Appendix A: Brief Descriptions of Sampled Deposits

HERJA

The epithermal vein system at Herja, consisting of more than 180 veins, is located in the metallogenic district around Baia Mare, northern Romania. Veins are hosted by Samartian-Pannonian volcanics and Neogene and Paleogene sediments. Herja is one of a number of major polymetallic ores of epithermal type of Neogene age in the Carpathians and Apuseni Mts. associated with subduction and slab-detachment (Neubauer et al., 2005).

The Herja veins follow fractures orientated along a ENE-WSW trend which are associated with a subvolcanic body of pyroxene andesite and porphyritic quartz microdiorite (Cook and Damian, 1997). Veins are classified in two sets, the southern and northern. The southern vein set are surrounded by porphyritic quartz microdiorite while the northern veins are enclosed by altered sediments (Cook and Damian, 1997). Hydrothermal activity associated with andesitic volcanism has been dated via the K-Ar method between 11.5 and 8 Ma, with mineralisation occurring at 8.8 ± 0.6 Ma (Edelstein et al., 1992; Lang et al., 1994). As a whole, the system extends to more than 1000 m at a width of 1200 m. Pb and Zn are relatively evenly distributed throughout; little evidence exists for any vertical zonation (Borcos et al., 1975).

The ore is massive, often drusy without abundant vugs, and consists of sphalerite, galena with lesser chalcopyrite, pyrite, pyrrhotite, marcasite, tetrahedrite and various sulphosalts. Gangue minerals are quartz and calcite. Mineralisation is interpreted as being single phase, with pyrite and pyrrhotite deposited first followed by sphalerite and galena. Idiomorphic chalcopyrite, galena and marcasite were deposited last at temperatures probably well below 200 oC, often coating other minerals (Borcos et al., 1975).

TOROIAGA

The Toroiaga epithermal Cu-Pb-Zn-Ag-Au system is part of the Neogene Toroiaga-Tiganul sub-volcanic Massif, Maramures Mountains, northwest Romania (100 km east of Herja). The deposit is comprised of a number of polymetallic hydrothermal veins, some of which are several hundred meters long, which plunge sharply to the southwest (Cook, 1997). These polymetallic veins are interpreted as healing fractures associated with the last of five injections of magma into the epithermal system (Borcos, 1967).

The epithermal system is vertically zoned with chalcopyrite increasing downwards while sphalerite, galena, a rich variety of sulphosalts and gold increase upwards (Borcos et al., 1982). The primary ore minerals at Toroiaga are Au-bearing pyrite and pyrrhotite (at lower levels), chalcopyrite, marcasite, arsenopyrite, sphalerite and galena. The presence of porphyry copper mineralisation beneath the epithermal vein system was proposed by Socolescu (1954) and supported by Chioreanu et al. (1993) but not confirmed. The mine was closed in 2003; additional exploration was carried out in 2006-2008 but failed to establish significant additional reserves.

KOCHBULAK

The Kochbulak deposit is located in the Kochbulak-Kairagach caldera in the Chatkel-Kurama ore district, Uzbekistan. The caldera is located at the intersection of the Southern Angren and Lashkerek-Dukent fault zones and is filled with andesites, dacites and minor volcanics (Akcha and Nadak formations), rhyolite (Oyasai and Kyzylnura formations) and other subvolcanic intrusions (Islamov et al., 1999). Mineralisation is primarily concentrated within volcanics of the Nadak formation. Volcanic rocks have been mildly affected by a propylitic alteration while faults and ore zones concentrate more intense chlorite-epidote and silica alteration (Islamov et al., 1999). These ore zones are controlled by structures resulting in three types of ore; steeply dipping veins, flat lenticular lodes and ore pipes.

Mineralisation is classified in three groups; gold-pyrite, gold-polysulphide and gold-telluride (Islamov et al., 1999). The gold-pyrite mineralisation is most prominent at depth and is typified by low grades of finely dispersed gold in pyrite. The gold-polysulphide group is most prominent at upper levels with gold associated with a complex assemblage of Cu-Pb-Zn-Bi and –Sb minerals (Plotinskaya et al., 2006). The gold-telluride group has gold associated with tellurides such as calaverite, petzite, sylvanite, hessite, stützite and empessite and is most prominent close to surface. Developed reserves at Kochbulak are 5.6 Mt of ore at 13.4 g/t Au and 120 g/t Ag (Islamov et al., 1999).

