred resource is 4.3 million tonnes grading 0.043% Co (Mawson Resources, 2019).

5.3. *Mesoproterozoic deposits in Fennoscandia*

Mafic-ultramafic intrusions also formed in Mesoproterozoic times in a weakly extensional regime. This magmatism, which occurred in the pre-Sveconorwegian period (1.34–1.14 Ga), resulted in the development of several cobalt-bearing deposits on the western side of the Oslo Graben (Fig. 4) (Bingen et al., 2008; Sandstad et al., 2012). A notable example is the norite-hosted Ertelien deposit situated in the Kongsberg Complex in southern Norway with a cobalt grade of 0.06% and remaining resources of 2.7 million tonnes. The deposit was in production from 1688 to 1920, mainly producing nickel and copper, although after 1789 cobalt was also recovered (Sandstad et al., 2012). Subsequent metamorphism during the Sveconorwegian orogeny had a strong influence on the area and on ore remobilisation.

The genesis of deposits in the Modum district of the Kongsberg Complex, including the Skuterud deposits, is controversial. Cobalt mineralisation is likely related to deformation and metamorphism during the Sveconorwegian orogeny, which resulted in sulfide mobilisation and hydrothermal activity (Grorud, 1997). These deposits have recently been classified as metasediment-hosted Co-Cu-Au deposits (Slack, 2013). The Skuterud mine commenced cobalt extraction in 1776 and was the main global source of cobalt blue in the 1820s and 1830s (Eilu et al., 2012b). The Flåt Ni-Cu-Co deposit at Evje, another historic producer of cobalt, nickel and copper, is hosted by a Late Sveconorwegian diorite intrusion (Pedersen et al., 2009; Sandstad et al., 2012). The magmatic Ni-Cu-Co deposits at Dalen, Stormyra (Jotunheimen Nappe Complex) and Hosanger, near Bergen are related to the Sveconorwegian orogeny but are situated in allochthonous units within the Caledonides in south-west Norway (Fig. 4) (Sandstad et al., 2012).

5.4. *Phanerozoic deposits in Norway and Sweden*

The Caledonides in Norway and Sweden contain various metal deposits, mainly related to the rifting and break-up of Rodinia (700–600 Ma), the opening of the Iapetus Ocean and finally, during the Silurian, the collision of the continents Laurentia and Baltica (Grenne et al., 1999). These events resulted in the formation of VMS-type deposits related to either rifting or immature and mature arc systems, with some reported to contain cobalt (Grenne et al., 1999). The Løkken deposit, south-west of Trondheim, is the largest ophiolite-hosted (Cyprus-type) VMS deposit in the world with a pre-mining ore tonnage of 30 million tonnes grading 0.07% Co (Sandstad et al., 2012; NGU, 2020). The Fosdalen deposit, located north of Trondheim, is even larger with a pre-mining ore tonnage of 35.5 million tonnes. Fosdalen is a magnetite-pyrite-dominated VMS deposit developed within a mature arc system. Here, cobalt is reported to occur in cobalt-bearing pyrite, but no cobalt grade is available. The Sulitjelma district in Nordland County and the Vaddas district in Troms County contain several cobalt-bearing VMS deposits. Their origin is related to mainly rift-type volcanism that occurred during the convergence of Laurentia and Baltica in a transtensional regime (Grenne et al., 1999).

Magmatic Ni-Cu-Co deposits hosted by orogenic mafic–ultramafic intrusions are also found in the Caledonides. These deposits possibly originated from oblique rift-type magmatism and have low PGE contents compared to other mafic intrusion-hosted Ni-Cu-Co deposits (Barnes, 1987). The Råna deposit near Narvik has a reported cobalt grade of 0.03% and a pre-mining ore tonnage of 17.69 million tonnes (NGU, 2020). Small deposits of the same type and age occur in the Trondheim Nappe Complex (Grenne et al., 1999).

The last metallogenic event in Fennoscandia occurred due to the opening of the Oslo Rift during the Permo-Carboniferous, tectonically related to the last phase of the Variscan orogeny (Larsen et al., 2008). The Ag-Co-As-vein deposits of Kongsberg, south-west of Oslo, are interpreted to be related to Permian magmatism, where cobalt occurs mainly in Ni-Co-arsenide minerals such as the rammelsbergite-safflorite series (Neumann, 1944; Sandstad et al., 2012; Kotková et al., 2018).

5.5. *Mesozoic Kupferschiefer in central Europe and related deposits*

The Kupferschiefer deposits are one of three supergiant stratiform sediment-hosted Cu-Co (SSHC) districts recorded in the Earth's history, together with the Central African Copperbelt and the Udokan deposit in Siberia (Hitzman et al., 2010). The Kupferschiefer deposits are situated in the Central European basin, which evolved from crustal extension, magmatic underplating and crustal heating in the Late Carboniferous after the Variscan orogeny (Borg et al., 2012). The basin consists of Lower Permian Rotliegend with terrestrial red-bed sedimentary rocks and felsic to mafic magmatic rocks, overlain locally by conglomerates and sandstones, and by the nearly basin-wide Kupferschiefer, a black 0.3–0.6 m-thick bituminous to carbonaceous shale. This unit is covered by the Zechstein limestone and evaporitic sequences, which were deposited in several evaporitic cycles of marine transgression and regression (Borg et al., 2012). The basin extends from Poland across Germany as far west as the eastern margin of the UK. It was historically exploited in Germany and Poland for copper, lead, zinc, precious metals and, to a lesser extent, cobalt (Borg et al., 2012). Current mining operations are located at Lubin, Polkowice-Sieroszowice and Rudna in Lower Silesia, south-west Poland (Szamalek et al., 2017). The sulfide ore occurs in the Kupferschiefer, as well as in the underlying sandstone and conglomerates and the overlying carbonate and anhydrite units. Cobalt generally occurs as cobaltite, but other cobalt-bearing sulfarsenides and sulfide minerals have been described such as skutterudite, bravoite, safflorite, gersdorffite and siegenite. The cobalt-bearing minerals are found as inclusions within copper-rich minerals (Piestrzyński and Pieczonka, 2012; Pazik et al., 2016). The average cobalt concentration in the Kupferschiefer deposits of Poland is estimated to be 0.005–0.008%, which is much lower than in the Central African Copperbelt where cobalt grades exceeding 1% characterise some deposits (Pazik et al., 2016; Slack et al., 2017). However, the ore tonnage in the Kupferschiefer is very large with a remaining economic to sub-economic resource of 1 392.4 million tonnes in the operational mines in Poland (Szamalek et al., 2017). However, the cobalt grades are too low to currently support economic extraction of this metal.

In some places cross-cutting veins have remobilised the primary ores to form Co-Ni-Bi-vein mineralisation, known as Kobalt-Rücken (Borg et al., 2012). Examples of this style of mineralisation can be found in the Spessart district and at Richelsdorf in Germany (Wagner and Lorenz, 2002; Borg et al., 2012). Cobalt was produced with copper from the Kupferschiefer at Schweina in central Germany between 1441 and 1714. During this period cobalt was used for colouring glassware and ceramics, even though it was not recognised as a chemical element until 1735 (Marshall and Marshall, 2003). Cobalt was recovered together with other by-products, such as nickel, molybdenum, selenium, REE, vanadium, cadmium and thallium, in the processing plants at Mansfeld and Sangershausen in the former German Democratic Republic after the Second World War (Borg et al., 2012).

