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A review of nickel mineralisation and ore potential in the Arthrath intrusion, Aberdeenshire.

Economic Minerals Programme

Commissioned Report CR/07/146

BRITISH GEOLOGICAL SURVEY

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Foreword

This report has been prepared by the British Geological Survey (BGS) on behalf of Metallum Resources plc. It describes the results of a desk-study reviewing existing information on the Arthrath nickel-copper prospect in Aberdeenshire. It also comments on the potential for the discovery of additional mineralisation in the area and provides recommendations for further work designed to test this potential.

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Syn- to post-orogenic mafic-ultramafic intrusions of Ordovician age underlie extensive areas of the Caledonide belt in north-east Scotland. Scientific studies over the last forty years by Aberdeen University and the British Geological Survey (BGS) have revealed a complex assemblage of cumulate and other rock types in these bodies, locally altered and disrupted by late, high-temperature shearing. In detail the geology of most of these intrusions remains poorly known on account of the thick till deposits that cover most of the region.

Significant magmatic nickel-copper sulphide mineralisation was discovered at two localities in these intrusions by Exploration Ventures Ltd (EVL) during a major exploration programme conducted between 1968 and 1973. Around the farms of Littlemill and Auchencrieve on the flank of the Knock intrusion EVL outlined a small deposit that has been intensely disrupted by shearing. At the second prospect, located in the Arthrath intrusion close to Ellon, disseminated and net-textured magmatic nickel-copper sulphide mineralisation was identified in five zones over a strike length of more than four kilometres. Anomalous concentrations of platinum-group elements (PGE) and cobalt are found locally in these zones. At Arthrath investigations by EVL and later workers have indicated that there has been much less tectonic disruption than in the Knock intrusion with the consequent preservation of thick intervals, locally exceeding 100 metres, of sulphide mineralisation.

Review of existing data in the light of deposit models for magmatic nickel-copper sulphide deposits worldwide suggests that there is good potential for the discovery of economic mineralisation of this type in the Arthrath intrusion. Further investigations are recommended to evaluate the potential in two settings in this body. First, given the limited drilling carried out to date and the lack of clear understanding of the controls on the known mineralisation, additional work is required to elucidate the lateral and vertical continuity of mineralisation identified by EVL. The second target is located in the broader area at the junction between the Arthrath intrusion and the larger Arnage mass to the west where investigations should be carried out to test the application of the conceptual model developed for the world-class Voisey's Bay nickel-copper-cobalt deposit in Canada.

The first stage of a future exploration programme should involve a thorough review by appropriate experts of the results of all previous work in the area. This should be followed by field investigations, including both geochemical and ground geophysical surveys and drilling. It is important that the programme at Arthrath take into account the results of work carried out in other parts of the region, such as Huntly-Knock, where the geology and mineralisation controls are better understood. Drill targets should be identified on the basis of the results of previous work, supplemented by new overburden/soil geochemistry and ground geophysical surveys (magnetic, electromagnetic and gravity). In order to acquire adequate data to identify an economic resource compliant with international reporting standards it is recommended that a diamond drilling programme of at least 15 boreholes be carried out in the most prospective zone identified from previous work and new surface investigations.

2 Introduction

There is a long history of geological investigation of the basic igneous intrusions in north-east Scotland. First mapped in detail in the nineteenth and early twentieth centuries by the Geological Survey of Great Britain, subsequent academic studies, chiefly by researchers at Aberdeen University and at the British Geological Survey (BGS), have significantly enhanced our knowledge of these bodies and in particular have highlighted their complexity. Significant magmatic nickel-copper mineralisation was first recognised in these intrusions as a result of major exploration programmes carried out by Exploration Ventures Limited (EVL) between 1968 and 1973. EVL focused their activities in two main areas: the Littlemill-Auchencrieve zone on the flank of the Knock intrusion near the town of Huntly in the west of the region; and the Arthrath area, located near the town of Ellon in the eastern part of the region (Figure 1).

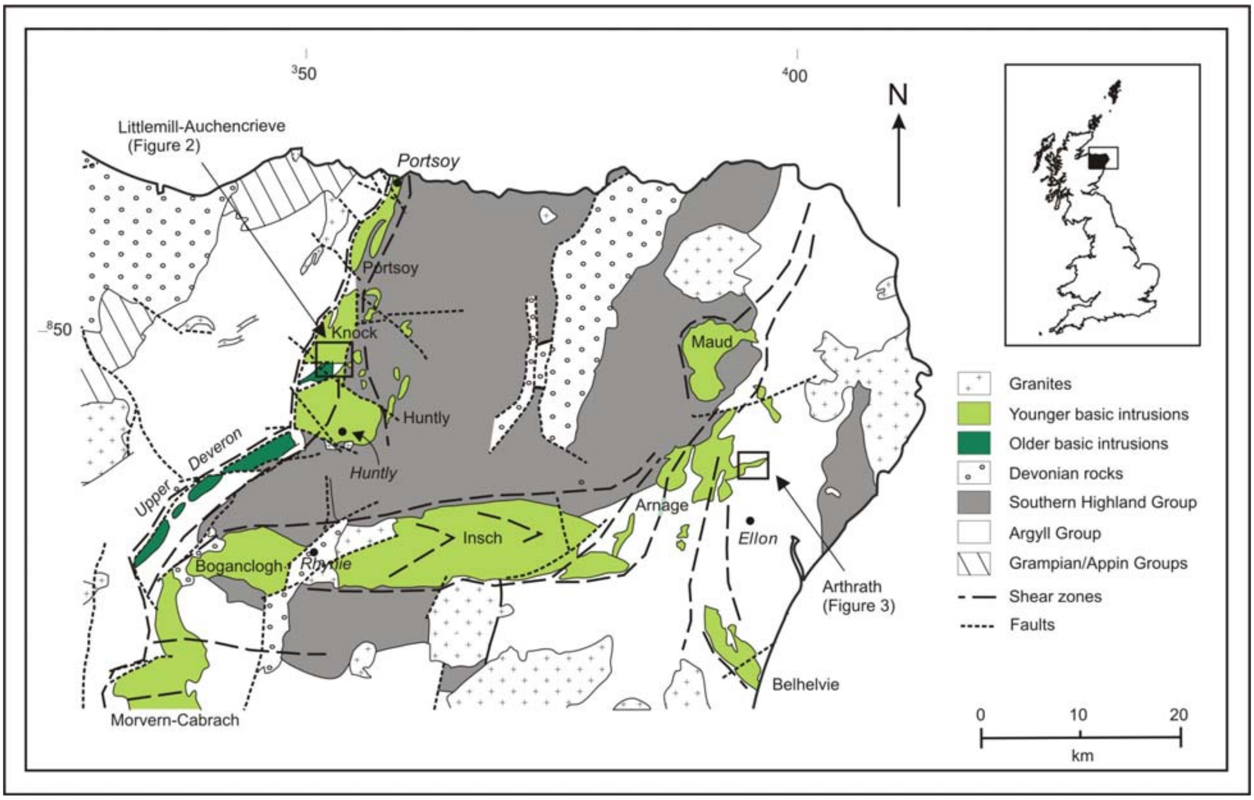

Figure 1 The geology of north-east Scotland showing the locations of the Ni-Cu prospects at Arthrath and Littlemill-Auchencrieve

This report first summarises current knowledge of the geology of the Huntly-Knock intrusions and the magmatic nickel-copper mineralisation at Littlemill-Auchencrieve. These are the best-known areas in the region and provided an important benchmark against which to compare and contrast the much less well-known Arthrath area. The regional and local geological settings are discussed in order to provide essential background to understanding the results of the exploration activities in the Arthrath area. The report also describes academic studies of the nickel-copper-platinum-group element (PGE) mineralisation carried out in the last decade by Aberdeen University and the British Geological Survey working mostly with data and sample materials derived from the EVL programme.

On the basis of this information, and in the light of current knowledge of magmatic nickel-copper deposits worldwide, the potential for the discovery of additional mineralisation of this type at Arthrath is discussed. A programme of further work designed to test this potential is outlined.

The results of drilling carried out at Arthrath by Alba Mineral Resources plc during 2005 are discussed briefly. The subsequent exploration programme carried out by Alba and its partners during 2006 is not discussed as little information about this work is in the public domain.

3 Regional geology

3.1 GEOLOGY OF NORTH-EAST SCOTLAND

North-east Scotland lies within the Grampian Highlands which comprise largely the eroded root zone of the Caledonian mountain belt (the Caledonides) which developed in late Precambrian to early Palaeozoic times and now extends from the east coast of North America to Scandinavia and Greenland. Late Precambrian metamorphosed sedimentary rocks of the Dalradian Supergroup, and a wide variety of igneous rocks intruded into them, form most of the Grampian Highlands. Clastic sedimentary rocks and associated lavas of late Silurian and Devonian age outcrop widely in several small basins in north-east Scotland. Devonian sedimentary rocks along the southern coast of the Moray Firth represent the southern margin of the major continental Orcadian Basin. The Grampian Highlands are bordered by major tectonic dislocations, the Highland Boundary Fault to the south and the Great Glen Fault to the north.

The Dalradian metasedimentary rocks comprise thick sequences of mainly shallow-marine origin. The lower part (Appin Group) of the Dalradian Supergroup consists of quartzite-shale-limestone sequences of great lateral continuity. These pass up into the Argyll Group in which deposition became more restricted to relatively small fault-bounded basins with increasing influence of turbidite deposition and the extrusion of basic volcanic rocks in its upper parts. The succeeding Southern Highland Group is dominated by greywacke sandstone and siltstone sequences, with locally extensive basic volcanic rocks in some areas.

The structure of the Grampian Highlands is complex and not completely understood. Early recumbent nappe folding, directed towards the north-west is dominant, although others facing south-east are also recognised. The nappe folds were subsequently deformed by at least two further episodes of folding and faulting. In general metamorphic grade decreases from upper amphibolite facies in the north-west to greenschist facies in the south-east. This general pattern is disrupted in the north-east Highlands where there is extensive development of migmatite in the Argyll Group rocks of Angus and southern Aberdeenshire. In northern Aberdeenshire there are low pressure-high temperature andalusite- and sillimanite-bearing assemblages, probably related to high heat flow produced by the intrusion of large volumes of intrusive igneous rocks.

Magmatic activity reached its peak during and after the late stages of the Caledonian deformation and metamorphism. During the Ordovician major layered basic masses and granites were emplaced, followed in the late Silurian and early Devonian by large granitic plutons and associated volcanic rocks and dyke swarms. Two suites of minor intrusions are also found within the Grampian Highlands: (i) late Carboniferous to early Permian thick dykes of quartz-dolerite are widespread, including in Aberdeenshire; and (ii) thin dykes and small vents of lamprophyre occur in the South-west and Central Highlands. In the south-western Highlands there are several basaltic dyke swarms associated with the Palaeogene (Tertiary) volcanic province.

During the Quaternary it is probable that an ice-cap was centred on the Northern Highlands and the South-west Highlands during several glacial episodes. Glacial deposits, including tills, and fluvioglacial deposits relate mainly to the last glaciation (the Devensian, which culminated about

18 000 BP). Over most lowland areas, including much of Aberdeenshire, a till blanket, up to 35 m thick, obscures the bedrock. The till comprises a mixture of boulders, clays, sands and gravels of both local and exotic origin.

3.2 MAFIC-ULTRAMAFIC ROCKS IN NORTH-EAST SCOTLAND

Two classes of mafic-ultramafic intrusions are widespread in north-east Scotland (Read, 1919, 1923): an 'Older' group which were intruded prior to the Caledonian regional deformation and metamorphism; and a 'Younger' group which post-dated these events. The 'Older' rocks include ultramafic, mafic and felsic lithologies, generally highly deformed and pervasively metamorphosed. The 'Younger' group includes a similar range of compositions but is dominated by the 'Younger Basic' rocks which comprise several major intrusions including the Huntly, Knock, Insch, Belhelvie, Boganclogh, Morvern-Cabrach, Maud, Haddo, Arnage and Arthrath bodies (Figure 1).