BAITA BIHOR

Baita Bihor is a Cu-Au-Pb-Zn-Mo skarn deposit located in the northernmost district of the Upper Cretaceous Banatitic Magmatic and Metallogenetic Belt (Ciobanu et al., 2002). This belt extends for 1500 km through Romania, Serbia and Bulgaria, and hosts many intrusion-related ore deposits. The host rocks at Baita Bihor are sedimentary and metamorphic rocks of Permo-Mesozoic and Paleozoic ages, respectively. The skarn system at Baita Bihor (Cioflica et al., 1971; 1977) consists of around 10 orepipes controlled by major faults in the area. A large granite pluton some 1-1.2 km below the surface is responsible for the mineralisation. Ages for intrusion and mineralisation coincide at ~ 74 Ma (Ciobanu et al., 2002; Zimmerman et al., 2008).

The mine closed in 2007. Commodities exploited included Cu, Mo, Zn, Pb and Mo; the main ore minerals are bornite, chalcopyrite, molybdenite, sphalerite and galena. Lesser pyrrhotite, pyrite and magnetite are also present. More than 100 different minerals have been reported, making it well known among mineralogists. The deposit is particularly noted for the unusual enrichment in Bi, which is hosted primarily by a wide range of rare Bi-sulphosalts, many of which are only known from this single locality (e.g. cuproneyite; Ilinca et al. 2012). The abundance of Bi and intimate association of Bi-minerals in the Cu-ores presented a significant problem in ore processing, and was one reason for closure of the operation.

Ores are contained in skarns varying from magnesian (spinel – forsterite – chondrodite – phlogopite) to calcic (scapolite – diopside – wollastonite – vesuvianite) in composition. There is a marked west-to-east metal zonation (Mo-Cu-Pb/Zn) across the orefield, but each orepipe also features similar zonation trends from the core of each orepipe to the skarn-marble contact, sometimes with superposition of discrete zones due to telescoping (Cook et al. 2009, unpubl. consultancy report).

ORAVITA

The Oravita deposit is located ~350 km away from Baita Bihor along the Late Cretaceous Banatitic Magmatic and Metallogenetic Belt, Romania (BMMB; e.g., Ciobanu et al., 2002). The BMMB contains a range of magmatic-hydrothermal mineralization styles relating to the same magmatic event, and formed in subduction settings during Neotethys closure. Oravita is one of the many Cu–Au skarns that are satellite to porphyry Cu–Mo-intrusions within the Banat region (SW Romania and Serbia), known for its rich deposits (e.g., von Cotta, 1864). As with many Cu skarns, it also contains base metal ores and minor W-mineralization (Gheorghitescu, 1975; Cioflica and Vlad, 1981; Constantinescu et al., 1988). Oravita is one of the few localities where gehlenite skarns are known along the BMMB (Katona et al., 2003; Marincea et al., 2011). Although such skarns are barren, they provide an upper temperature limit (~750 °C) for initiation of the skarn system close to intrusion contacts.

ASSAREL

The Assarel Cu-Au deposit (130 Mt reserves @ 0.44% Cu, 0.2 g/t Au) is situated in the Panagyurishte ore district of the central Srednogorie zone, Bulgaria, an ore district featuring a pairing of large porphyry systems with epithermal ‘massive sulphide’ deposits (von Quadt et al., 2005). The Panagyurishte district follows a NNW-SSE orientated structural corridor within the Banatitic Magmatic and Metallogenic Belt (BMMB; Ciobanu et al., 2002), a belt of Late Cretaceous calc-alkaline magmatism. The deposit consists of stockwork-style porphyry mineralization within volcanic host rocks (Angelkov and Parvanov, 1980; Bogdanov, 1987). Geochronology points to multiple generations of intrusion in the Medet-Assarel orefield in the 85-70 Ma period (e.g., Zimmerman et al., 2008). The dominant hypogene quartz + chalcopyrite ± pyrite assemblage is associated with sericitic and sericitic-propylitic alteration. Galena and sphalerite are found mostly in veins at depth, and in the upper part of the deposit where high-sulphidation mineralization overprints porphyry style ore (Strashimirov et al., 2002). Ore mineralogy studies have been carried out by Bogdanov (1987), Petrunov et al. (1991), Strashimirov (1993) and Popov et al. (2000).