The Cheshire Basin in the United Kingdom lies west of the Central European Basin and is a post-Variscan graben structure. This basin contains sediment-hosted epigenetic copper-rich polymetallic mineralisation, best developed at Alderley Edge (Warrington, 2012). Besides copper and lead mining, there was minor production of cobalt in the early 19th century. The cobalt occurs chiefly with nickel as secondary asbolane and erythrite but some is also present in primary arsenides and sulfides (Carlon, 1979; Warrington, 2012). The mineralisation is not related to an organic-rich layer like the Kupferschiefer, but is hosted in Triassic sandstones, post-dating the Zechstein era (Naylor et al., 1989; Warrington, 2012).

5.6. *Mesozoic to Palaeozoic nickel–cobalt laterite deposits in the Balkans and Turkey*

Several large laterite nickel deposits occur in the Balkans (Albania, Bosnia and Herzegovina, Greece, Kosovo, North Macedonia, Serbia) and Turkey (Herrington et al., 2016). A few of these are exploited as mines that produce ferronickel for the stainless steel industry. The laterites are situated in: (1) the Western Ophiolite Belt, stretching from Bosnia to

Turkey; and (2) the Eastern Ophiolite Belt (also known as Eastern Vardar Zone) lying sub-parallel and dominantly north of the Western Ophiolite Belt (Herrington et al., 2016) (Fig. 5). The ophiolite complexes were emplaced during the Late Mesozoic to Cenozoic (Smith and Spray, 1984; Dilek, 2006). The majority of lateritic deposits in the Balkans formed during the first phase of lateritic weathering in the Late Jurassic to Early Cretaceous (Apostolikas, 2009). Weathering of these ultramafic rocks under subtropical to tropical climatic conditions led to the formation of significant Ni-Co laterite deposits (Thorne et al., 2012b). While many lateritic profiles remained in their place of origin (in-situ laterites), others have been eroded, transported and redeposited, forming sedimentary laterite deposits (Apostolikas, 2009; Herrington et al., 2016). These reworked deposits are either situated on karstified carbonate rocks (karst-type laterites) or ophiolitic rocks (sedimentary Ni-Co ores). In some deposits both in-situ and redeposited laterites can be found (Boev et al., 1996; Herrington et al., 2016). Subsequently, high eustatic sea levels resulted in the deposition of pelagic and neritic limestones, which cover many of the in-situ lateritic ores. A second phase of lateritic weathering resulted in the formation of another generation of laterite deposits during Eocene and Miocene times. These deposits are exclusively of the in-situ type and are found in Greece, Albania, Kosovo and Turkey (Apostolikas, 2009). This section focusses on those lateritic deposits in the Balkans known to be enriched in cobalt. Key features of the most important cobalt-bearing laterite deposits are shown in Table 6.

The Western Ophiolite Belt hosts deposits in Bosnia, Albania, Serbia, Greece and Turkey. The Brezik Tadići deposit in Bosnia comprises chiefly sedimentary oxide ore derived from the underlying harzburgitic ophiolite. It is unique on account of its high cobalt grade, 0.1–0.38%, mostly in the form of asbolane, occurring in an Fe-oxyhydroxide-rich unit (Herrington et al., 2016). However, little else is known about this deposit. The largest nickel deposit in the Balkans is at Mokra Gora in Serbia, which is an in-situ oxide-dominated laterite of Late Cretaceous age with an estimated resource of 1000 million tonnes of ore (Monthel et al., 2002). There is little reliable data on the cobalt grade in this deposit. Apostolikas (2009) reported 0.15% Co in 240 million tonnes of ore, although this is not necessarily representative of the whole deposit. In Albania laterite deposits are developed in three notable mining districts, Kukes, Librazhd-Progradec and Devolli (Albania Energy Association, 2011; Herrington et al., 2016). At Kukes and Librazhd-Progradec weathered ultramafic rocks are overlain by a nickel-rich ferruginous oxide ore. The Kukes district is dominated by reworked pelitic oxide ores with a nickeliferous zone up to 20 m thick, but it also includes saprolite ore at the base (Herrington et al., 2016). The cobalt contents of the silicate zone and the oxide zone are similar in both districts with 0.04–0.05% Co and 0.05–0.06% Co, respectively. The laterites in the Devolli district developed in-situ with a silicate zone (0.06% Co; up to 5 m thick) overlain by an oxide-dominated zone (0.04% Co; up to 8 m thick) (Albania Energy Association, 2011; Thorne et al., 2012a).

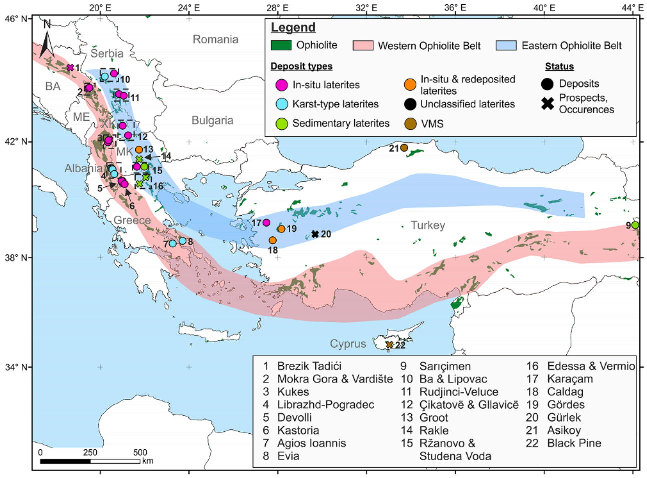

Fig. 5. Cobalt-bearing Ni-Co laterites and VMS deposits in the Balkans and Turkey in relation to the major ophiolite complexes modified after Asch 2005 (© BGR, Hannover) & Herrington et al. 2016. Deposits are labelled and districts with several deposits are outlined by dashed lines. Explanation of abbreviated country names: BA, Bosnia & Herzegovina; ME, Montenegro; MK, North Macedonia; XK, Kosovo.

Greece has many important laterite deposits and accounts for about 80% of nickel production from the Balkans (INSG, 2015). The main deposits are Kastoria (8.7 million tonnes resource at 0.06% Co), Agios Ioannis (43.6 million tonnes resource at 0.05% Co) and Evia (228.3 million tonnes resource at 0.05% Co), all currently being mined by Larco (Apostolikas, pers. comm., 2019). Kastoria is hosted by the same serpentinised rocks as the adjacent Devolli deposits in Albania and has a similar oxide-dominated lateritic profile (Herrington et al., 2016). The cobalt concentration varies between 0.02% in the lower saprolite zone to 0.16% in the oxide zone (Eliopoulos and Economou-Eliopoulos, 2000). Agios Ioannis, the largest of three deposits in the Lokris district, is developed on karstified Jurassic limestone. The deposit is composed of saprolite blocks in a pisolitic matrix, overlain by the dominant oxide ores, which grade into a bauxitic laterite. Cobalt was enriched by metal redistribution, together with nickel and manganese, in asbolane in the basal saprolitic layer (Eliopoulos et al., 2012). The average cobalt grade in the deposit is 0.05% (Apostolikas, pers. comm., 2019). The largest Ni-Co laterite deposit in Greece is at Evia. It comprises five open pit mines in which the ore is dominantly hosted in ferruginous pelitic to pisolitic zones in variable profiles. It is developed on either weathered saprolitic serpentinite, unweathered serpentinite or karstified Triassic to Jurassic limestone, similar to Agios Ioannis (Valeton et al., 1987). The average cobalt concentration in the mines is 0.05% (Apostolikas, pers. comm., 2019).