The 'Younger Basic' intrusions are believed to represent various sheet-like laccolithic intrusions that were emplaced at about the same stratigraphical level into Neoproterozoic metasedimentary rocks of the Dalradian Supergroup near the peak of regional metamorphism (Buchan type, high T, low P) around 470 Ma ago (Dempster et al., 2002). Although they post-date the regional deformation they have undergone local high-temperature deformation along major shear zones (Ashcroft et al., 1984). They are interpreted as representing a suite of sheet-like laccolithic intrusions derived from a high alumina tholeiite parent magma (Clarke and Wadsworth, 1970). They comprise a wide range of mafic and ultramafic lithologies of cumulate and non-cumulate origin, although due to the widespread superficial cover most of these intrusions are poorly known in detail. Cumulate rocks are best developed in the Insch, Huntly, Belhelvie and Knock intrusions where they generally exhibit a simple history of texture development, with deformation restricted to shear zones. On the basis of detailed petrological studies, chiefly of the Insch intrusion, a zonal sequence of cumulate rocks has been identified. This comprises Lower, Middle and Upper cumulate zones (Wadsworth 1970) which are used as a reference point for comparison between individual intrusions. Each zone or subzone is characterised by the appearance or disappearance of various cumulus phases. The progressive fractionation of magma is evident in the gradual passage from ultramafic to mafic and felsic compositions, and also by the cryptic variation of cumulus mineral phases from one zone to the next. The most common sequence for the crystallisation of cumulus minerals in the 'Younger Basics' is: olivine, olivine-plagioclase, olivine-plagioclase-clinopyroxene-orthopyroxene, plagioclase-orthopyroxene-clinopyroxene and olvine-plagioclase-orthopyroxene-clinopyroxene. Local divergence from this sequence occurs, notably in complex contact zones at Knock and Arthrath where orthopyroxene is unusually abundant (Fletcher, 1989).

A range of modified cumulate lithologies is also widely recognised, especially in proximity to shear zones. These rocks are sometimes referred to as granular gabbros as they have been recrystallised to finer grained anhedral granular textures. Schistose fabrics are also commonly developed.

Most of the 'Younger' syntectonic intrusions also include various contaminated and xenolithic igneous rocks which owe their origin to partial or complete assimilation of rocks of sedimentary origin. Contaminated gabbros are mainly orthopyroxene-bearing rocks, including orthopyroxene-gabbros and norites with subordinate biotite, amphibole and garnet, and quartz-biotite norites, commonly associated with cordierite norites. Xenolithic gabbros are highly contaminated heterogeneous rocks, closely associated with other varieties of contaminated rocks and granular gabbros, forming either irregular patches or discordant dyke-like bodies. They contain locally abundant biotite and garnet, together with variable amounts of amphibole, orthopyroxene, cordierite, quartz, sillimanite, spinel, graphite, sulphides and apatite. The xenoliths are most commonly composed of pelitic, semipelitic, quartzitic and calc-silicate lithologies. In some areas, notably in the Knock intrusion, rafts of metasediment with dimensions exceeding 100 m have been identified (Fletcher and Rice, 1989). Elsewhere available evidence indicates a complex interleaving of cumulate rocks, contaminated and xenolithic gabbros and metasedimentary rocks. This may result from an original complex intrusive geometry modified by contemporaneous high-temperature shearing and assimilation of metasedimentary rocks in marginal or roof-zone settings.

The Haddo House and Arnage intrusions comprise mainly quartz-biotite-norites with subordinate olivine norite showing granular textures. They are closely associated with cordierite-bearing xenolithic rocks which include xenoliths of Dalradian quartzite, psammite, semi-pelite and pelite. Read (1935) considered the cordierite-bearing rocks to be produced by large-scale contamination of the basic magma by the assimilation of Dalradian country rocks. Gribble (1967, 1968), however, rejected this hypothesis in favour of an origin for the xenolithic rocks by partial melting of the Dalradian metasediments.

Metamorphic aureoles are developed along the margins of some of the intrusions, but many are incomplete e.g. along the southern margin of the Insch intrusion and the western margin of the Huntly intrusion the aureoles have been removed by intense shearing. Elsewhere hornfels-like rocks occur in shear-bounded slices distant from the nearest outcrops of basic rocks.

Although the 'Younger Basic' intrusions post-date the earliest regional deformation their relationship to the later deformation events and the (Buchan) metamorphic peak remains unclear (Dempster et al., 2002). The 'Younger Basic' intrusions are part of the short-lived Grampian orogenic episode (~ 480–465 Ma) that is post-dated by isostatic uplift (465–435 Ma) and the 'main' phase of Caledonian orogenesis in Scotland, including granitoid batholith emplacement, ending at ~395 Ma (review of Oliver 2001). The tectonic setting of the Grampian orogenic episode remains unclear: for example, the subduction of a back-arc basin (Highland Border back-arc) may have occurred, or, the Grampian episode may be related to the collision of the Midland Valley Arc with Laurentia, due to the subduction of the northern Iapetus Ocean (Oliver 2001). Either way, in relation to the 'Younger Basic' magmatism, both models imply that partial melting of the upper mantle was subduction-related and this is broadly consistent with the low high-field-strength element to light-rare-earth element ratios found in these rocks (Thompson et al., 1984).

Pre-tectonic 'Older Basic' rocks outcrop in two main districts in north-east Scotland (Styles, 1994). They occur as discontinuous concordant sheets and pods in an elongate belt, termed the Portsoy Lineament, running in a south-south-westerly direction from the coast at Portsoy over a distance exceeding 30 km. These rocks are referred to as the Succoth-Brown Hill (S-BH) type, after the largest intrusion located in the upper Deveron valley to the south-west of Huntly (Gunn et al., 1996). The S-BH group is typified by clinopyroxenites and olivine-clinopyroxenites, locally in tectonic contact with metagabbros. They have a distinctive mineral chemistry, very different from the olivine cumulates of the 'Younger Basics'. All rock types in the S-BH group have undergone multiple phases of recrystallisation and alteration with several stages of deformation evident in outcrop and thin section and with primary magmatic textures rarely preserved. The other group, known as the harzburgite type, comprises small bodies of ultramafic rocks located mainly peripheral to the Insch and Boganclogh intrusions (Styles, 1994 and 1999). They are also found in smaller bodies along the Portsoy Lineament. They comprise harzburgites and dunites, with subordinate lherzolite, which exhibit relatively simple textures, extensive serpentinisation and little late deformation. They are not associated with metagabbros, rather they occur in sharp contact with little deformed 'Younger' gabbroic rocks and metasediments.

Ashcroft et al. (1984) identified a suite of major shear zones in this region which were shown to be long-lived structures, separating an autochthonous Dalradian sequence in the north-east Grampians from the main allochthonous tract in the central and western Highlands to the south and west. Extensive igneous activity has occurred along these shear zones. In particular the broad shear belt which runs southwards from Portsoy, regionally termed the Portsoy Lineament (Fettes et al., 1986), was, according to Read (1919), the principal site for the 'Older Basic' intrusions. It has also been the locus of considerable post-'Younger Basic' deformation. Similar deformation has been widely recognised elsewhere within shear zones bounding and transecting 'Younger Basic' intrusions - notably at Huntly (Munro and Gallagher 1984), at Insch (Ashcroft and Munro 1978; Munro 1986) and at Belhelvie (Boyd and Munro 1978). Alteration and recrystallisation accompanying deformation in these zones have produced structural and mineralogical features similar to those in the 'Older Basic' bodies. A simple distinction between the two groups of intrusions therefore breaks down in some areas and some workers have cast doubt on the 'Older' status of some of the more deformed and sheared intrusive bodies e.g. Fettes and Munro (1989).

4 Review of exploration history and scientific studies

4.1 COMMERCIAL EXPLORATION

Prompted by the booming nickel market and the discovery of economic nickel deposits in Western Australia, Rio Tinto Zinc (RTZ) and Consolidated Goldfields (CGF) initiated, in 1967 and 1968 respectively, independent programmes of exploration for nickel mineralisation in the layered intrusive complexes of north-east Scotland. Subsequently in July 1969 RTZ and CGF formed a joint venture company, Exploration Ventures Limited (EVL), to undertake coordinated exploration throughout the region. CGF carried out investigations to the west of national grid line 375000 and to the north of the river Dee; RTZ worked to the east of this line. The investigations undertaken by EVL in the western sector are described in an excellent summary report, comprising several volumes of text and figures, compiled by Wilks (1974). A copy of this document is housed in the BGS archives at Murchison House, Edinburgh. Numerous additional reports and maps relating to EVL work are also available on open-file at BGS, but the records are far from complete and it is often difficult to evaluate in detail exactly what was done and the results obtained. The work undertaken by RTZ over the eastern part of the region is much less well documented than that carried out by CGF in the western sector. Our knowledge of RTZ’s activities is based chiefly on two compilations, a short paper by Rice (1975) and an unpublished manuscript for a paper by Wilks and Smith (1976) that is held in the BGS archives.

Much of the drillcore from the EVL investigations was discarded when the programme in north-east Scotland ended in 1973. However, various short sections, principally of mineralised core, were lodged with Aberdeen University and a few complete boreholes, including some from Ruthven, Brodiesord, Belhelvie and Arthrath, were donated to BGS. In recent years BGS has acquired all the core previously held by Aberdeen University.

In the late 1970s Amax Exploration UK Ltd followed up the EVL Cu-Ni exploration programme with the full cooperation of EVL. Unfortunately records of the work carried out by Amax are sparse. They undertook an extensive programme of shallow drilling over the Huntly-Knock-Portsoy intrusions in 1976 and 1977 and in the Arthrath area between 1976 and 1979. The author of this report is familiar with the Amax work in the Knock intrusion which BGS reviewed during its mapping programme in the mid-1980s. It should be pointed out that, in the Knock area at least, there was little quality control of the drilling programme. It is believed that geological observations were in some instances made by drillers rather than by geologists. Doubt must also be cast on the quality of the geochemical samples collected during these programmes. Amax also conducted diamond drilling in the Belhelvie intrusion (5 boreholes) and at Arthrath (1 borehole).

EVL conducted extensive programmes of geochemical and geophysical survey together with associated float and outcrop mapping. Approximately 13 400 stream sediment and 103 000 soil samples were collected in the region between 1968 and 1973. Most samples were analysed for Cu and Ni only, although in some areas Mo, Pb and Zn were also determined. Platinum-group element (PGE) determinations were also made on a small number of rock samples.

At an early stage in the exploration Cu and Ni anomalies were identified in the Huntly-Knock, Belhelvie, Bourtie and Arthrath-Dudwick areas. Checking of reports of metal toxicity reported by the Macaulay Institute of Soil Research confirmed the presence of anomalous values of Cu and Ni in soil at Arthrath and Belhelvie. Orientation surveys in these areas indicated that B-horizon soils, generally collected at depths of 20–50 cm, provided the highest metal values. These were adopted as the standard sample type throughout the area, both to follow up anomalous results and also to fill in where drainage cover was inadequate. Combined induced polarisation (IP), magnetic and resistivity surveys were used to assess the geochemical anomalies, initially at Arthrath, and subsequently elsewhere such as at Huntly-Knock and Belhelvie.

EVL also carried out two airborne geophysical surveys over the region: (i) a fixed-wing airborne magnetic survey conducted by Fairey Surveys Ltd comprising 7875 line-km flown at 402 m line spacing with a terrain clearance of 152 m. and (ii) a helicopter-borne combined magnetic and electromagnetic survey flown by Barringer Research comprising 5538 line-km flown along lines spaced at 322 m with a terrain clearance of 61 m. BGS has digitised the results of these surveys using contour plots produced by EVL. Despite strenuous efforts by BGS in the late 1980s, the original data collected by EVL have not been traced.

4.1.1 Littlemill – Auchencrieve, Knock

Systematic exploration of the Huntly and Knock intrusions commenced in late 1969 leading to the discovery of several prospective zones. A total of 59 boreholes amounting to 9224 m was drilled by EVL, ending in May 1973. The most encouraging results were derived from the south-eastern flank of the Knock intrusion on the farms of Littlemill and Auchencrieve, near the village of Ruthven, where sub-massive to massive Ni-Cu sulphides were discovered (Figure 2). This programme outlined a resource of 3 million tonnes grading 0.52% Ni and 0.27% Cu in two sub-parallel, near conformable zones dipping towards the north-west.