BOR

Also hosted in the BMMB is the Bor porphyry system, Serbia. Similar to Panagyurishte, the Bor district is also characterised by hypabyssal intrusions within contemporary volcanic host rocks. However, mineralization within the Bor district occurs over a greater vertical extent and exposed porphyritic intrusions close to mineralization are less common and sometimes only inferred at depth. Ore occurs as stockworks below a high-sulphidation epithermal system; massive sulphide mineralization grades down to porphyry style some 800 m below the current surface (Janković, 1990; Janković et al., 1998). A feature of the district is the large vertical extent of mineralisation exposed across the district. Porphyry-style mineralisation occurs in a variety of styles and at various locations as stockworks in plutonic cupolas (Valja Strz), at the same level as dyke swarms above intrusions (Veliki Krivelj), and as stockworks above intrusions, but below high-sulphidation epithermal ores (Bor; Janković, 1990).

ELATSITE

The >300 Mt Elatsite porphyry copper system is located in the Panagyurishte metallogenetic district in central Bulgaria. This district contains hypabyssal intrusions with approximately coeval volcanic rocks that host the ore. At Elatsite, the porphyritic intrusion is either monzonite or diorite, and is exposed adjacent to the mineralisation (Strashimirov and Popov, 2000). Coupled with the porphyry system is high-sulphidation epithermal-style massive sulphide mineralisation at Chelopech (Kouzmanov et al., 2002). Porphyry ore stockworks are concentrated along the boundary between the porphyry intrusion and the schist/granite basement. The system has a strong potassic alteration and lesser argillic alteration. Mineralisation has been dated at ~92-90 Ma (Von Quadt et al., 2005; Zimmerman et al., 2008), placing it within the same upper Cretaceous metallogenic belt as Baita Bihor (Ciobanu et al., 2002).

The Elatsite deposit is moderately gold-rich, contains a number of rare polymetallic minerals and, notably in the massive magnetite-bornite core, also platinum group metals (Dragov and Petrunov, 1996; Kouzmanov et al., 2000; Strashimirov et al., 2002). Galena-sphalerite-chalcopyrite assemblages are found in distal cm-scale veins at the perimeters of the porphyry mineralisation.

VORTA

Vorta is a massive and disseminated Zn-Pb-(Cu)-(Ag)-(Au) deposit located in the Vorta-Dealul Mare-Barbura belt, Barasti Formation, Romania. Mineralisation is ophiolite hosted and Middle to Late Jurassic in age. The deposit is composed of lenses of variable grade that are discontinuous along an east-west alignment (Ciobanu et al., 2001). Mineralisation comes in two types, the first being massive but compact lenticular and spheroidal bodies with the second being disseminations and veinlets which surround and overprint the massive mineralisation. The fine-grained ore is contained in a reworked, remobilised quartz rich breccia hosted within alkali basalt lavas altered to a calcite-quartz-chlorite-albite assemblage (Ciobanu et al., 2001). The deposit is non-metamorphosed and it is believed to closely resemble VMS-style mineralization formed at the ocean floor.

KAPP MINERAL

The small Kapp Mineral prospect is located 2.5 km east of Isfjorden Radio in the Hecla Hoek Complex, which extends along the entire west coast of Spitsbergen, Svalbard Archipelago. The basement rocks of the archipelago are Precambrian and to a lesser extent lowermost Paleozoic. These rocks, comprising a wide range of metamorphosed sedimentary and igneous lithologies, outcrop widely on Western Spitsbergen. Beginning in the Silurian, around 400 million years ago, these rocks were involved in the formation of the Caledonide mountain chain. Erosion of the mountain chain and development of a central basin began in the Devonian after the end of mountain building, enabling the deposition of thick volumes of sedimentary rocks. This was followed by continued sedimentation throughout the Carboniferous and Permian, and into the Mesozoic as Svalbard moved northwards. The complex is a thick metamorphosed sequence consisting of latest Precambrian, Eocambrian and lower Paleozoic rocks of both igneous and sedimentary origin.