The Eastern Ophiolite Belt hosts deposits in Serbia, Kosovo, Northern Macedonia, Greece and Turkey and continues east into Iran (Fig. 5) (Herrington et al., 2016). In the Metahoia district in Serbia the ore is dominantly a clay-silicate saprolite ore, where nickel and cobalt are chiefly incorporated in smectite minerals such as nontronite (Herrington et al., 2016). The Veluce and Rudjinci deposits are fairly small containing 14 million tonnes at 0.08% Co and 3 million tonnes at 0.05% Co, respectively (Berger et al., 2011). The deposits in Kosovo are also clay-silicate-dominated with proven reserves of 4.3 million tonnes at Çikatova grading 0.03% Co and 6.5 million tonnes at Gllavica grading 0.07% Co (ICMM, pers. comm., 2019). The latter shows a well-preserved profile from a basal harzburgite, overlain in turn by a saprolitic nontronitic clay zone, a goethitic zone and a cap of silica-rich duricrust (Herrington et al., 2016). The highest nickel concentration, up to 3%, is found in the saprolitic clay zone. In contrast, cobalt reaches its maximum of 0.04% higher up towards the goethitic zone (Maksimovic, 1966; Herrington et al., 2016).

The most important deposit in North Macedonia is Ržanovo, close to the southern border with Greece, which has a reserve of 43 million tonnes at 0.06% Co (Fig. 5) (Boev et al., 2009). It is composed of a 30–50 m-thick nickeliferous iron ore, lying sub-vertically between Jurassic serpentinites and Cretaceous limestones. The ore has been largely redeposited after lateralisation with subsequent low-grade metamorphism leading to the deposition of sulfides, including pyrite, millerite and cobalt sulfides, as described by Boev et al. (2009). Several similar but much smaller deposits and occurrences are located in the Eastern Ophiolite Belt of Greece about 70 km south of Ržanovo. Edessa and Vermio are estimated to have 1.5 and 2 million tonnes of ore, respectively, and reported cobalt values in the range of 0.01– 0.14% (Eliopoulos et al., 1997; INSG, 2015). Economou-Eliopoulos (2003) showed that cobalt is enriched in zoned chromite grains, up to 3.2 wt% Co, together with manganese and zinc, in the saprolite zone at Vermio and Edessa. It is suggested that cobalt was remobilised during diagenesis after laterite formation.

Important laterite deposits are also found in western Turkey. The

Table 6
Selected cobalt-bearing laterite deposits in the Balkans. Cobalt resources are calculated from the cobalt grade and the total ore tonnage.

Name	Location	Laterite sub-type	Status	Cobalt resource (tonnes metal)	Resource code	References
Bitincka	Western Ophiolite Belt, Devolli district, Albania	In-situ laterite	Operating mine, ferronickel production, no cobalt	4 590	Historic estimate	INSG 2015, Hastorun 2016
Guri Kuq	Western Ophiolite Belt, Librazhd-Pogradec district, Albania	In-situ & karst-type laterite	Operating mine, ferronickel production, no cobalt	39 975	Historic estimate	Herrington et al., 2016 INSG 2015, Hastorun 2016
Mamez	Western Ophiolite Belt, Kukes district, Albania	In-situ laterite	No information available on past activity	21 415	Historic estimate	Herrington et al., 2016; Albania Energy Association, 2011; INSG, 2015
Krivaja - Konjuh	Western Ophiolite Belt, Tuzla Province, eastern Bosnia and Herzegovina	In-situ laterite	No information available on past activity	No information available	None	Herrington et al. 2016
Agios Ioannis	Western Ophiolite Belt, Lokris district, Greece	In-situ & karst-type laterite	Operating mine, ferronickel production, no cobalt	21 800	JORC	Eliopoulos et al., 2012; Apostolikas, pers. comm., 2019
Evia	Euboea district, Western Ophiolite Belt, Greece	In-situ & karst-type laterite	Operating mine, ferronickel production, no cobalt	68 500	JORC	Eliopoulos et al., 2012; Apostolikas, pers. comm., 2019.
Mokra Gora	Western Ophiolite Belt, Dinaric Province, western Serbia	In-situ laterite	investigated in the second half of the 20th century	360 000	Historic estimate	Apostolikas (2009); Herrington et al. (2016); Kamberović et al. (2014)
Gllavicë	Eastern Ophiolite Belt, Drenica & Dobresevac ore fields, Kosovo	In-situ laterite	Operating mine, ferronickel production, no cobalt	4 553	Soviet classification	ICMM, pers. comm., 2019
Ržanovo	Eastern Ophiolite Belt, Studena Voda district, North Macedonia	Redeposited laterite	Operating mine, ferronickel production, no cobalt	24 670	Historic estimate	Boev et al., 2009; Herrington et al., 2016; Serafimovski et al., 2013
Çaldag	Eastern Ophiolite Belt, Manisa, western Turkey	In situ & redeposited laterite	Exploration for nickel and cobalt	18 950	JORC	Helvacı et al., 2017; Thorne et al., 2009; Evrensel, 2019
Gördes	Eastern Ophiolite Belt, Manisa, western Turkey	In situ & redeposited laterite	Operating mine, producing a mixed nickel–cobalt hydroxide	15 280	JORC	Buyukakinci, 2008; Avğan, pers. comm., 2020; Herrington et al., 2016; Zorlu, 2019

Çaldag deposit is of the oxide-dominated laterite type, with weathering profiles composed of a limonitic zone overlying a hematitic zone directly above a serpentinite protolith (Thorne et al., 2009). A silcrete zone covers the oxides in most places. The general absence of Ni-silicates below the oxide zone is a unique feature of this deposit, suggesting that secondary leaching and transportation is very poorly developed at Çaldag (Thorne et al., 2009). Goethite is the main ore mineral containing up to 3 wt% Ni. It formed near the basal zone close to the weathered ultramafic rock. However, nickel and cobalt are also incorporated in asbolane, serpentine and smectite (Helvacı et al., 2017). The Karaçam and Gördes deposits have similar profiles, but include a well-developed nontronitic clay-silicate zone (Eliopoulos et al., 2012; Herrington et al., 2016). The Gördes mine currently produces a mixed nickel–cobalt hydroxide by high-pressure acid leaching, but further refining is carried out elsewhere. It is planned to quadruple production and add a nickel and cobalt sulfate production line for the battery industry (Zorlu Holding, 2018). The mining company reports a proven reserve of 15,280 tonnes of cobalt metal with a cobalt grade of 0.03% (Avğan, pers. comm., 2020; Zorlu, 2019).