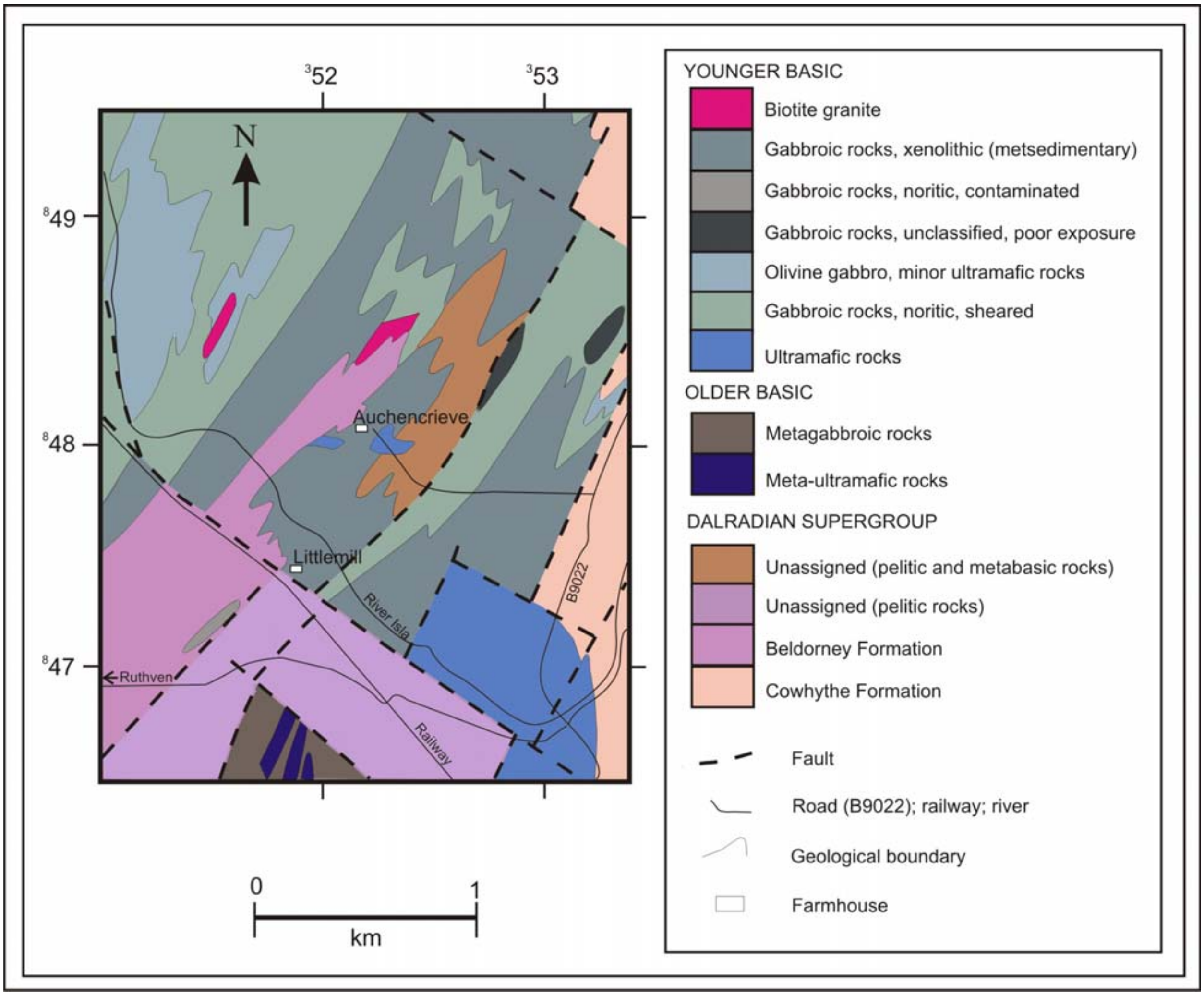

Figure 2 The geology of the south-east corner of the Knock intrusion around the farms of Littlemill and Auchencrieve

The Knock intrusion underlies approximately 25 km^2 to the north of the Huntly intrusion. Natural exposure is sparse and most information is derived from drilling and ground magnetic surveys conducted by BGS, Aberdeen University and EVL. These studies have allowed a more detailed understanding of the geology and mineralisation to be established than at Arthrath. The following account summarises the main points and serves to highlight the complexities and the remaining uncertainties.

The Knock mass comprises a complex sequence of interlayered, discontinuous, steeply dipping lenses and sheets of cumulates, modified cumulates, contaminated rocks and metasedimentary rocks. The external boundaries of the intrusion are nowhere exposed but evidence from boreholes indicates that the contacts are complex and commonly sheared. In addition, evidence from numerous boreholes indicates the presence of sporadic shearing throughout the intrusion, but it appears to be most intense in the south-eastern sector.

Cumulate rocks in the Knock intrusion comprise mainly troctolites and norites. Norite and other orthopyroxene cumulates underlie extensive areas. In the south-eastern part of the intrusion a narrower belt of orthopyroxene-bearing cumulates comprising at least five layered units, each 10–25 m in thickness can be traced for about two kilometres. These units comprise orthopyroxenite, norite and clinopyroxene-norite with good cumulate textures.

Granular gabbros and norites occur close to the western margin of the Knock body. These mainly fine-grained rocks are partly or wholly recrystallised and amphibolitised. They are heterogeneous, commonly schistose and locally mylonitic. Remnants of primary igneous textures are sporadically observed. Extensive bodies of contaminated and xenolithic gabbroic rocks are found along the eastern and northern margin of the intrusion. In these zones it is suggested that there is a heterogeneous transition produced by a sheeted intrusive mechanism, modified by later shear deformation, is proposed.

Narrow bands at least one kilometre in length comprising predominantly metasedimentary rock have been mapped within the main Knock body in three areas. They comprise predominantly pelitic and semipelitic schist and gneiss, commonly hornfelsed. They are inferred to have a lenticular form as correlation between adjacent boreholes is not possible. They are intercalated with variable, but subordinate, amounts of xenolithic, contaminated and cumulate gabbros. Locally, rafts of metasediment with maximum dimension exceeding 100 m have been identified from boreholes in the southern part of the Knock intrusion.

In the Knock intrusion nickel-copper mineralisation occurs in two areas, on the farms of Littlemill and Auchencrieve, in the structurally complex south-eastern marginal zone of the intrusion. The mineralisation is hosted by a complex sequence of olivine cumulates, commonly xenolithic and graphitic, noritic cumulates, contaminated gabbros and metasedimentary rocks. The sulphide zone which averages about 10 m in thickness comprises a roughly conformable unit of disseminated, sub-massive and massive sulphides, extending over the whole length of the drilled area, 450 m. The basic rocks, metasediments and the mineralisation strike between north-east and east-north-east and dip northwards at between 50° and 70°. Sub-massive and massive units are highly irregular and discontinuous in form with sharp external contacts but both sharp and gradational internal contacts. The main body of sub-massive ore at Littlemill has a maximum strike length of 160 m and maximum 30 m true width. It is open below the deepest drilled intercept at 180 m. Textural features indicate that the sulphides were injected in liquid form into a zone of structural weakness which was already brecciated or was brecciated during sulphide injection. Further deformation prior to cooling caused considerable remobilisation of the early-formed sulphides, particularly chalcopyrite. Disseminated sulphides are more widespread and occur both within and beyond the main sulphide zone. The Auchencrieve sulphide zone, located about 600 m north of Littlemill, comprises a less continuous zone of narrow intervals of massive and sub-massive sulphide hosted by a similar range of lithologies. This zone is cut by a number of discordant mela-olivine gabbro and peridotite bodies containing disseminated sulphides.

Pyrrhotite, chalcopyrite and pentlandite are the main ore minerals, with most of the primary sulphide comprising 80% pyrrhotite and 10% each of chalcopyrite and pentlandite. However, the relative proportions of each vary both within and between textural types. Chalcopyrite is most abundant in deformed net and vein type ores. Other primary sulphides observed in minor amounts include molybdenite, cobaltite and sphalerite. Violarite and secondary pyrite occur near surface and in faults and fractures. Covellite, chalcocite and malachite are important Cu hosts in the oxidised zone. The sulphide abundance and textures are complex and vary rapidly over short distances: disseminated and net-textured sulphides are clearly magmatic in origin. Elsewhere banded, brecciated and vein textures indicate the importance of ductile deformation and/or injection of sulphide liquids. Hydrothermal activity is widespread with hornblende and biotite related to ductile shearing commonly evident. Graphite is ubiquitous in both mineralised zones, especially in zones of deformation, where it forms up to 30% of the rock commonly associated with sulphide which it replaces or is replaced by. It exhibits a multitude of textural forms, intergrowths and deformation effects.

4.2 SCIENTIFIC STUDIES BY ABERDEEN UNIVERSITY AND THE BRITISH GEOLOGICAL SURVEY

There is a long history of research at Aberdeen University into the structure and genesis of the Caledonian basic intrusions. For more than 20 years, commencing in the 1960s, Munro and his co-workers undertook mapping and shallow drilling investigations mainly in the Huntly-Knock-

Portsoy area (Munro, 1970; Munro and Gallagher, 1984; Munro, 1984; Gallagher, 1983; Fletcher, 1989; Fletcher and Rice, 1989).

The research at Aberdeen University in the Huntly area, together with the data derived from the EVL drilling and geophysical programmes, led to major improvements in the understanding of the structure and complexity of the basic intrusions. It was concluded that the contact relations and internal structures of these plutons have been greatly disrupted by post-magmatic deformation. The Huntly–Knock–Portsoy intrusions were interpreted as lying within a major north–south-trending steeply-dipping mylonite zone, comparable to those which have affected the Belhelvie and Insch masses.

A number of apparently discrete cumulate bodies, ranging in size up to a maximum dimension of 4 km, are found within the Huntly and Knock intrusions. These rocks display distinctive textural, mineralogical and chemical features consistent with a common origin as layered rocks similar to those found in large stratiform intrusions. The small size of these bodies, together with the regular pattern of cryptic variation within each, was interpreted to be due to disturbance of a single large intrusion. Moreover, by examination of the cryptic variation in the principal cumulus phases (olivine, plagioclase and clinopyroxene), it was possible to place the individual cumulate masses in a 'stratigraphical' order and, thereby, to assess the magnitude of tectonic displacement which has taken place. It was concluded that considerable relative displacements have taken place and that there is no consistent or coherent relationship between the present spatial distribution of the cumulate bodies in the Huntly–Knock–Portsoy area and the original stratigraphy. This deformation was attributed to post-magmatic regional shearing and mylonitisation, as described by Ashcroft et al. (1984).

Between 1985 and 1989 Fletcher undertook research on the genesis of the Cu-Ni mineralisation in the Knock intrusion (Fletcher, 1989; Fletcher and Rice, 1989; Fletcher et al., 1989). Fletcher also produced a revised geological map for the Huntly and Knock intrusions that differed substantially from that of Read (1923). Fletcher's work highlighted the internal complexity of these intrusions, in particular the role of late deformation in controlling the present contacts both marginal to and within these bodies. Fletcher and Rice (1989) interpreted the Huntly and Knock intrusions as parts of an original larger stratiform intrusion of possible laccolithic form. Subsequent deformation produced the distribution of lithologies now observed.

Most of the basic igneous bodies in the region were first mapped at 6" to the mile during the nineteenth century. Revision mapping of the whole East Grampian region by BGS, and by Aberdeen University under contract to BGS, was carried out in a major multidisciplinary programme (the East Grampian Project, EGP) commencing in 1983. The region was mapped at a scale of 1:10 000 and new 1:50 000 scale geological maps published from the early 1990s onwards.

The Ellon map sheet (87W), published in 1991, was mapped by Aberdeen University on behalf of BGS, but little new detail was resolved within the Arthrath body or the nearby larger Arnage, Haddo House and Maud intrusions. The revised Huntly map sheet (86W), including the Huntly and Knock intrusions, built on the work carried out at Aberdeen University and incorporated much information from the EVL archive. This led to the publication of a considerably revised and detailed new map in 2000.

Between 1985 and 1989 BGS conducted further investigations into the mineral potential of the basic intrusions in north-east Scotland under the auspices of the Mineral Reconnaissance Programme (MRP) funded by the Department of Trade and Industry. The main focus of this work were the platinum-group elements (PGE). MRP activities comprised geochemical and geophysical surveys, together with a limited diamond drilling programme. Following initial reconnaissance drainage and rock sampling over the Belhelvie, Insch and Boganclogh intrusions, the investigations concentrated on the Huntly and Knock masses and the 'Older Basic' bodies cropping out in the upper parts of the Deveron catchment to the south-west of Huntly. The results of these investigations have been reported in Gunn et al. (1990), Gunn and Shaw (1992), Styles (1994) and Gunn et al. (1996).

MRP surveys over the Knock intrusion were directed towards the identification of PGE-Cu-Ni mineralisation at its eastern margin, along strike from the mineralisation investigated by EVL at Littlemill and Auchencrieve. Three boreholes were drilled to investigate anomalies detected during reconnaissance IP surveys over the eastern margin of the intrusion. These boreholes failed to locate significant metalliferous mineralisation.

BGS did not carry out any mineral exploration in the Arthrath-Arnage-Haddo House-Maud district during this period.

Limited studies of PGE in the ores from Littlemill-Auchencrieve and more widely in the Huntly and Knock areas were carried out by Fletcher (1989) and Fletcher and Rice (1989). At Littlemill a maximum of 574 ppb Au+Pt+Pd occurs in a remobilised net-textured sulphide ore with 1.5% Cu and 0.7% Ni. Recent geochemical studies by BGS (McKervey et al., 2007) on specimens of archived drillcore from Littlemill have confirmed PGE values up to about 500 ppb Pt+Pd, with highly variable Pd/Pt values. The highest PGE values are found in massive sulphide ores of various types. Palladium in these rocks correlates with Fe, Co, Ni, Sb and Bi, confirming an association with the sulphide mineralisation. However, the abundance of Pt does not correlate with that of Pd, consistent with the highly variable Pd/Pt values.