Lead-Zn ores at Kapp Mineral were worked on a small scale in the 1920’s. Sphalerite and galena occur within a brecciated carbonate phyllite (Flood, 1969). The breccia zone, from which the bulk of the ore was exploited is several metres wide and contains a mass of crosscutting calcite veins. Many of these are barren, but some contain veinlets of sphalerite and galena a few cm in thickness.

BROKEN HILL

The giant (>300 Mt) Broken Hill Pb-Zn-Ag orebody lies in the south-eastern part of the Curnamona Craton, South-eastern Australia, within Early to Middle Proterozoic meta-sedimentary and meta-volcanic rocks of the Willyama Supergroup (Haydon and McConachy, 1987). These rocks encompass a range of metamorphic lithologies including pelitic, quartzofeldspathic and mafic rocks (Pidgeon, 1967; Haydon and McConachy, 1987). They were deposited in a continental back-arc environment between ca. 1710-1640 Ma, and were subsequently deformed during the Olarian Orogeny ca. 1600-1580 Ma (Clarke et al., 1986; Stevens, 1986; Stevens et al., 1988; Stüwe and Ehlers, 1997). There is a regional progressive increase in metamorphic grade from northwest to southeast, ranging from andalusite grade to granulite grade (Binns, 1964). Sedimentary rocks of the Adelaidian sequence (ca. 820-750 Ma) were unconformably deposited onto the metamorphic rocks during break-up of the Rodinia supercontinent. Both the Adelaidian and Willyama Supergroups then underwent deformation during the Delamerian Orogeny (520-500 Ma).

There is a substantial literature on the genesis of the Broken Hill orebody (Greenfield et al., 2003; Webster, 2006; Spry et al., 2008). Phillips et al. (1985), Plimer (1986) and Parr and Plimer (1993) argued that deposition of the Broken Hill ore deposit was coeval with bimodal felsic–mafic volcanism and pre-metamorphic alteration. The most commonly accepted (sedimentary-exhalative) genetic model therefore encompasses formation by hydrothermal processes and subsequent multi-phase high-grade metamorphism and deformation. This has been favoured by many authors (Stanton and Russell, 1959; Both and Rutland, 1976; Laing et al., 1978; Plimer, 1979; 1984; 2007; Parr and Plimer, 1993; Marshall and Spry, 2000; Spry et al., 2007).

Overprinting of the Broken Hill deposit during high-temperature metamorphism led to substantial recrystallization of both ore and host rock assemblage. An alternative model involving syntectonic introduction of metals during peak metamorphism or post-tectonic replacement has been proposed (Stillwell and Edwards, 1956; Stillwell, 1959; Lewis et al., 1965; Nutman and Ehlers, 1998; Rothery, 2001; Gibson and Nutman, 2004). A second alternative model considers metamorphic melting of a primary sediment-hosted mineralization (Lawrence, 1967; Mavrogenes et al., 2001). Some researchers (Mavrogenes et al., 2001; Frost et al., 2002; 2005) have argued that extensive melting of the sulphide assemblages may have occurred. Others (e.g. Spry et al., 2008) suggest that although there may have been localised partial melting of minor parts of the ore, there was no substantial liquidation of the sulphides during the metamorphic event.

BLEIKVASSLI

The Bleikvassli deposit is located ~45 km southeast of Mo i Ranan north-central Norway. Mining between 1957 and 1997 produced about 5.0 Mt of ore grading 4.0% Zn, 2% Pb, 0.15% Cu and 25 g/t Ag. The main orebody is made up of interlayered lenses of massive sulphide ore hosted within amphibolites, quartzites, mica schists and quartzofeldspathic gneisses of the Uppermost Allochthon, Scandinavian Caledonides (Ramberg, 1967; Stephens et al., 1985; Bjerkgard et al., 1997). The deposit is believed by most researchers to be of SEDEX-type (Vokes, 1963; 1966; Skauli, 1990; 1992; 1993; Skauli et al., 1992a; 1992b; Moralev et al., 1995; Cook et al., 1998).