5.7. *Other cobalt-bearing deposits*

Cobalt-bearing deposits and occurrences of other types are widely distributed in Europe outside Fennoscandia (Fig. 6). These are described in terms of their regional geodynamic setting, which is largely determined by three major orogenies:

1. Caledonian orogeny: closure of the Iapetus Ocean and convergence of Laurentia, Baltica and Avalonia (Cambrian–Devonian), with the most pronounced effects evident in the British Isles (and Scandinavia as already discussed) (McKerrow et al., 2000).
2. Variscan orogeny: convergence of Gondwana and Laurussia (Late Palaeozoic), most prominent in central Europe, from Spain in the west to the Czech Republic in the east (Matte, 2001; Kroner and Romer, 2013; Gutzmer and Markl, 2019).
3. Alpine orogeny: convergence of Africa, Iberia and Europe (Cretaceous–Oligocene), most prominent in the Pyrenees, the Alps and the Mediterranean countries (Rosenbaum et al., 2002).

5.7.1. *Greenland*

In Greenland cobalt occurrences are known at Maniitsoq and in the Disko Bugt, central-west Greenland, and in Moriussaq in the north-west (Stensgaard et al., 2017). The Maniitsoq exploration project, situated in Archaean rocks of the Greenland Norite Belt, is currently being assessed for cobalt together with nickel, copper and PGEs. The targets are magmatic sulfide deposits hosted by noritic-pyroxenitic intrusions with cobalt mainly incorporated in pentlandite and pyrite. Reported drill intercepts are in the range 0.01–0.27 % Co (North American Nickel Inc., 2015). Another active exploration project for magmatic sulfide deposits is located in the Disko Bugt, where surface samples have cobalt concentrations up to 0.2% (Blue Jay Mining Plc, 2020).

5.7.2. *United Kingdom and Ireland*

Cobalt occurs as a minor constituent of base metal ores at several localities in the United Kingdom (Petavratzi et al., 2019). These ores were mined in the past mainly for copper, lead and zinc, and locally for silver and nickel. In the 18th and 19th centuries production of cobalt-bearing polymetallic ores from mines in south-west England, north Wales, central Scotland and Cheshire amounted to just a few hundred tonnes (Fig. 6).

Cobalt-bearing deposits in rocks of Cambrian to Devonian age are found in Scotland, northern England and Wales. Most show a relationship to Caledonian deformation or magmatism, although some are also affected by later events. In Wales, cobalt is a minor component of polymetallic (lead, zinc, copper and silver) vein mineralisation in the Central Wales Orefield. Here the ores are polyphase, emplaced between Devonian and Permian times, in Upper Ordovician and Lower Silurian clastic marine sedimentary rocks (Mason, 1997). Cobalt production in Wales is only reported from Foel Hiradugg, near Aberystwyth, where it occurs as asbolane, associated with Fe-Mn oxides in a clay-filled fissure

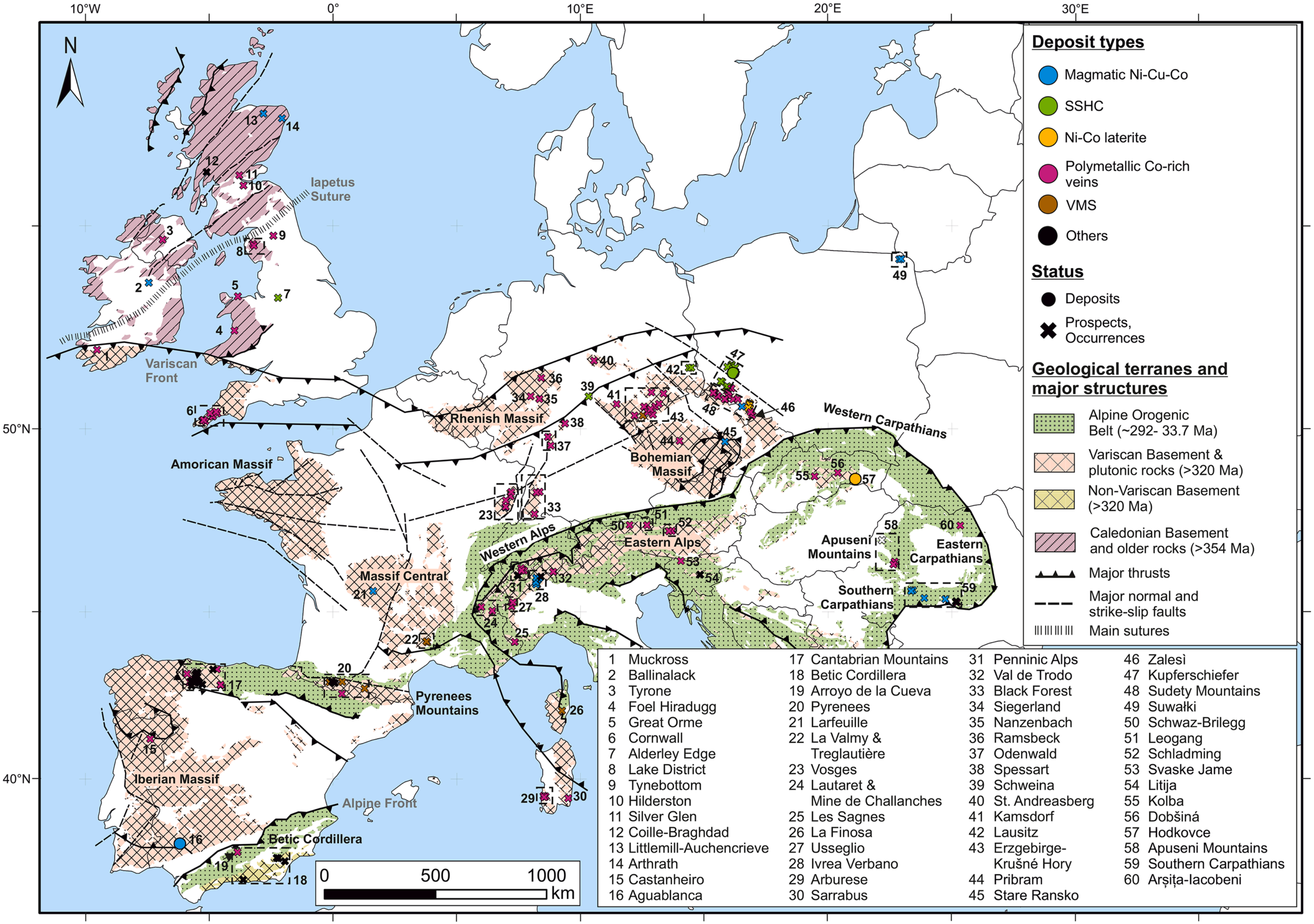

Fig. 6. Cobalt-bearing deposits in central and west Europe in relation to important geotectonic events. Deposits are labelled and districts with several deposits are outlined by dashed lines. Geological terranes and structures interpreted after Asch 2005 (© BGR, Hannover) as well as (Woodcock and Strachan (2000), Heinrich and Neubauer (2000), Vergés et al. (2002), Dill et al. (2008), Murphy et al. (2010), Vergés and Fernàndez (2012) and Cuccuru et al. (2015)).