McKervey et al. (2007) also reported the occurrence of discrete grains of platinum-group minerals (PGM) in two samples from Littlemill. In one sample bismuth-rich merenskyite (PdTeBi) occurs along a sulphide-silicate grain boundary, while in the other froodite ($PdBi_2$) and an uncharacterised PdSb mineral were found with grains of native gold and native bismuth in fractures in a mylonitic metanorite rock enclosed within massive sulphide. These observations, together with the geochemical patterns noted above and detailed petrographic studies, support the suggestion of Fletcher and Rice (1989) that the original base and precious metal mineralisation has been remobilised during amphibolite-facies shearing.

In addition to studies of Ni-Cu sulphide deposits, BGS also carried out exploration for stratiform magmatic PGE mineralisation over the Huntly intrusion. Disseminated magmatic sulphide (pyrrhotite-chalcopyrite) mineralisation is widespread in the cumulate rocks, but PGE contents do not exceed 50 ppb Pt and 63 ppb Pd. The widespread occurrence of interstitial magmatic sulphide mineralisation throughout the sequence indicates that the magma was continuously at or near sulphur saturation and thereby effectively scavenged low levels of the PGE from the melt over a long period. There is no evidence for a single event which gave rise to sulphur saturation and which might have produced local high PGE concentrations.

A different style of PGE mineralisation was identified in the western part of the Huntly intrusion. In an area underlain by olivine cumulate rocks, irregular discordant bodies, up to a few metres wide, of graphite- and sulphide-bearing orthopyroxene-rich pegmatites contain high precious metal concentrations, up to a maximum of about 700 ppb Au+Pt+Pd. Occurrences of this type in the Bin Quarry, about 4.5 km north-east of Huntly, were investigated by drilling but no significant continuity at depth was identified.

'Older Basic' rocks of the S-BH type were studied by BGS at several localities in the upper Deveron valley. High PGE values occur locally in the S-BH intrusion, and also nearby at Kelman Hill in more altered and sheared varieties of the ultramafic lithologies, with the highest values in pyroxene-rich types. This enrichment, up to a maximum of about 270 ppb Pt+Pd, is associated with high Pd/Pt values and locally accompanied by Au enrichment up to about 370 ppb. Limited mineralogical studies identified a small number of tiny (ca. 5 μm) complex Pt-bearing grains. These comprise Pt-Cu alloy overgrowths on nickel arsenide cores in a vein through serpentine in the wehrlite host rock. The mineral paragenesis and textural features suggest an origin related to late low-temperature processes associated with serpentinisation.

No PGE enrichment has been identified in ultramafic rocks of the Harzburgite type located along the Portsoy Lineament and peripheral to the Insch and Boganclogh intrusions in east–west shear zones.

4.3 OTHER MINERAL OCCURRENCES IN NORTH-EAST SCOTLAND

A small number of significant metalliferous mineral occurrences not discussed above are briefly described here.

In the Belhelvie 'Younger Basic' intrusion on the east coast near Aberdeen, Pt values of 2-88 ppb, Pd of 2-113 ppb and Rh of 2-7 ppb were reported in intrusive rocks named 'picrite/dunite' of which little else is known (Fletcher, 1989).

There is an important occurrence of epithermal gold mineralisation in Lower Devonian volcano-sedimentary rocks at Rhynie in Aberdeenshire. This is a significant gold discovery not least because it represents a style of mineralisation hitherto unknown in the Scottish Highlands (Rice and Trewin, 1988). Commercial investigations at Rhynie, comprising trenching and drilling of seven boreholes, were undertaken by Moray Firth Exploration plc. Further research, involving detailed mineralogical, noble gas and stable isotope studies, confirmed that the ore mineral and alteration assemblages were deposited in the upper part of a low-sulphidation epithermal system (Rice et al., 1995). No detailed records of the commercial exploration are available to BGS, but it appears that the economic potential for underlying epithermal vein or stockwork mineralisation remains untested.

The Rhynie discovery stimulated company interest in a drainage anomaly for arsenic identified by the BGS Regional Geochemical Survey in the Towie and Cushnie areas, 16 km south of Rhynie. Prospecting and trenching by Navan Resources identified local concentrations of gold, up to 2.05 ppm in outcrop and 5–6 ppm in float. The gold is probably shear-related and occurs mainly in quartz veins within limonite/goethite after pyrite.

In the late 1960s, EVL investigated several occurrences of anomalous molybdenum values in soils noted in the Soil Survey Memoir covering the Aberdeen, Inverurie and Fraserburgh area. Molybdenite-bearing quartz vein float was discovered by EVL at 4 localities; Middleton, Balquinhadachy, Souter Head and Quilquox. Open-file reports on these projects are available at BGS. Detailed follow-up of this work, including drilling of 7 boreholes, was carried out by BGS at Middleton, near Inverurie (Colman et al., 1989). Minor molybdenite mineralisation was intersected. Selected core samples were analysed for a total of 16 elements including Cu, Mo, Zn and As, but not Au or Ag.

5 Review of investigations at Arthrath

The Arthrath intrusion is located about 30 km north of Aberdeen, close to the small town of Ellon. It was identified by RTZ in an area previously mapped as underlain by granite gneiss when they followed up reports of nickel toxicity in crops in the area. Detailed soil sampling was carried out and anomalous values of nickel and copper were found on the farms of Arthrath, Dudwick and Mains of Coldwell (Figure 3). The soil geochemical data, in conjunction with detailed ground magnetic and IP-resistivity surveys, led to the identification of five zones of disseminated nickel-copper sulphide mineralisation. The mineralised zones, from west to east, Coldwells, Nether Arthrath, Mains of Dudwick, Ardganty and Muirtack, extend over a distance of approximately 4 km east–west. They occupy relatively low ground to the south of the Hill of Dudwick (174 m).

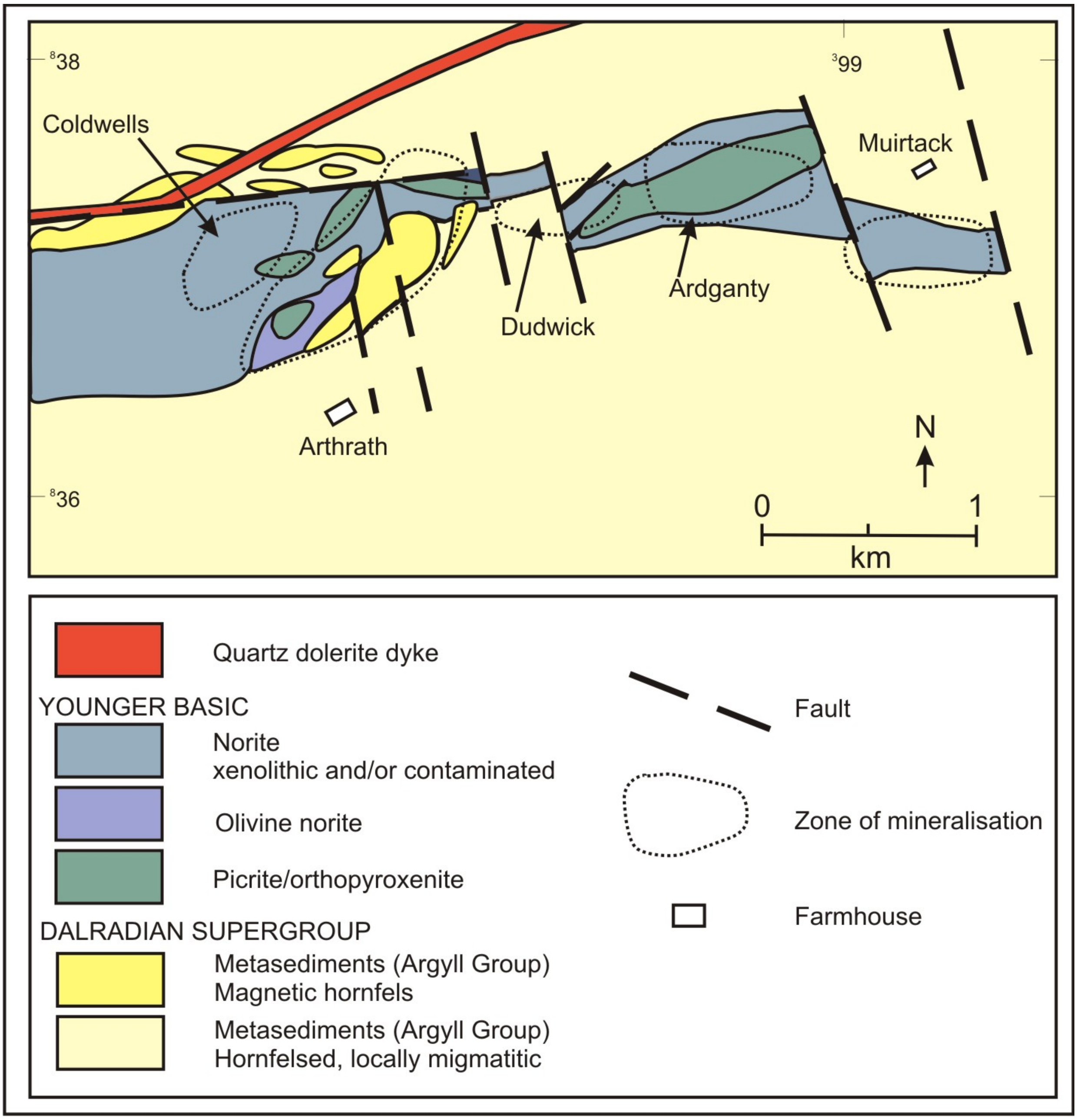

Figure 3 The geology of the Arthrath prospect

5.1 DATA SOURCES

BGS has a substantial archive of documents, maps and physical materials from the EVL programme at Arthrath (Appendix 1). These include:

- Descriptive logs for all 36 boreholes drilled by RTZ.
- Summary graphic logs, location plan and drill sections for boreholes AD 22-36. The graphic logs show estimates of volume% sulphide and of assay values for Ni and Cu throughout each borehole; numerical data (%Ni and %Cu) is given for most mineralised intervals.
- Detailed maps and plans of geophysical and geochemical surveys, including results.

None of this material is currently available in digital form.

Apart from material held in the BGS archives, most information concerning the Arthrath area is derived from four main sources:

1. A short paper by Rice (1975), who worked for RTZ in north-east Scotland, entitled 'Geochemical exploration in an area of glacial overburden at Arthrath, Aberdeenshire'. This provides some detailed geological, geochemical and geophysical information relating specifically to Arthrath. On the basis of the distribution of drift cover in the area, the nature of the Ni-Cu soil anomalies and evidence from the upper portions of boreholes, the author concluded that Arthrath was located in a periglacial area and that the present geochemical patterns indicate that little ice scouring has taken place. Consequently the geochemical patterns seen today are little different from those that existed prior to glaciation.

2. An unpublished manuscript by Wilks and Smith (1976), entitled 'Exploration and geology of nickel and copper deposits in north-east Scotland'. This document summarises the methods utilised by EVL throughout the region and provides brief case histories for Littlemill-Auchencrieve, Arthrath and Belhelvie. This account provides some information on the work carried out at Arthrath that is not available elsewhere.

3. A paper by Fletcher et al. (1997), entitled 'Geology and stable isotope study of the Arthrath mafic intrusion and Ni-Cu mineralisation, north-east Scotland'. This study compiled various geological information derived from EVL work and presented new petrographic, mineralogical and isotope data for EVL drillcore samples. A genetic model for the mineralisation at Arthrath was developed on this basis.

4. A paper by McKervey et al. (2007), entitled 'Platinum-group elements in Ordovician magmatic Ni-Cu sulphide prospects in northeast Scotland.' This study presented the results of new petrographic, mineralogical and geochemical studies of EVL drillcore from Littlemill and Arthrath leading to development of a new metallogenic model.

5.2 SUMMARY OF EVL WORK AT ARTHRATH

RTZ conducted systematic sampling of B-horizon soils, at 200-foot intervals, along north–south lines, spaced 1000 feet or 500 feet apart. High amplitude coincident Ni-Cu anomalies were identified at Arthrath, Dudwick and Ardganty. Drilling in these zones subsequently revealed strong oxidation and leaching in bedrock underlying these anomalies. The mineralisation later identified at Coldwells and Muirtack, not clearly identified by soil geochemistry, was found by drilling to be hosted in fresh, unaltered bedrock beneath the till blanket.

Detailed ground magnetic surveys were conducted along north–south lines, either 200 or 100 feet apart, with observations at 50-foot intervals. This data was not easy to interpret due to the overlapping magnetic susceptibilities of the pyrrhotite-bearing ores, magnetic hornfels and serpentinised olivine-bearing rocks. Nevertheless the magnetic data was very useful in delineating various contacts and fault zones within and marginal to the Arthrath intrusion.

More than 80 line-kilometres of IP/resistivity surveys were carried out between Coldwells in the west and Muirtack in the east. This method gave an excellent response, clearly defining a more or less continuous anomalous zone over approximately 4 km.

On the basis of the detailed geochemical and geophysical results EVL identified several drilling targets. Between August 1968 and April 1970 a total of 21 diamond drillholes were drilled in four zones (excluding Dudwick). In a second phase of drilling a further 15 boreholes were drilled in six zones (including two at Cairnadailly to the west, which failed to intersect mineralisation). The drilling carried out by EVL in the various mineralised zones at Arthrath is summarised in Table 1.

Zone	Number of boreholes	Metres drilled
Coldwells	7	1134
Arthrath	12	2671
Dudwick	2	260
Ardganty	4	685
Muirtack	9	1925
Cairnadailly	2	175
Total	**36**	**6850**

Table 1 Summary of EVL drilling at Arthrath

Several EVL boreholes intersected thick intervals of disseminated magmatic sulphide mineralisation, hosted chiefly by various xenolithic and noritic rock types. For example:

Borehole AD25 (drillcore held by BGS);

Between 38.80-122.55 m, blebby interstitial sulphide, commonly 3-5 volume%, locally richer over narrow interval; minor sulphide continues to ca. 180 m. Assay data include:

8 m, from 102.00 m, @ 0.57% Ni, 0.34% Cu

5.3 m, from 174.00 m, @ 0.70% Ni, 0.43% Cu

Borehole AD27

Between 25-80 m, mineralised with mostly 2-4 volume% sulphides. Assay data include:

10.00 m, from 55.04 m, @ 0.24% Ni, 0.13% Cu

0.5 m, from 133.71 m, @ 1.42% Ni, 0.9% Cu

12 m, from 156.73 m, @ 0.21% Ni, 0.15% Cu

Borehole AD31

Between 28-150 m, mineralised with >2 volume% sulphides. Assay data include:

19.5 m, from 48.62 m, @ 0.28% Ni, 0.19% Cu

22.4 m, from 80.06 m, @ 0.36% Ni, 0.22% Cu.

Assay data are not available in the BGS archive for boreholes AD1-21, but descriptive logs record thick mineralised intercepts in some of these holes.

The extensive and widespread nature of the base-metal mineralisation is highly encouraging. However, it is clear from the fact that boreholes were drilled both vertically and inclined in various directions that the controls on the mineralisation were far from clear to EVL.

In 1977 Amax drilled a single borehole (77DDA1) at Tillydesk, about 600 m south-west of the Coldwells zone. This borehole intersected weak Ni-Cu mineralisation (up to ca. 0.1% Ni and 0.1% Cu) over an interval of more than 90 m of contaminated norite from a depth of about 35 m.

During 2005 Alba Mineral Resources plc carried out a limited programme of core drilling (3 boreholes) in the Muirtack zone in order to verify the results of EVL and to investigate the down-dip potential in that zone. Substantial intersections of disseminated magmatic sulphide mineralisation were reported in boreholes 05-AH/2 and 05-AH/3. The following summary has been taken from press releases on Alba's website (http://www.albamineralresources.com):

Borehole 05-AH/02

109.7 m @ 0.26% Ni, 0.29% Cu, 0.019% Co, from 17.3 metres,

including 7.8 m @ 0.51% Ni, 0.54% Cu, 0.033% Co, 169 ppb Pd+Pt+Au, 4.1 g/t Ag, from 103.2 metres.

Borehole 05-AH/03

78.6 m @ 0.20% Ni, 0.18% Cu, 0.016% Co, from 184.4 metres,

including 7.4 m @ 0.36% Ni, 0.18% Cu, 0.026% Co and 73 ppb Pd+Pt+Au

and 12.1 m @ 0.28% Ni, 0.28% Cu, 0.024% Co and 67 ppb Pd+Pt+Au

On the basis of these results and those previously obtained by EVL, Alba concluded that the mineralised body in this zone may extend down-dip to at least 350 m from surface. The author has first-hand knowledge of the drilling carried out in 2005 and there is no reason to doubt the quality of the results given above. Further drilling is required to confirm the continuity of the mineralisation at depth.

5.3 GEOLOGY

The Arthrath intrusion is a lenticular body, about 7 km long and up to 1 km wide, extending eastwards from the Arnage basic intrusion. EVL compiled a geological map on the basis of mapping float boulders and the few isolated outcrops, together with borehole and geophysical data (Figure 3). The intrusion is overlain by fluvioglacial drift deposits which attain a maximum thickness of 25 m, although the presence of outcrops and locally abundant angular float suggest thinner cover in the western and central parts. An east-north-east-trending quartz-dolerite dyke is mapped on the higher ground to the north on the basis of scattered outcrops and magnetic data. The fluvioglacial deposits, comprising clays, sands, gravels and rock debris, have been interpreted as frost-heaved bedrock originating during periglacial episodes (Rice, 1975).

The country rocks are mainly semi-pelites, with minor pelites, quartzites and calc-silicate horizons, assigned to the Stuartfield Division of the Upper Argyll Group (Middle Dalradian). They dip and young steeply to the north. The majority of the rocks are non-migmatitic hornfels, although high-grade migmatites (sillimanite±K-feldspar) occur locally adjacent to the intrusive rocks. Sulphide mineralisation in the country rocks is generally sparse, although locally fine disseminated pyrite and pyrrhotite are abundant. The Arthrath body is concordant with the Dalradian stratigraphy and comprises a complex sequence of xenolithic norites, mafic-ultramafic cumulates and hornfelsed metasedimentary rocks. External contacts are steep (40–80º), concordant with the Dalradian country rocks and dip to the north. The intrusion is bounded in places by east–west shear zones. These are cut by later faults trending north-west and west-south-west which displace or terminate the outcrop of the basic igneous rocks.

The dominant rock types within the Arthrath body are xenolithic norite and orthopyroxenite which are characterised by fine-to coarse-grained ortho- to meso-cumulate textures. Subordinate olivine norite, gabbronorite and peridotite are widespread. Within the xenolithic norite irregular bodies and lenses of orthopyroxenite, olivine norite, picrite (plagioclase-bearing peridotite), dunite, hornfels, contaminated (quartz- and biotite-bearing) noritic hybrid rocks and gabbronorite are found. Highly heterogeneous noritic hybrid rocks are generally associated with marginal contact zones. Contacts between the various rock units may be sharp or gradational, tectonic or intrusive. Xenoliths are common in all rock types and comprise mainly semi-pelitic to pelitic hornfels, with local calc-silicates, norite and garnetiferous norite. They are generally in the range 1–10 cm, although may be much larger, and may form up to 50% of the rock. Reactions between the xenoliths and noritic hosts have produced various hybrid rock types in some of which ghost outlines of xenoliths are apparent. Granite veins, from a few cm up to 2 m in thickness, cut the noritic rocks in most boreholes. Partial to complete amphibolitisation and serpentinisation have affected most pyroxene- and olivine-bearing rock types, especially adjacent to shear zones and fractures.

5.4 PETROGRAPHY OF THE IGNEOUS ROCKS

Limited petrographic and mineralogical studies by Aberdeen University and BGS have been carried out on samples taken from the EVL drilling programme, 1969-73. Specimens studied are mainly from AD 17, 24, 25, 28 and 34 (details given in Fletcher et al., 1997, and McKervey et al., 2007).

Fine- to coarse-grained cumulate norites and gabbronorites are dominant, although subhedral granular variants are common. Interstitial phases are plagioclase±clinopyroxene±biotite. Textural heterogeneity occurs on the thin-section-scale with fine- to medium-grained granular domains coexisting with coarser-grained domains. Amphibole is common as an overgrowth on pyroxenes and olivine is serpentinised to varying degrees. The cumulus mineral assemblage (mainly orthopyroxene, plagioclase and olivine) and their mineral chemistry determined by electron microprobe analysis are comparable with Lower Zone rocks found in Insch and Huntly-Knock. Cumulus chrome spinel occurs in some peridotites and melanorites.

The cumulus crystallisation sequence is:

1. Olivine-chrome spinel
2. Olivine-orthopyroxene-chrome spinel
3. Orthopyroxene-plagioclase
4. Orthopyroxene-plagioclase-clinopyroxene

Crystal lamination (parallel alignment of plagioclase and orthopyroxene grains) and modal layering are locally observed but cannot be used to give a reliable indication of any magmatic ‘stratigraphy’ on account of their sparse distribution.

A wide spectrum of textural and mineralogical variations is present in the xenolithic and contaminated norites. In addition to their variable content of xenoliths of metasedimentary origin, both igneous and granular textures are present, often within short distances of one another. The major silicate phases, orthopyroxene and plagioclase, are widely accompanied by biotite and spinel, locally with quartz, apatite, garnet, cordierite and fibrolite.

5.5 SULPHIDE MINERALISATION

Fine-grained interstitial disseminated sulphide mineralisation (<1%) is widespread throughout the Arthrath intrusion and occurs in all rock types. In the five mineralised zones identified by EVL the sulphide mineralisation consists principally of disseminated sulphides (5–20 volume%), with interstitial network sulphides (20–40%) locally developed, and rare sub-massive (40–80%) intervals and stringer veins. A typical mineralised norite has 50-70% orthopyroxene, 5-7% clinopyroxene, 20-40% plagioclase, 5-15% sulphides and minor amounts of biotite, ilmenite, magnetite and amphibole.

Sulphide mineralisation is erratically distributed within the known mineralised zones. Within individual boreholes well mineralised norites pass into unmineralised sections of the same lithology. Elsewhere in the same hole xenolithic norites may be highly mineralised. The transition from sulphide-rich to sulphide-poor may be sharp or gradational. No consistent patterns in the style or grade of mineralisation within an individual zone were identified by EVL. The textures of the ore vary considerably: fine to coarse-grained disseminated and interstitial sulphides are most common, but coarsely crystalline patches and massive aggregates are locally developed.

The sulphides present are pyrrhotite, pentlandite and chalcopyrite, with traces of pyrite. These may occur as monomineralic blebs or as composite intergrowths. Pyrrhotite occurs as individual crystals or aggregates of rounded crystals, commonly remobilised along fractures. Chalcopyrite forms rounded blebs within pyrrhotite and is locally remobilised in veinlets. Pentlandite occurs mainly as flame lamellae within pyrrhotite and less commonly as fine granules along pentlandite grain boundaries. Coarse granular pentlandite is rare.

The disseminated and network sulphide are found in the interstitial spaces between cumulus and granular silicates and may be intergrown with intercumulus biotite, amphibole or ilmenite. These textures are clearly of magmatic origin, with local remobilisation along grain boundaries, cleavage planes and fractures related to deformation or hydrothermal processes. There is generally little oxidation of sulphides beneath the drift, except in areas of fracturing and hydrothermal alteration where the sulphides have been altered to magnetite, mackinawite, pyrite and marcasite. Pentlandite is partially or completely altered to violarite in the upper parts of some boreholes.

There has been no comprehensive systematic study of mineral chemistry or whole rock geochemistry in the Arthrath intrusion in general or the zones of mineralisation. The only data available, from Fletcher et al. (1997) and McKervey et al. (2007), are summarised in Table 2. McKervey's data is derived from borehole AD25.

	Fletcher et al. (1997)	**McKervey et al. (2007)**
Orthopyroxene	En 75 – En 83	En 70 – En 81
Plagioclase	An 47 – An 78	An 63 – An 73
Olivine	Fo 78 – Fo 83	Fo 80 – Fo 81
Ni in olivine	0.042 – 0.085 wt % Ni	0.09 wt % Ni

Table 2 Summary of available mineral chemistry data from Arthrath

Apart from the assay data for Cu and Ni presented in graphical form in the EVL summary borehole logs, little geochemical data for the Arthrath drillcore has been published. Fletcher (1989) presents a summary of PGE data provided by Fleck Resources who analysed approximately 960 samples of EVL drillcore from the Arthrath, Belhelvie, Knock and Portsoy intrusions. Pt, Pd, Rh, Au, Ag, Cu, Ni, Co and Cr were determined in these samples by Acme Analytical laboratories, Vancouver. These samples were derived from shallow grooves cut into the core over one-metre intervals. On account of the small sample size and the apparent lack of any consideration for variations in sulphide content or rock type these data should be treated with caution. In particular the small sample size means that the reported precious metals values are not necessarily reliable.

In 115 samples of unmineralised picrite (mela-norite) from AD25 Fletcher reported maxima of 9 ppb Pt, 4 ppb Pd, and 2 ppb Rh. In 169 samples of contaminated norite, containing generally 2–5% sulphides, from AD25 reported maxima were 201 ppb Pt, 138 ppb Pd and 7 ppb Rh, accompanied by high Ni (up to 1%), Cu (up to 0.6%), and Co (up to 287 ppm). 170 samples of weakly mineralised contaminated norite from AD24 were also analysed. Reported maxima were 24 ppb Pt, 23 ppb Pd and 3 ppb Rh.