in Carboniferous limestone. Cobalt ore production is estimated at 240 tonnes between 1878 and 1880 (North, 1962). In the Lake District of England high cobalt concentrations have been recorded at Scar Crag and Dale Head North, near Keswick, both in the vicinity of Late Caledonian granitic intrusions (Ixer et al., 1979; Stanley and Vaughan, 1982). Cobalt extraction was attempted in the mid-19th century at Scar Crag, but this was never successful (Postlethwaite, 1975). In central Scotland two historic silver mines (Silver Glen and Hilderston) produced small amounts of cobalt in the 18th century. At both localities the mineralisation is associated with Carboniferous fault structures. It is hosted by Lower Devonian volcanic rocks at Silver Glen and by Lower Carboniferous sedimentary rocks at Hilderston (Hall et al., 1982; Stephenson et al., 1982; Moreton, 1996). In north-east Scotland mafic–ultramafic intrusions occur in the Caledonian rocks comparable to the Råna intrusion in the Norwegian Caledonides. Extensive drilling, mostly in the 1970s, for nickel, copper and PGE was carried out at Littlemill-Auchencrieve, near Huntly, and at Arthrath, near Ellon. Recent studies of archived drill cores have identified cobalt concentrations up to 0.2%, but little is known about the cobalt deportment in these deposits (McKervey et al., 2007).

In south-west England cobalt mineralisation is associated with late mineralised fractures that cut the main copper and tin ore bodies in the Cornubian Orefield (Rollinson et al., 2018). While the main-stage mineralisation is associated with Variscan convergence, the cross-cutting structures are post-Variscan (Gleeson et al., 2001). Cobalt was recovered from nine mines between the mid-18th century and the 19th century, with total production of a few hundred tonnes of ore (Hamilton Jenkin, 1979; Rollinson et al., 2018).

Recent drilling for 'Irish style' zinc-lead mineralisation in Lower Carboniferous limestones at Ballinalack in the north-east of Ireland revealed a sulfide-bearing mafic dyke with elevated PGE and cobalt concentrations, up to several hundred ppm of cobalt in narrow intercepts (Group Eleven, 2020). No further information is available but the dyke is believed to extend over an area exceeding 3 km by 7 km.

5.7.3. *Spain*

The complex tectonic and magmatic history of the Iberian Peninsula has contributed to the formation of a variety of cobalt-bearing deposits (Fig. 6). The only known magmatic Ni-Cu-Co deposit is Aguablanca in south-west Spain. This deposit is hosted in a gabbronorite intrusion (341 Ma), emplaced along a Variscan shear zone at a convergent plate margin, in a similar setting to that of the Råna intrusion in Norway (Barnes, 1987; Piña et al., 2010; NGU, 2020). The average cobalt grade in the deposit is 0.02%, chiefly incorporated in pentlandite (Ortega et al., 2004; Tornos et al., 2006). The open-pit mine was closed in 2016, but production is planned to resume underground after legal and environmental requirements are fulfilled. It is unclear if cobalt has been recovered at Aguablanca in the past as the ore concentrate was processed elsewhere and there is no information about cobalt production (Valoriza Minería, 2017).

Cobalt-bearing polymetallic vein deposits are known in the Cantabrian Mountains of north-west Spain, in the Betic Cordillera in the south-east and in the Pyrenees along the border with France. In the Cantabrian Mountains, the Providencia mine is the type locality of the cobalt-bearing mineral villamaninite, which occurs, together with other sulfides and sulfarsenides, in epithermal veins associated with Late Variscan faults (Fernández et al., 1985; Paniagua et al., 1988; Boni et al., 2000). Recent investigations reported cobalt concentrations up to 0.21%, but exploration has ceased at present (Riedel Resources, 2018). In the central Pyrenees the San Juan de Plan deposit was mined for cobalt between 1730 and 1936 (Fanlo et al., 2004). The polymetallic assemblage is hosted in Palaeozoic limestone, but the mineralisation age cannot be clearly defined and might be related both to Variscan and Alpine deformation events. In the Betic Cordillera Co-Cu-Ni mineralisation occurs in a quartz vein stockwork in dolomitic rocks at Cerro Minado (Huércal-Overa), possibly related to the Alpine orogeny. The mine was historically exploited mainly for cobalt and copper and is currently being reassessed (Valoriza Minería, 2020). Previous studies have classified the deposit as MVT on account of the carbonate host rocks and the nature of the fluids, but the presence of cobaltite and gersdorffite is unusual in most MVT deposits (Bertran-Oller et al., 2012).

5.7.4. *France*

The Vosges Mountains in north-east France are part of the Variscan Belt and comprise sedimentary and volcanic rocks of Ordovician to Carboniferous age The Vosges Mountains are closely related to the Schwarzwald (Black Forest) from which they are separated by the Upper Rhine Graben (Fig. 6) (Wickert et al., 1990; Franke, 2000). Post-Variscan polymetallic vein deposits are known at Sainte Marie Aux Mines (von Eller and Weil, 1962) and at Kruth (Fluck, 1972). Copper and lead were the main products in Sainte Marie Aux Mines, before nickel and cobalt extraction commenced in the 18th century. At Kruth high-grade cobalt veins were exploited in the 20th century.

Vein-type deposits containing various Ni-Co minerals also occur in the western Alps (Chermette and Termier, 1970; Maurel and Picot, 1973; Tuduri, 2001). However, cobalt was only recovered during the 19th century from the silver mine at Challanches, situated in the Belledonne crystalline massif about 20 km south-east of Grenoble (Chermette and Termier, 1970).

Several SEDEX deposits in the central Pyrenees are reported to host small quantities of Ni-Co sulfarsenides as well as Ge-, Ga-, Sn-, Ag- and Au-bearing minerals (Oudin et al., 1988; Cugerone et al., 2018) (Fig. 6). The cobalt-bearing minerals occur within post-sedimentary stratabound and vein-type mineralisation related to Variscan deformation and overprint the original synsedimentary Pb-Zn mineralisation (Cugerone et al., 2018). Despite the low cobalt content this metal was intermittently extracted at Pierrefitte, near Argelès-Gazost and from some other small deposits in the same district in the 18th century and ceased following the French Revolution. About 6 000 tonnes of cobalt pigment per year were produced at a nearby factory (Jorré, 1936).

Other minor occurrences of cobalt are found in the Massif Central and on Corsica, but these are not known to have been mined in the past (Pierrot and Sainfeld, 1961; FRAME, 2019).

5.7.5. *Italy*

In Italy cobalt is reported in the Alpine region of Piedmont in the north-west of the country, as well as on Sardinia (Fig. 6). In Piedmont there are seven abandoned mines that formerly worked magmatic deposits comprising Fe-Ni-Cu ores with subordinate cobalt in ultramafic layered intrusions and pipes (Ferrario et al., 1982; Sessa et al., 2017). These deposits are situated in the Ivrea-Verbano zone, exposed during the Alpine orogeny. Mineralisation is, however, considered to have formed during the Variscan orogeny, related to partial melting of lithospheric mantle (Locmelis et al., 2016; Sessa et al., 2017). Nickel, copper and cobalt were produced from the late 19th century up to the Second World War with cobalt production grades of up to 0.3%. Alligator Energy Ltd. is currently re-assessing the mines Campello Monti, La Balma, Alpe Laghetto, Bec d'Ovaga and Castello di Gavala, but no resource estimates are available at present (Alligator Energy Ltd., 2018). In south-west Sardinia cobalt is known in the Arburese vein system, situated close to the Late Variscan Arbus pluton. In this area Ni-Cu mineralisation predates the Pb-Zn-Ag veins of the Montevecchio district, historically one of the most important mineral resources in Italy (Moroni et al., 2019). Cobalt is recorded in at least four mines in the area and small quantities were sporadically mined during the early 19th century. However, lead, zinc and silver were always the main targets (GEMMA, 2019; Moroni et al., 2019).