McKervey et al. (2007) investigated chiefly the PGE geochemistry and mineralogy by studying drillcore from boreholes AD24 and AD25. They presented multielement geochemical data for 33 samples representative of the main lithologies and styles of mineralisation present. Individual samples varied in length between 10 and 60 cm. Of these two samples contain more than 1% Ni and only one sample has a Cu value greater than 0.5%. Fourteen samples have PGE contents greater than those typical of ultramafic rocks. The highest Pd value, 458 ppb, occurs in massive sulphide with 1.69% Ni, 0.41% Cu and very low Pt and Au contents. The second highest Pd value (207 ppb) occurs in a coarse-grained contaminated gabbro with abundant disseminated sulphide and local narrow bands of massive sulphide. It also contains 42 ppb Pt, 57 ppb Au, 0.85% Ni and 0.59% Cu. Only three samples have significant Pt contents, ranging from 35–47 ppb Pt. Pd/Pt values vary widely around a median value of 2. The highest Pd values occur within or close to sulphide-rich zones at depths of about 109 m and 179 m in AD25.

Enrichment of Au is also locally present (up to 2669 ppb). In general, all samples containing high PGE values are massive or sub-massive ores but many such samples do not have anomalous PGE contents. The abundance of cobalt is greatest in the sulphide ores from this suite of samples: the average Co content of 10 samples containing more than 0.25% Ni is 374 ppm Co, with a maximum of 980 ppm.

The dataset of McKervey et al. shows positive correlations between Pd and total Fe, Ni, Cu, Co, S, Bi, Te, Se, Ag and Au suggesting that these elements occur in the same or coeval phases, such as pyrrhotite, chalcopyrite and pentlandite. Pt has a significant positive correlation with Cu, total Fe, Ag and Bi. By comparison with Arthrath, inter-element relationships are much less clear in the Littlemill boreholes. Pd is correlated with Fe_2O_3, Co, Ni, Bi, Te, Se and S but the data are much more scattered. Pd is not correlated with Pt, Au or Cu. Pt has no significant correlation with any other elements determined and is largely independent of S content.

McKervey et al. studied the mineralogy of 44 samples taken from throughout borehole AD25, and supplemented by a few additional samples from AD24. Forty-six out of 87 polished sections made from these samples were subjected to automated electron microprobe searching for platinum-group minerals (PGM) on a 1- or 2-µm grid, using the back-scattered electron signal to locate minerals with high atomic number. PGM thus located were characterised using energy-dispersive spectra (EDS) and, if possible, wavelength-dispersive analysis (WDS). In total, 37 PGM occurrences were characterised by WDS analysis and a further set of occurrences (~20) were imaged and characterised by qualitative EDS analysis.

The majority of PGM occurrences found at Arthrath are in the sulphide-rich zones in AD25, between depths of 102.75–109.75 m, and 176.2–179.3 m. However, PGM were also found in four sections from borehole AD24. All PGM occurrences are of merenskyite ($PdTe_2$) and one occurrence of melonite ($NiTe_2$) was also found. The merenskyite present contains appreciable Ni substituting for Pd and the melonite contains substantial Pd. All merenskyite analyses show Bi substituting for Te. Other precious metal-bearing minerals found at Arthrath were native gold, hessite ($AgTe_2$), and an uncharacterised BiTe mineral. Merenskyite at Arthrath most commonly occurs included in pyrrhotite or pentlandite, but it has also been found along sulphide-silicate grain boundaries and more rarely in fractures within sulphide or silicate.

5.6 MINERAL POTENTIAL AT ARTHRATH

5.6.1 Deposit models and exploration criteria for magmatic Ni-Cu sulphide deposits

Magmatic Ni-Cu±PGE deposits are the most important source of nickel worldwide. Copper, cobalt and the PGEs, mainly palladium, are important co-products or by-products. In some deposits gold, silver, chromium, sulphur, selenium, tellurium and lead are also recovered from the ores. Deposits of this type are relatively rare; there are only 142 deposits and camps in the world that contain more than 100 000 tonnes of global resources of metal (Hulbert and Eckstrand, 2005). Magmatic nickel sulphide deposits are all spatially and genetically related to bodies of mafic or ultramafic rocks. They are formed when mantle-derived mafic and ultramafic magmas become saturated in sulphide and segregate immiscible sulphide liquid. For an economic deposit to form the sulphides precipitated from this liquid must be concentrated into a restricted physical space to constitute ore.

The dominant ore minerals are sulphides, pyrrhotite (Fe_7S_8), pentlandite ($[Fe,Ni]_9S_8$), and chalcopyrite ($CuFeS_2$), which generally constitute more than 10% by volume of the host rock. Nickel grades are typically in the range 0.5-3.0% Ni, with attendant Cu in the range 0.2-2.0%. PGE contents vary widely from a few part per billion (ppb) up to, exceptionally, 10 parts per million (ppm). The size of the deposits ranges from a few hundred thousand tonnes up to a few tens of million. Globally two nickel-copper camps are predominant, each containing more than 10 million tonnes of nickel metal: Sudbury, Ontario, Canada and Noril'sk-Talnakh, Russia. The most important PGE deposits without significant associated magmatic sulphide mineralisation occur in large layered mafic-ultramafic intrusions, such as the Bushveld, South Africa, Stillwater, USA and the Great Dyke, Zimbabwe.

Magmatic sulphide deposits occur in diverse geotectonic settings in rocks ranging in age from Archaean to Permo-Triassic. They are associated with magmas of various types. As a result of this diversity these deposits have been classified in several different ways (Naldrett 1989, 2004). A relatively simple scheme was proposed by Eckstrand and Hulbert (2007) who recognised four principal classes:

1. a meteorite-impact mafic melt with basal sulphide ores. Sudbury is the only known example of this type.
2. Rift- and continental-flood basalt, with associated dykes and sills. Important examples include Noril'sk-Talnakh, Jinchuan, China and Duluth, USA.
3. Komatiitic (magnesium-rich) volcanic flows and related intrusions. Important examples include Kambalda, Australia, Thompson and Raglan, Canada and Pechenga, Russia.
4. Other mafic-ultramafic intrusions. Important examples include Voisey's Bay, Canada, Selebi-Pikwe, Botswana and Råna, Norway.

Over the past 50 years commercial exploitation of this type of deposit and associated academic research have led to major advances in our understanding of their genesis. The relatively simple concept of the collection of sulphides in embayments along the base of a mafic intrusion underpinned much early exploration, including that carried out by EVL in north-east Scotland. Although this concept has not been abandoned, it has been considerably refined as a result of studies of the komatiite-related deposits in Western Australia, of the Noril'sk-Talnakh district and, more recently, of the Voisey's Bay deposit in Labrador, Canada. This work has highlighted the importance of magma dynamics and the focusing of magma flow in the separation and concentration of liquid sulphides from the magma, rather than static, gravity-driven settling. Of particular importance has been the appreciation that sites of decreased flow rates are often loci for sulphide accumulation.

Studies of the Voisey's Bay deposit have been particularly instructive. They confirmed the importance of magma dynamics but also suggested the major significance of magma conduits, such as dykes. They suggested that repeated pulses of magma flowed through the conduit, allowing the later magma to rework, upgrade the metal tenor of and to concentrate early-formed, low-tenor sulphides. This model is supported by mineralogical and isotope data provided by various workers (Li et al., 2001; Arndt et al., 2003).

In order to form an economic deposit the magma must have sufficient contents of dissolved nickel, copper and PGE. On account of their chalcophile character these metals will preferentially partition into a liquid sulphide when that is formed. However, the mechanism whereby a given magma becomes sulphur saturated is not fully understood. The principal process responsible for triggering sulphide immiscibility is generally regarded as assimilation of sulphide-bearing country rock. However it is also known that the incorporation of siliceous wallrock has the effect of decreasing the sulphur solubility of the magma and can thus lead to the sulphur saturation. Clearly this has important implications for exploration.

The general consensus is that the following are the principal requirements for the formation of a magmatic nickel-copper sulphide deposit:

1. A primitive mafic-ultramafic magma, capable of carrying the ore metals. This will typically be olivine bearing, with high MgO content (>10% MgO). Fractionation of olivine will rapidly deplete the nickel content of the magma such that sulphides subsequently derived from the magma will have low Ni contents.
2. A sulphur-undersaturated magma, capable of carrying the ore metals to a high level in the crust.
3. Proximity to a prominent crustal suture along which deep-sourced magmas can ascend.
4. Evidence of interaction with country rocks, preferably sulphur-bearing, to trigger sulphide immiscibility. Evidence may be geological, petrographic, mineralogical or isotopic.
5. A conduit for magma flow. This may be a feeder dyke, sill or lava channel.
6. An open system through which repeated pulses of magma flowed, allowing reworking, upgrading and concentration of sulphides.

It is instructive to review key aspects of the Voisey's Bay deposit on account of their potential application to exploration for similar deposits in north-east Scotland. The overall resource at Voisey's Bay (reserves plus inferred and indicated resources is 136.7 Mt @ 1.59% Ni, 0.85% Cu and 0.06% Co (Naldrett, 2004). In the Ovoid deposit, which is currently being exploited by open-pit mining, the published reserve (proven + probable) is 32 Mt @ 2.75% Ni. 1.59% Cu, 0.14% Co (Inco Annual Report, 2005). Little PGE data has been published for the Voisey's Bay deposits, but Naldrett (2004) quotes 0.19 g/t total PGE.

The Voisey's Bay intrusion is a small part (30 km^2 of a large Proterozoic magmatic system (ca. 20 000 km^2) that includes granites, anorthosites, ferro-diorite and troctolite, located astride a major collisional suture separating two distinct basement terranes. The country rock to the deposit is the sulphur-bearing Tasiuyak gneiss which appears to have supplied a portion of the sulphur in the Ni-Cu ores. The Voisey's Bay deposit is hosted by the oldest, least evolved troctolite that predates the extensive anorthosites. The deposit comprises a number of orebodies distributed along a steep dyke-like feeder zone, with sulphide accumulation occurring preferentially where the fluid flow regime changed, such as points at which the feeder system widened and thickened and where the magma flow slowed (the Reid Brook and Ovoid deposits) and where the feeder dyke entered into the base of the magma chamber (the Eastern Deeps deposit).

The key elements of the genetic model for Voisey's Bay have been summarised by Naldrett (2004):

1. The deposit is related to two magma chambers, one 1.5 km stratigraphically higher than the other, linked by a feeder dyke.
2. Primitive magma rose into the crust, interacting with mid-crustal gneisses and thus acquiring a crustal trace element and isotopic signature.
3. Continuing its ascent, the magma swelled out to form the lower magma chamber (Reid Brook), where it reacted with the Tasiuyak Gneiss country rock leading to sulphur saturation.
4. Olivine fractionation and segregation of the sulphide liquid led to a reduction in the Ni and Cu contents of the initial magma.
5. The initial magma was forced out of the lower magma chamber, along with some of the sulphide that has segregated from it, and rose up the feeder to develop an upper chamber, 1-

5 km vertically above the lower chamber. Sulphides were deposited in and near the feeder zone.

6. Fresh, undepleted magma entered the lower magma chamber, forcing the early magma upwards and disrupting early cumulates, and picking up sulphides and country rock inclusions, and transporting them up the feeder system to spread out in the lower part of the upper chamber.
7. As the new magma interacted with already deposited sulphides it upgraded their content of the chalcophile elements (Ni and Cu).

5.6.2 Genetic models for Ni-Cu-PGE mineralisation at Arthrath

Two models have been developed to explain the genesis of the mineralisation found by EVL in the Arthrath intrusion and at Littlemill-Auchencrieve in the Knock intrusion. Both are based on studies of the relatively limited drillcore remaining from the EVL programme.

Fletcher et al. (1997) assessed the role of country-rock assimilation in controlling the mineralisation at Arthrath through a study of oxygen and sulphur isotopes in rocks and minerals. The data they derived shows that the mineralisation is dominated by magmatic sulphur. This appears to be at odds with a wealth of other evidence, geological, isotopic and mineralogical, that supports assimilation.

The observed crystallisation sequence and the presence of primary biotite and amphibole in Arthrath, as well as the nearby Haddo House and Arnage intrusions, may have been caused by an initially dry magma that later assimilated country rocks, thus raising the water and silica levels and pushing the fractionating magma along a quartz-normative trend. Sr and O isotope data provide evidence in support of incorporation of country rock Sr and O into the basic magmas. Oxygen isotope data from norite, xenoliths and from orthopyroxene at Arthrath presented by Fletcher et al. (1997) supports a significant contribution of crustal oxygen. They also conclude that assimilation of country rocks must have been underway at an early stage in the crystallisation of the melt, prior to the appearance of orthopyroxene, in order to explain the observed values.

The abundance of orthopyroxene and its early appearance (before clinopyroxene) in the Arthrath intrusion are unusual when compared to other 'Younger Basic' bodies. However, it is significant to note that the mineralised contact zone at Littlemill-Auchencrieve is very similar in this respect to Arthrath.