5.7.6. *Germany and the Czech Republic*

Both Germany and the Czech Republic have been important past producers of cobalt, mainly from polymetallic vein deposits. Many different commodities have been extracted from these deposits, including silver, cobalt, copper, iron, nickel, bismuth, uranium and fluorine (Kissin, 1992). The Erzgebirge-Krušné Hory region, located along the border between the two countries to the north-west of the Bohemian massif, was an important producer of these commodities in the past (Fig. 6) (Hösel et al., 1997). The Ni-Co-As assemblage is associated with major faults that were reactivated during the post-Variscan and were mineralised during the Triassic to Jurassic (Hösel et al., 1997; Kroner and Romer, 2010). Several historic mines of this type are known with Jachymov in the Czech Republic and Schneeberg in Germany among the best-studied examples (Hösel et al., 1997; Baumann et al., 2000; Lipp and Flach, 2003; Ondrus et al., 2003). Schneeberg produced cobalt from 1573 up to the 1930s (Lipp and Flach, 2003). After the Second World War extraction from several mines was mainly focused on uranium, but rich Bi-Co-Ni ore was also extracted here (Hiller and Schuppan, 2008; Wismut GmbH, 2011). The Schlema-Alberoda mine produced 199 tonnes of cobalt metal up to 1978 with cobalt grades ranging from 0.51% to 3.78% (Hiller and Schuppan, 2008). Exploration is currently underway at Aue, located close to the Schneeberg workings (Vital Metals Ltd, 2018), and also at Eichigt (Lithium Australia NL, 2018) and at ENORA (SME AG, 2019). No resource estimates compliant with the CRIRSCO-reporting template have been published for these deposits, but analysis of hand specimens has yielded high cobalt values, up to 0.8% at Aue and 0.6% at Eichigt (Lithium Australia NL, 2018; Vital Metals Ltd, 2018). At ENORA a historic estimate indicated 15,000 tonnes of contained cobalt metal (SME AG, 2019).

Polymetallic Co-rich vein deposits related to Variscan structures are also found elsewhere in Germany: the Harz mountains south-west of Hannover; the Odenwald south of Frankfurt (Main); the Spessart east of Frankfurt (Main); the Rhenish massif in west Germany; and the Schwarzwald south-west of Stuttgart (Fig. 6) (Dill et al., 2008; Markl et al., 2016; Burisch et al., 2017). The Wittichen district in the Schwarzwald was an important cobalt and silver producer in the 18th century with extraction of about 125 tonnes of cobalt (Staude et al., 2012). At St. Andreasberg in the Harz Mountains cobalt was produced only for a short time due to low grades (Liessmann, 2010). The Siegerland district in the Rhenish Massif contains a few polymetallic vein deposits in which cobalt minerals such as carrollite-linnaeite have been reported (Wagner and Cook, 1999). Cobalt production at Junckernburg is estimated to have been approximately 1 358 tonnes between 1770 and 1847 (Hellmann, undated).

In the Czech Republic pre-Variscan stratiform pyritic VMS-type ores at Tisova, 20 km east of the German border, are currently being explored for cobalt, gold and copper (Fig. 6) (Hösel et al., 1997; 21C Metals, 2020). Initial drill intercepts have cobalt grades up to 0.9% (Auroch Minerals, 2018).

5.7.7. *Poland*

In addition to SSHC deposits various other cobalt-bearing deposit types are present in Poland (Fig. 6). The Sudety Mountains, situated along the border with the Czech Republic and Germany in south-east Poland, contain several polymetallic cobalt-bearing deposits similar to the nearby Erzgebirge-Krušné Hory mineralisation (Dill et al., 2008; Mochnacka et al., 2015; Szamalek et al., 2017). Cobalt is especially enriched at the Przecznica mine, where it was recovered from the end of the 18th century to the middle of the 19th century (Madziarz, 2013). Cobalt is hosted in sulfarsenides, such as cobaltite and safflorite, as part of a polymetallic assemblage that accompanies the tin-dominated ore. The same mineralisation is described from the nearby historic tin mines at Gierczyn and Krobica (Mochnacka et al., 2015). Other cobalt occurrences in the Sudety Mountains are Ni-Co laterite deposits near Skzlary that were previously exploited for nickel (Dublińska et al., 2000; Szamalek et al., 2017; FRAME, 2019). In north-east Poland two magmatic Fe-Ti-V deposits are known in the Suwałki mafic massif within Precambrian basement covered by one kilometre of Phanerozoic rocks (Morgan et al., 2000; Szamalek et al., 2017). In these deposits cobalt occurs in Ni-Co sulfides, such as pentlandite and linnaeite, which are associated with the dominant Fe-Ti oxide assemblage (Morgan et al., 2000). This area was explored in the 1970s for Ti and V, but was deemed uneconomic at that time due to the low metal concentrations present (Szamalek et al., 2017).

5.7.8. *The Carpathians in Romania and Slovakia*

Cobaltiferous ores in Romania are found mainly in the Southern Carpathians in the west of the country where they are associated with Alpine magmatism of Late Cretaceous age. Cobalt minerals such as cobaltpentlandite and carrollite occur in skarn deposits (e.g. at Băiţa Bihor) and in polymetallic veins related to large granitic intrusions (e.g. at Avram Iancu, Fig. 6 (Berza et al., 1998; Cook and Ciobanu, 2001). In Slovakia cobalt-bearing siderite-quartz-sulfide veins are reported in the Western Carpathians at several locations. (Fig. 6) These veins are hosted in the Variscan Germeric Unit, but both Variscan and Alpine processes are thought to have been involved in their formation (Radvanec et al., 2004; Kiefer et al., 2017). Exploration for cobalt, as well as nickel, copper and silver, is currently underway at the historic mine sites of Dobšiná and Kolba in the Western Carpathians. Dobšiná produced cobalt in the 19th century and new drilling has identified cobalt grades up to 1.92% (European Cobalt, 2019). A laterite deposit similar to those in the Balkans is described at Hodkovce in the Western Carpathians of Slovakia. The laterite profile developed on top of serpentinised peridotite and has an estimated 17 million tonnes of ore with a low cobalt grade of 0.016% (Baco et al., 2015).

5.7.9. *Alpine deposits in Austria and Switzerland*

In the eastern Alps in Austria diverse cobaltiferous vein deposits formed during the Alpine orogeny in the mining districts of Schladming (Zinkwand), Leogang and Schwaz-Brilegg (Fig. 6) (Paar and Chen, 1985; Pohl and Belocky, 1999; Robl et al., 2004; Weber et al., 2019). High cobalt grades supported cobalt production at Schladming and in the Leogang district intermittently from the 16th century up to 1959; exploration is currently underway in both areas (Weber et al., 2019). Sampling of waste dumps at Leogang identified cobalt concentrations up to 0.68%, but results of subsequent drilling have been disappointing (High Grade Metals, 2018). The polymetallic ores at Leogang are hosted in Upper Silesian to Upper Devonian carbonate rocks. Cobalt is reported to reside in Ni-sulfides such as gersdorffite and polydymite (Paar and Chen, 1985; Weber et al., 2019).