Other observations that support the assimilation of metasedimentary rocks includes the presence of abundant xenoliths, some preserved as ghost outlines, the unusual mineralogy of the norite, and the complex and heterogeneous intercalation of basic igneous rocks and metasedimentary rocks. Resorbed olivine has also been observed widely in thin section. This may be explained by the reaction of olivine with silica to produce orthopyroxene ($MgSiO_3$). Some metasediments show evidence of partial melting of the country rock which was experiencing amphibolite facies regional metamorphism at the time of emplacement (e.g. Read 1966; Gribble 1970).

In contrast, the sulphur isotope data presented by Fletcher et al. (1997) is more difficult to explain by crustal contamination as the values are well within the magmatic range and show limited variation. They proposed that the magma was close to sulphur saturation on emplacement and that immiscibility occurred before significant fractionation had taken place as a result of the assimilation of a small amount of country-rock sulphur. This would account for the association of the mineralisation with Lower Zone (olivine-bearing) cumulates and the low values of Ni contained in the cumulus olivine at Arthrath.

McKervey et al. (2007) produced a different model for the petrogenesis of the mineralised rocks at Arthrath and Littlemill-Auchencrieve based chiefly on new geochemical, mineralogical and petrographic studies of EVL drillcore samples. This model attempts to explain some of the apparent ambiguities of the geochemical and isotopic data of Fletcher et al. (1997). In particular the isotopic studies found average $\delta^{34}S$ for igneous rocks and sulphides in both prospects to be broadly 'magmatic', falling in the range 0.5 ± 2.4‰ at the Huntly and Knock intrusions (igneous rocks) and –0.9 ± 0.5‰ (igneous rocks) and –1.2 ± 1.0‰ (sulphide) at Arthrath (Fletcher et al., 1989; Fletcher et al., 1997).

McKervey et al. investigated the role of crustal contamination using the S/Se ratio of the rocks. Variations in S/Se, in particular increasing S/Se with increased magmatic differentiation, can discriminate between crustal (>3000) and magmatic (<3000) sources of sulphur in Cu-Ni-PGE-bearing mineral deposits. S/Se values for both Arthrath and Littlemill exceed 3000 in almost all samples. At Arthrath, S/Se values average 5985, whereas at Littlemill the average value is 4980, and for both prospects S/Se values are relatively constant with depth. It appears therefore that the S/Se ratios of the mineralised rocks are consistent with their derivation from crustally contaminated magmas. However, in borehole AD25 at Arthrath there is no correlation between the location of sulphide-rich zones and increasing S/Se suggesting that, although the magmas appear contaminated, they may have been contaminated at an earlier stage in their petrogenesis and thus there is no link to suggest that the zones of Cu-Ni-PGE mineralisation formed as the direct result of crustal contamination.

Thus far all grains of olivine analysed from Arthrath are characterised by low Ni contents (Table 2). Furthermore, the rocks with low Ni-in-olivine examined by McKervey et al. contain sulphide (<1%), sometimes found as inclusions within the olivine, and these rocks are also biotite-bearing. It is suggested therefore that, for the olivine-bearing rocks in the lower part of borehole AD25 at Arthrath, sulphide saturation preceeded crystallisation of low-Ni olivine. This, along with the relatively low Ni and PGE tenors of both prospects, points to a possible role for an earlier sulphur saturation event in these rocks (Fletcher et al., 1997) and would be consistent with crustal contamination of the rocks at a relatively early stage in their petrogenesis.

McKervey et al. found that one of the Ni-Cu-PGE-rich zones in borehole AD25 is associated with a distinctive orthopyroxenite lithology co-incident with cryptic variations in the composition of orthopyroxene. The texture of the orthopyroxenite suggests that cumulate processes were involved in the formation of this lithology. A sulphide-bearing orthopyroxenite unit displaying some cryptic mineralogical variations within a sequence of noritic rocks has been interpreted in the Proterozoic Bjerkreim-Sokndal layered intrusion, Norway, to result from the mixing of relatively primitive and more differentiated magmas (Jensen et al., 2003). It is suggested therefore that the Arthrath orthopyroxenite unit associated with the upper sulphide zone in borehole AD25, and the occurrence of texturally heterogeneous noritic rocks with it, indicates that mixing/mingling of primitive and more differentiated rocks occurred in the Arthrath intrusion providing an alternative mechanism for the development of sulphur immiscibility.

If, as argued above, mixing/mingling of primitive and more differentiated rocks was the cause of sulphur immiscibility then this process should be evident in the differentiation trends of the rocks from the zones of Ni-Cu-PGE mineralisation. In order to test this theory further the rocks described by McKervey et al. (2007), and those by Fletcher (1989) from the Littlemill-Auchencrieve mineralised zone (contact zone), were compared to examples of the Younger Basic Lower, Middle and Upper differentiation series from the published literature. The Lower, Middle and Upper differentiation series are essentially unmineralised rocks in that they do not contain the sulphide-rich zones that occur at Arthrath and Littlemill-Auchencrieve.

Careful study of the mineral chemistry of these groups of rocks allowed McKervey et al. to propose a model involving processes of magma mixing/mingling with relatively late, primitive magmas containing enhanced Ni-Cu-PGE concentrations emplaced into pre-existing intrusions undergoing differentiation. This would explain why only the most evolved mineralised rocks show strong affinity with the differentiation series (i.e. they are products of differentiation that have been modified at a late stage by the arrival of new primitive magmas resulting in the formation of sulphide-rich zones). Whereas the relatively primitive mineralised rocks define new compositions and 'trends' because they have an entirely different differentiation history from the differentiation series. Thus the composition of the host rocks to the zones of Ni-Cu-PGE mineralisation can vary depending on which part of the differentiation series (Lower, Middle, Upper) is invaded by the newer magma. However, it should be noted that the mineralised rocks, even the most primitive ones, have characteristics (biotite-bearing; high, relatively invariant Se/S ratios; and olivine with relatively low Ni-contents) that would suggest that some, if not all, of these relatively late magmas have experienced an earlier differentiation history involving crustal contamination and sulphur saturation (Fletcher et al., 1997).

Previous studies of the Littlemill prospect have suggested that the geochemical (PGE-Ni-Cu-Fe) patterns indicate remobilization of base and precious metals during amphibolite facies shearing (Fletcher and Rice 1989). By contrast, at Arthrath, Pd values correlate with Fe_2O_3, Ni, Cu, Co, S, Bi, Te, Se, Ag, and Au indicating an orthomagmatic control by primary sulphide liquid remains the dominant mechanism. In addition, the mode of occurrence of the PGM at Arthrath, where the Pd-bearing mineral merenskyite is most commonly found enclosed in sulphide or along sulphide-silicate grain boundaries, supports this hypothesis. Thus it may be concluded that the varied distribution of Pd at Littlemill reflects hydrothermal dissolution and remobilization of primary PGE and host sulphide. In contrast, at Arthrath, the distribution of PGE retains a greater degree of orthomagmatic control by primary sulphide liquid.

The following are the principal conclusions of the work carried out at BGS and presented in McKervey et al. (2007):

1. Crustal contamination is not favoured as the mechanism for sulphur immiscibility recorded in the zones of Cu-Ni-PGE mineralisation in these rocks because of the lack of correlation between high S/Se ratios and sulphide-rich zones in either of the prospects.
2. An orthopyroxenite lithology at the Arthrath prospect, associated with cryptic variations in orthopyroxene composition and a zone of Cu-Ni-PGE mineralisation, is interpreted as the product of the mixing/mingling between relatively late, primitive magmas and earlier magmas that had already differentiated to more evolved compositions.
3. The mineral compositions of all the rocks associated with the sulphide-rich zones from both prospects are consistent with a model involving mixing/mingling between new influxes of primitive magmas into the chamber as the mechanism for sulphur immiscibility and the formation of the sulphide-rich zones.
4. The Ni-Cu-PGE abundances at Arthrath are predominantly of magmatic origin, whereas those at Littlemill-Auchencrieve have a similar origin but have also been substantially modified by later hydrothermal activity.

5.6.3 Application of models to the Arthrath intrusion and implications for exploration

The genetic and empirical models for magmatic nickel-copper sulphide deposits in general, together with those specifically developed in relation to Littlemill-Auchencrieve and Arthrath, provide critical guidance for exploration for this deposit type in north-east Scotland.

The association with primitive mafic-ultramafic rocks is clearly a criterion fulfilled by the 'Newer Basic' intrusions which include olivine cumulates (Lower Zone) at several localities, including Huntly, Insch, Belhelvie and Arthrath. Separation of an immiscible sulphide liquid that settles down to the base of the crystallising magma is a fundamental premise on which exploration for these deposits has been based for several decades, and was the basis for the EVL programme in north-east Scotland. In this region recognition of the basal contact of the individual intrusions is highly problematic on account of the very poor bedrock exposure, especially in the eastern half of the region, and the complex geology of these masses. For example within the Huntly intrusion at least ten discrete bodies of cumulate rocks have been identified, and no consistent 'younging' direction or basal contact can be identified. Furthermore there is evidence for significant disruption by late deformation events on both a regional and local scale which make reconstruction of the original form of the intrusion very difficult. There is also considerable evidence for interaction with and assimilation of country rocks.

Available evidence suggests that similar features and geological complexity are widespread in the region resulting in the development of heterogeneous assemblages of a diverse range of rock types within small areas. Despite this, it is clear that ore-forming processes have been operative in at least two areas, Littlemill-Auchencrieve on the south-eastern marginal contact zone of the Knock intrusion and at the Arthrath prospect near Ellon. At Littlemill-Auchencrieve the effects of post-magmatic deformation and hydrothermal alteration have been such that there is extreme variability along strike at the level of the mineralisation. A small resource was outlined by EVL, but, on account of the later deformation, it was not possible to define an economic deposit.

At Arthrath there is a similar development of Lower Zone cumulate rocks and a wealth of evidence supporting interaction with country rocks that might have induced sulphur immiscibility. On account of limited borehole evidence and the lack of an adequate number of mineral analyses, it is not possible to identify a base or a 'younging' direction within the intrusion. Furthermore the presence of sheared contacts and cross-faulting within the Arthrath intrusion combine to make such a search difficult.

It is clear that at Arthrath there is only a limited understanding of the internal structure of the intrusion and the distribution of mineralisation. The spatial and genetic relationships between the lithologies observed in drillcore are unclear. Sulphide mineralisation is hosted by a range of rock types and occurs in a variety of textural forms with both gradational and sharp contacts. EVL clearly did not understand the controls on the mineralisation because in most of the mineralised zones they drilled both vertical and inclined holes, in more than one direction. Further work is required to characterise the five mineralised zones identified by EVL and to verify that they actually exist. This will require both surface investigations and drilling to determine their boundaries along strike and at depth.

The importance of the segregation of the sulphide liquid from a relatively unevolved magma is important for the development of economic nickel grades. If the olivines present are evolved iron-rich varieties then the nickel tenor of sulphide derived from the same magma will be low and economic sulphide mineralisation will not develop. Primitive magmas carrying magnesian olivine (>Fo80) and containing more than 2000 ppm Ni indicate a nickel-rich magma from which an immiscible sulphide liquid has not segregated. The limited olivine data available from Arthrath (Table 2) support the conclusion that the parental magma may be MgO-rich basalts, comparable with those in the parental magmas of other fertile intrusions in orogenic settings, such as the Svecofennian Ni-Cu intrusions in Finland and the Råna intrusion in Norway.

Available data for the Ni content of olivines in the Arthrath intrusion are very limited. Data reported by Fletcher et al. (1997) and McKervey et al. (2007) indicate levels <1000 ppm Ni. These values indicate that the olivines crystallised from melts already saturated in Ni and thus not likely to source significant sulphide mineralisation with high metal contents. Nevertheless a more systematic study is required in order to delineate sulphur-saturated and sulphur-undersaturated portions of the intrusions. The fact that the intrusions are relatively large and that they contain olivine-bearing ultramafic and mafic rocks provide positive evidence in support of their potential to host nickel sulphide ores. Furthermore the large extent of the Newer Gabbros indicates that large volumes of mantle-derived magmas were potentially available for emplacement along crustal sutures.

Evidence for contamination by crustal rocks is widespread in the region, especially so with the more evolved magmas that crystallised Middle Zone rocks, gabbros and norites. Due to early olivine fractionation and associated incorporation of nickel, contamination of these magmas would not give rise to sulphide mineralisation rich in nickel. Positive evidence for crustal contamination of the early fertile parent magma would significantly enhance the prospectivity for high-grade nickel deposits at Arthrath. It is also important to further test the model of McKervey et al. (2007) at Arthrath, in particular by studying textural and mineralogical variations that might indicate magma mixing and possible related sulphide mineralisation.