In Switzerland cobaltiferous vein deposits have been described at Kaltenberg, Pipji, Grand Praz, and Colliou Inferieur in the Penninic Alps (Fig. 6) (Kreissl et al., 2018; FGS, 2019). Historic cobalt production was recorded at Kaltenberg between 1864 and 1942 (FGS, 2019). Multiple mineralisation stages are recognised in these deposits with recent age data revealing hydrothermal events spanning more than 200 million years from the Middle Triassic to Early Miocene (Kreissl et al., 2018).

5.7.10. *Cyprus and Turkey*

The Troodos ophiolite complex in Cyprus was obducted during the Late Cretaceous, at about the same time that the ophiolite belts in the Balkans were emplaced. Mafic volcanic rocks of the ophiolite are host to important copper-rich VMS deposits (Galley et al., 2007). A recent exploration programme, known as the Treasure project, focussed on both base and precious metals in four separate prospects around the Troodos ophiolite complex in southern Cyprus (Fig. 5). Initial drilling intercepts at the Black Pine prospect, north of Limassol, identified cobalt grades up to 0.37% (BMG Resources Ltd., 2015). High cobalt values have also been reported in several other VMS deposits in Cyprus, in which cobalt is typically enriched in pyrite (up to 0.39%) and chalcopyrite (up to 0.13%) (Martin et al., 2019). Several Cyprus-type VMS deposits of similar age are also known in Turkey, but Aşıköy in the Kure district in the north of the country is the only one where cobalt has been documented (Fig. 5). Copper, gold and silver are currently extracted from Aşıköy which has an ore reserve of 11.23 million tonnes. Historic cobalt grades of 0.3% have been reported in the ore at Aşıköy and various cobalt minerals, such as linnaeite, have been described (Çakir, 1995; Yigit, 2009).

6. Discussion

6.1. Harmonised cobalt resource estimates

Classification of the cobalt-bearing deposits in Europe (Fig. 2, Table 4) shows that the majority of the cobalt tonnage (55.6%) is in the non-compliant historic estimates category (Fig. 2) (classes 334 and 344). These data show that most known cobalt resources are not well known geologically and require significant further evaluation to prove their commercial viability. It is important to note that mining companies that are already producing cobalt, or closely monitor cobalt in their nickel or copper resources, could relatively quickly turn measured (class 221) and indicated (class 222) resources into reserves (classes 111 and 112) and, therefore, convert potentially commercial quantities into commercial ones. Nevertheless, resources in advanced exploration projects (classes 221 and 222) might still need several years to prove economic viability, acquire permits and raise capital.

The largest share of cobalt resources (16.4%) in potentially commercial projects is in class 223 (inferred resources). These require a significant amount of additional investigation to prove feasibility. Another important point is that non-compliant historical estimates are available for a much larger number of deposits ($n = 109$) than resource estimates in the commercial ($n = 3$) and potentially commercial ($n = 14$) classes. This highlights that many more deposits occur in Europe for which cobalt resources could be present, but our knowledge of their potential is limited and consequently their future development is uncertain. In many cases these deposits are likely to be too small to be economic, although further investigations could lead to the identification of larger commercially viable resources. There are also 24 deposits with a combined compliant historic resource of 111 107 tonnes of cobalt. These have been thoroughly explored in the past and have a higher degree of confidence in the resource estimate than non-compliant historic estimates. However, their potential feasibility should to be reviewed according to current economic, regulatory, environmental and social conditions.

6.2. Implications from the UNFC classification

The UNFC classification framework is a useful tool for communicating resource estimates and their associated level of uncertainty (UNECE, 2019). It is designed to facilitate reliable comparison on national, regional and global scales and can be applied to many different commodities and deposit types. However, this flexibility can lead to a degree of subjectivity in the data interpretation and classification process especially where data uncertainty is high. In the case of by-product metals, such as cobalt, the UNFC classification can be particularly problematic because resource and reserve data are often available only for the main extractable commodities in a deposit (e.g. copper and nickel) and not for the by-product (e.g. cobalt). Where a cobalt grade is reported it is commonly not updated as exploration and development proceed because the focus is generally on the main product(s) rather than any by-products. In other cases, a total cobalt tonnage may be given for resources and reserves without any subdivision into the reserve and resource sub-classes, thus making assessment of their commercial potential difficult. More reliable estimates of Europe's resource potential could be determined if mining and exploration companies consistently reported data on potential by-products. Revisions to existing reporting templates and classification systems are also required to enable the classification of mineral systems (e.g. polymetallic deposits), rather than of individual commodities.

Although the UNFC classification has not been widely adopted in Europe, the European Commission is keen to promote its use to provide harmonised resource estimates for the European Union and facilitate long-term sustainable resource management. Further adjustments to the UNFC scheme might be necessary to ensure consistent application by government and industry in all sectors.

6.3. Known cobalt resources and prospective areas in Europe

This study shows that 104 cobalt-rich deposits in Europe are currently being explored, of which 79 are located in Finland, Norway and Sweden. The Fennoscandian Shield and the Caledonian Belt in these countries are high-priority exploration terrains for a variety of cobalt-bearing deposit types. Komatiitic and mafic–ultramafic magmatic Ni-Cu-Co (PGE) deposits are widely known in association with early rifting in the Fennoscandian Shield and synorogenic magmatism. The largest cobalt endowments, in the Kevitsa and Sakatti deposits in northern Finland, are comparable in size with those in magmatic nickel-copper sulfide deposits elsewhere in the world. Rasilainen et al. (2012) used the three-part quantitative assessment method developed by the U. S. Geological Survey (Singer, 1993; Cunningham et al., 2008) to calculate the probability of identifying undiscovered resources in various cobalt-bearing deposits in geologically favourable areas in Finland. Results indicate that there is considerable potential for new discoveries of synorogenic magmatic deposits and komatiite-hosted deposits in Finland. In contrast the potential for the discovery of additional Outokumpu-type deposits is considered to be small (Rasilainen et al., 2012; New Boliden, 2019).

A major development in Finland is the black shale-hosted Sotkamo (Talvivaara) deposit in the Kainuu Schist Belt north of Outokumpu. This deposit currently has the largest cobalt resource and reserve in Europe. Bioleaching technology is used to process the low-grade ore at the mine and simultaneously provides environmental benefits at the operation (Riekkola-Vanhanen, 2013; Pakostova et al., 2017). The occurrence of similar, unexploited, cobaltiferous black shale deposits, located near the Sotkamo mine, indicates further cobalt resource potential in the Kainuu Schist Belt.

In addition, the Svecofennian, Sveconorwegian and the Caledonian orogenies in Fennoscandia resulted in the formation of several other deposit types in which cobalt is locally enriched. These include chiefly metasediment- and felsic metavolcanic-hosted Co-Cu-Au, VMS, skarn and polymetallic vein deposits. The Kuusamo Belt in north-east Finland includes several metasediment-hosted Co-Cu-Au deposits and has significant potential to host important cobalt resources of this type (Rasilainen et al., 2020).