Based on the model for the Voisey's Bay deposit, the feeder channels to the main magma chambers and their entry points into these chambers are preferred sites for high-grade sulphide deposits. The feeder channels tend to contain more primitive high-MgO cumulates than the evolved rocks within the main magma chamber. It might be envisaged that the Arthrath intrusion represents a feeder channel for the Haddo House-Arnage intrusions. A detailed petrochemical study would be required to verify this hypothesis. By analogy with the Voisey's Bay deposit, it might be proposed, in simple terms, that the intersection of the east-west Arthrath intrusion with the much larger Arnage-Haddo House bodies to the west represents the point at which the feeder zone entered the main magma chamber. If this were the site of repeated pulses of undepleted magma flow then it would be a highly favourable target for the development of high-grade magmatic nickel-copper sulphide mineralisation of the type developed at Voisey's Bay.

Geological information over the western end of the Arthrath intrusion is particularly sparse and therefore testing the applicability of the Voisey's Bay model in this area will not be a simple task. A programme of work for this purpose should take into account the potential effects of late deformation and the small size of the target. It should also examine all sources of potential evidence for the existence of a feeder zone and for contamination of an undepleted fertile magma.

Nevertheless the considerable strike extent of the mineralisation already demonstrated at Arthrath, together with the considerable thickness of the intercepts of sulphide mineralisation in drillcore, provide strong justification for further exploration in the area. It is clear that magmatic processes have effectively produced significant low-grade sulphide mineralisation. The strike extent and thickness of the known mineralisation, together with observations by Fletcher et al. (1997) and McKervey et al. (2007), provide strong evidence for magmatic control on the mineralisation. On the basis of available evidence, unlike at Littlemill-Auchencrieve, post-magmatic deformation and alteration do not appear to have effectively ruled out the chances of delineating a large deposit at Arthrath.

6 Conclusions

The principal conclusions of this review are:

1. EVL identified nickel-copper sulphide mineralisation of magmatic origin by drilling in the Arthrath intrusion, close to the town of Ellon, in the eastern part of Aberdeenshire. The results of the EVL programme, together with those of subsequent academic and commercial studies, suggest that there is good potential for the discovery of economic mineralisation in the Arthrath intrusion.
2. The EVL drilling programme (36 boreholes; 6850 metres) identified five zones of mineralisation in drillcore over a strike length exceeding 4 km. Limited drilling by Alba Mineral Resources plc in 2005 verified the EVL results in one zone and suggested that the mineralised body in that area might extend down-dip to 350 m below surface.
3. The Arthrath intrusion is lenticular in plan at surface, extending over 7 km east–west and attaining a maximum width of about 1 km. The geology is poorly known in detail on account of a thick till cover that blankets most of the intrusion. Rock types intersected in drillcore comprise a complex sequence of mafic-ultramafic cumulates, xenolithic norites and metasedimentary rocks.

4. No resource figure compatible with international reporting standards has been published. However a figure of 17 million tonnes of ore grading 0.21% Ni and 0.14% Cu has been referred to by various authors, although the basis for this estimate remains uncertain.
5. Several EVL boreholes include thick (>100 m) intercepts of low grade disseminated and interstitial nickel-copper mineralisation, comprising pyrrhotite, chalcopyrite and minor pentlandite. Within these zones several intervals containing economic Ni-Cu grades were reported.
6. The combination of ground exploration methods employed by EVL, based on the analysis of shallow B-horizon soils and IP/resistivity surveys, worked exceptionally well in the Arthrath area.
7. Chemical analysis of a small number of samples from the EVL drilling programme, carried out in the last ten years by Aberdeen University and the BGS, has highlighted potentially significant low tenor enrichments in PGE (up to 200 ppb Pd) and cobalt (up to 900 ppm Co).
8. Petrographic, mineralogical and geochemical data from Arthrath support a dominantly magmatic origin for the mineralisation at Arthrath. Late shear deformation appears to have had only a limited effect on the rocks and included sulphide ores at Arthrath. This contrasts markedly with the Ni-Cu mineralisation discovered by EVL at Littlemill-Auchencrieve in the Knock intrusion.
9. The geology of the Arthrath intrusion remains poorly known in detail. It is not possible to compile a detailed geological map with the presently available data and thus no petrogenetic model has been developed.
10. Further work is required to elucidate the controls on the distribution of mineralisation at Arthrath. This will require a multidisciplinary effort to resolve, including a considerable amount of drilling to test the lateral and vertical continuity of mineralisation and to determine if, in fact, the zones identified by EVL exist.
11. Two models have been proposed for the Ni-Cu mineralisation in the Arthrath intrusion. One of these emphasises the role of crustal contamination as the trigger for sulphide immiscibility and hence for mineralisation. The other model emphasises the mixing of two distinct magmas as the key mechanism for the development of the high-grade ores. It is important that work continues to test and refine these models and thus to enhance their utility in future exploration.
12. It is reasonable to suggest that the Arthrath intrusion may be a feeder zone for the much larger mafic intrusion of Arnage and Haddo House located to the west. By analogy with models for magmatic Ni-Cu sulphide deposits elsewhere, especially the Voisey's Bay deposit, the junction between the two masses is, therefore, a potential site for the development of economic mineralisation.

7 Recommendations for further work

1. Further work is required to test the applicability of the Voisey's Bay model to the Arthrath intrusion and in particular to the area at and around the junction with the Arnage intrusion.
2. Additional work is necessary to test the continuity at depth and along strike within each of the five mineralised zones identified by EVL. It is also important to gain a better understanding of the zoning of the mineralisation. If this zoning actually does exist the nature of the contacts between the zones needs to be clarified and the distribution of mineralisation in these contact zones needs to be defined.

3. The first stage in any future exploration in the Arthrath area should be to acquire and digitise all available legacy data, from the EVL archive at BGS in particular. All spatial data should be integrated into a GIS covering both the outcrop of the Arthrath intrusion and extending for several kilometres in every direction.
4. The digitised helicopter-borne aeromagnetic data from the EVL programme should be acquired and assessed using modern software tools, including the calculation of depth solutions.
5. Available regional gravity data should be reviewed over the Arthrath intrusion and the surrounding area.
6. Surface investigations, including mapping and ground magnetic surveys, should be carried out over the intrusion and its contact zone with the Arnage body.
7. Additional soil geochemical surveys, possibly including selective or partial leach methods, should be carried out where existing data are unclear or absent.
8. It is understood that Alba Mineral Resources plc undertook a programme of ground electromagnetic survey using the UTEM method during 2006. The results of this work should be obtained and assessed by an appropriate specialist consultant. Consideration should be given to further work of this type if the initial results were favourable.
9. Given the complex and poorly known geology and the limited amount of drilling carried out to date, it is important to include a major drilling component in any future exploration programme. In order to identify a resource drilling of about 15 boreholes in proximity to known mineralisation, such as already indicated in the Muirtack zone, should be a priority. Additional drilling should also be carried out along strike from known mineralisation elsewhere in the intrusion and in the contact zone with the Arnage intrusion. These targets should be derived from the integrated analysis and modelling of geophysical and geochemical data and from all available drilling results.
10. It is important that detailed multielement geochemical analysis and complementary petrographic and mineralogical studies are carried out in a systematic manner on all drillcore. This will help to develop models for the petrogenesis and metallogenesis of the intrusion which, in turn, will provide valuable guidance for exploration and drill targetting. Drillcore should be routinely analysed not only for Cu and Ni, but also for Co, Pt and Pd. Gold and a range of other trace and major elements should also be determined in selected samples of mineralised drillcore. The determination of sulphur in mineralised samples is also important in order to assess the compositions of the sulphide (i.e. Ni content in 100% sulphides) and to assess spatial variations in this critical parameter.
11. Available evidence suggests that the Ni content of the sulphides at Arthrath is low. This could be due to a non-fertile parent or to the ineffectiveness of the scavenging process giving only local high-grade ores. The routine determination of the nickel content of olivines should be used as a guide to the nickel depletion of the mafic and ultramafic rocks.
12. Consideration should also be given to conducting gravity surveys to help identify bodies of high density, either ultramafic rocks (favourable targets for nickel sulphide mineralisation) or sulphide ores. A regional survey over the intrusion and the junction with the Arnage body would provide a useful complement to the electromagnetic and other data. More detailed coverage should be acquired around zones of known mineralisation to help elucidate their lateral and vertical continuity. A parallel programme to acquire petrophysical data (magnetic susceptibility, density and conductivity) on a representative suite of drillcore samples should be undertaken to facilitate 2-D and 3-D modelling of geophysical data.

Appendix 1 BGS data holdings for Arthrath

(all work funded under the Mineral Exploration Incentives Grant Act, MEIGA)

COMPANY:	EXPLORATION VENTURES LTD	REF: AE 21
		MRD 84/5/15
PROJECT: ARTHRATH DUDWICK		MRD 144/5/15

The following Open File material is held by BGS in Edinburgh; some is also available in Keyworth. Available for public inspection from 13.6.87.

- Extract from draft application – "Outline of proposed project ... geological considerations ... work programme ..." 6.8.71, with accompanying district location map. 1": 4 miles.

- 1972 Activity Report

  Re: DDHS AD22 to 34

  Submitted with MEG 1 on 6.1.72

  With 7 appendices ...

Appendix 1 – Pitting at Hawkhillock, with the accompanying figures (Figs 1 to 7 all reduced from 6": 1 mile). OS Sheet 93 NE, 1031.

Fig 1	Location of pits
Fig 2	Cu values at 6" pitting
Fig 3	Cu values at 1'– 1'6" pitting
Fig 4	Cu values at 3' pitting
Fig 5	Cu values at 5' pitting
Fig 6	Cu values at 7' pitting
Fig 7	Cu values at 9' pitting
Fig 8 to 15	Pit profiles ½": 1 foot

(Also analytical results for each pit.)

Appendices 2 to 4 – "Results of the Detailed expanding 3 electrode array IP Survey over conductors". With 9 figures.

Cairndailly (NJ93NW)

Fig 1	Position of detailed 3 electrode array (reduced from 6": 1 mile)
Fig 2	IP chargeability and resistivity profiles, Line A
Fig 3	IP chargeability curves, Line A
Fig 4	IP chargeability and resistivity profiles, Line B

Fig 5 IP chargeability curves, Line B

Ardarg (NJ93NE)

Fig 6 Position of 3 electrode array reduced from 6": 1 mile

Fig 7 IP chargeability and resistivity profiles

Fig 8 IP chargeability curves

Piltochie

Fig 9 IP chargeability and resistivity profiles

Appendix 5 – Detailed gradient array survey, Coldwells through to Muirtack, consisting of:

Figs 1 to 6 Chargeability and resistivity results plotted on 1: 5,000 plans (then reduced) NJ93NE and profile for the following areas: West Coldwells, East Coldwells, Mains of Dudwick, Muirtack, Ardganty

Appendix 6 - "Mise-a-la masse" IP survey part of NJ93NE. Reduced from 1: 5,000. Oct '72.

Appendix 7 - Results of drilling programme at Arthrath, consisting of 4 enclosures:

(i) Location plan

(ii) Graphic drill logs holes AD 22 to 34

(iii) Written drill logs holes AD 22 to 34 (73 pages)

(iv) Drill sections holes AD 22 to 34

- "Details of Methods Employed" – with accompanying Scintrex manual. Submitted with application 15.3.73.

- Geological report 9.8.71 to 31.12.71 with the following enclosures:

  Location plan 2½": 1 mile, OS Sheet NJ93

  Graphic drill logs of holes AD 1, 2, 3, 6 and 8

  3 plans showing Detail Soil Cu, Ni and Cr values. 6": 1 mile, NJ93NE, Nov '71

  Gradient array, IP Survey, 1: 5,000 enlargement, NJ93NE, Dec '71

  2 plans, IP resistivity and chargeability, Cairndailly, 6": 1 mile, NJ93NW, Dec '71

  3 vertical force magnetic field results all 1: 5,000 enlargement

  NJ93NE Muirtack

  NJ93NW East of Arnage

  NK03NW Auchleuchries

- EVL Ltd letter dated 26.10.73. Re: "Special Projects" enclosing the following summary reports:

  EVL Soils Research Project

  EVL Summary of Metallurgical Testwork

- 1973 Activity Report (submitted with MEG 1 on 31.7.74) with 4 enclosures:

Fig 1	Plan showing location of drill holes AD 1, 4, 5, 25, 26, 31, 33, 34, 35 and 36, 1: 5,000, NJ93NE, Jan '73.
Fig 2	Graphic drill logs AD 35 and 36. 1: 500, Jan '73
Fig 3	Written drill logs AD 35 and 36
Fig 4	Drill sections AD 35 and 36, 1: 500, Feb '73

- Extract from Riofinex letter dated 10 January 1975, G Cousins, Re: discrepancies in borehole grid references.

- Riofinex letter dated 4 November 1974 enclosing 5 Interim Reports on the Soils Research Project (see Belhelvie open file MRD 144/5/16).

- Amax. Diamond Drill Core Record. One borehole, 77DDA1 (8 x A3 sheets).

- DDH logs: AD 1 – AD 36.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: http://geolib.bgs.ac.uk.

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