In Sweden the Geological Survey (SGU) is currently focussing its investigations on the Bergslagen ore province, where cobalt was extracted in the 18th and 19th centuries (Hallberg and Reginiussen, 2019). In Norway the Kongsberg complex in the south was also an important cobalt producer in the past and exploration companies have shown interest in redeveloping mining here in recent years (specifically at the Skuterud mine; Berkut Minerals, 2019). In addition, VMS deposits in the central part of Norway also have cobalt potential but little is known about them. Cyprus-type deposits such as Løkken appear to be the most prospective for cobalt.

The Kupferschiefer deposits in Poland and Germany constitutes the overall largest copper resource known in Europe. These deposits have many similarities with those of the Central African Copperbelt, which contains by far the largest terrestrial cobalt resources in the world (Taylor et al., 2013; Slack et al., 2017). However, the cobalt grade is much lower in the Kupferschiefer deposits than in the DRC and Zambia and cobalt extraction is, therefore, uneconomic at present. New processing technologies could enable cobalt extraction from these deposits in the future, although further research is required to rigorously assess their cobalt resource potential (Pazik et al., 2016).

Laterite deposits in the Balkans and Turkey have considerable potential as future resources of cobalt. There are 27 deposits with known cobalt grades and tonnages, with several containing more than 10 000 tonnes of contained cobalt metal in Albania, Greece, North Macedonia, Serbia and Turkey. The largest deposit by far is Mokra Gora in Serbia with 1 000 million tonnes of ore. There is currently no production of cobalt from laterite deposits included in this study, but a sulphuric acid plant for the production of cobalt and nickel sulfate is planned to be operational at the Gördes mine in Turkey, soon (Zorlu Holding, 2018). Elsewhere nickeliferous laterite ores are processed in smelters to produce ferronickel meaning that cobalt cannot be recovered separately (Crundwell et al., 2011; Herrington et al., 2016). High-pressure acid-leaching is widely used outside Europe to extract cobalt from the limonitic ore in laterites and the process is also employed at Gördes. Experiments on lateritic ores from Greece have shown that cobalt and nickel can be separately recovered from low-grade saprolitic and limonitic ores using hydrometallurgical processes (Komnitsas et al., 2018, 2019). A shift to these technologies could, therefore, enable the Balkan region to become an important producer of cobalt in the future.

Cobalt-bearing deposits of other types are also known in Europe. Polymetallic cobalt-bearing vein deposits occur in several countries and have historically been of interest because of their high cobalt grades, commonly accompanied by enrichment in Ag, Bi, Ni, Cu and U. However, many of these deposits are small in size and are less likely to be of current economic interest because of the high cost of developing a new mine that might operate for only a short time period. Furthermore, the discontinuous ore distribution in some polymetallic vein deposits would make mining relatively expensive (Kissin, 1992). However, the use of portable and scalable mining and ore processing facilities, as well as the drive towards more sustainable and locally sourced raw materials, might improve the economic viability of small-scale mining in the future (Moore, 2018).

6.4. Outlook

Although cobalt is known to occur at many localities across Europe in a wide range of geological environments, considerable additional work is required before we have a reliable and comprehensive inventory of Europe's cobalt resources. There is an overarching need for better baseline geoscience datasets, including detailed modern geological maps and allied regional geophysical and geochemical surveys. Such fundamental data should be supplemented by new research on the processes responsible for the mobilisation and concentration of cobalt in the Earth's crust as this has largely been neglected in the past in favour of research into the major industrial metals and gold. Together achieving these goals will help to identify where and how to explore for cobalt and how to extract it efficiently from the minerals in which it occurs. Such data would also facilitate the estimation of potential for undiscovered cobalt resources in a range of deposit types.

This approach has been adopted in Finland, where the Geological Survey (GTK), in conjunction with industry and academia, and funded by the government, is undertaking assessments of the potential for the discovery of additional mineral resources. The government of Finland is also strongly supportive of the development of EV battery factories in Finland with the aim of becoming a key supplier to Europe's transport sector in the future (Finnish Minerals Group, 2020). A similar approach should be more widely adopted in Europe, with financial support provided by governments where appropriate. In addition to supporting research into cobalt metallogeny, mineralogy, ore processing and refining, governments should actively promote mineral exploration for cobalt. This may entail reconnaissance exploration and drilling by geological survey organisations at localities already known to have some cobalt mineralisation or over new prospective targets. Financial incentives for companies in the form of tax breaks or funding support for exploration activities focussed on cobalt should be considered. Such exploration incentive schemes have enjoyed considerable success in the past in promoting exploration activity in Canada and Australia (Khindanova, 2012; ACIL Allen Consulting, 2015). In addition, further research is required to improve the recovery of cobalt in processing and refining. The EC Horizon 2020 programme includes European research in this field (CROCoDILE, 2020; Natural History Museum, 2020). Such measures are aimed at alleviating concerns over the security of supply of critical metals such as cobalt from oversea sources. However, it is important to note that these activities are strategic in nature and may take many years to deliver tangible benefits. In addition to the continuing need for research, it may take several years, and often more than a decade, from the discovery of a new deposit to prove economic viability, acquire the necessary permits and raise funds to develop a mine.

The regular collection of mineral statistics to an agreed standard throughout Europe would assist in the compilation of a complete and reliable estimate of cobalt resources. Current reporting standards for resources in European countries, where they exist, vary considerably and are commonly difficult to compare. Widely applied harmonised resource classification systems such as the UNFC code can thus help to provide reliable estimates of metal resources and hence can be an important tool for policy makers.

Although the focus of this study is on cobalt deposits in the Earth's crust, a complete inventory of resources should include both primary and secondary cobalt sources. With Europe currently developing a battery manufacturing capacity alongside its well-established automotive sector there are increasing opportunities for creating circular business models to secure access to end-of-life batteries and thus to valuable supplementary sources of cobalt.

7. Conclusions

This study highlights the presence of substantial cobalt resources distributed widely across Europe in a variety of deposit types. The greatest cobalt resource potential lies in laterite deposits in the Balkans and Turkey and in magmatic and black shale-hosted deposits in Fennoscandia. Further investigations of cobalt in the SSHC deposits of the Kupferschiefer basin and in small, mainly polymetallic, deposits in central and northern Europe could add to the cobalt resource base.

A considerable research effort is required to enhance our understanding of the origin, distribution and abundance of cobalt in these deposits, both to guide exploration and to optimise the recovery of cobalt from the ores.

The data collected in this study has for the first time allowed the classification of Europe's cobalt resources using the UNFC system. The largest part of the known resources resides in non-compliant historic estimates. However, considerable investment will be required to prove the economic viability of these deposits. Improved mineral governance is also required to facilitate access to, and ensure sustainable management of Europe's indigenous cobalt resources.

The resource inventory compiled in this study does not fully reflect the cobalt resource potential of Europe because data are unavailable for several countries and reporting standards are difficult to compare. However, given increased research into cobalt metallogeny and extractive metallurgy, together with greater focus on cobalt exploration, there is considerable potential for the identification of additional resources in Europe.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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