The deposit underwent Caledonian metamorphism at peak conditions of roughly 570 °C and 7.5-8 kbar (Cook, 1993; Rosenberg et al., 1998). At least five phases of syn-metamorphic deformation are recognised (Bjerkgard et al., 1995). Spry et al. (1995) identified a syn-metamorphic sulphidation-oxidation halo enclosing the ores. Ore petrography is comprehensively described by (Vokes, 1963). Massive ores are medium-grained (mm-scale) and comprise assemblages of pyrite-sphalerite-galena ore with lesser amounts of pyrrhotite and chalcopyrite. Pyrrhotite and base-metal sulphides occupy the matrix between the pyrite metablasts. A distinct pyrrhotite-rich ore, usually with greater chalcopyrite content and often displaying a brecciated texture, with numerous, generally rounded, clasts of wall-rock schists and vein quartz occurs close to the footwall in the southern part of the deposit. Remobilisation of ore components is abundant, with a characteristic ‘wall rock mineralization’ that includes abundant, coarse Pb-As-(Sb)-sulphosalt-dominant assemblages emplaced in crosscutting veins within wallrock adjacent to massive ore (Vokes, 1963; Cook et al., 1998).

MOFJELL

The Mofjell deposit, located roughly 1 km south of the city of Mo i Rana, north-central Norway, is hosted within metapelitic quartz-mica-feldspar gneisses and amphibolites of the Mofjellet Group in the Rødjngsfjellet Nappe complex of the Uppermost Allochthon of the Scandinavian Caledonides (Saager, 1967; Bjerkgard et al., 2001). Bjerkgard et al. (1997) proposed that the Mofjellet Group was formed in a volcanic arc or a back-arc basin. The Mofjell deposit was under exploitation between 1926 and 1987, producing 4.3 Mt of ore grading 3.61% Zn, 0.71% Pb, 0.31% Cu, as well as sulphuric acid from pyrite. The presence of gold was confirmed during exploration work carried out since 1990; a remaining resource of ~4 Mt is indicated.

The deposit consists of three massive, stratiform lenses and has been metamorphosed at lower amphibolite facies conditions of approximately 550°C and 7 kbar (Bjerkgard et al., 2001). The ores and host rocks have experienced at least one stage of deformation and folding. Like Bleikvassli, the Mofjell deposit is interpreted to be of SEDEX-type (Bjerkgard et al., 2001). Sulphide recrystallization and mobilization of minor elements, including gold, is widespread with sulphosalt-rich remobilizate assemblages noted within thin veinlets, up to 3 cm in width, located in host rocks immediately adjacent to massive pyrite ore (Cook, 2001).

SULITJELMA

The Sulitjelma Cu-Zn orefield (Cook et al., 1990, 1993; Cook, 1996), central-north Norway, hosts over 20 sulphide bodies totalling around 35 Mt of massive sulphide. The sulphide bodies are dominantly, though not exclusively, located at the contact between the Otervatn Volcanic Formation, a dominantly basaltic sequence, and the overlying metasedimentary Furulund Group. Geology and metamorphism of the district are discussed by Boyle et al. (1985), Burton et al. (1989) and Boyle and Westhead (1992). The stratiform and stratabound sulphides are interpreted to have formed as a single stratigraphic interval via chemical exhalative precipitation of hydrothermal fluids onto the seafloor from hydrothermal vents (Cook et al., 1990). Deposit geochemistry is consistent with convective circulation of heated seawater and leaching of subjacent mafic volcanic rocks. Amphibolite facies regional metamorphism and accompanying deformation significantly modified the geometry of individual sulphide lenses and their spatial relationships with associated alteration (Cook et al. 1990). Isoclinal folding led to stacking of mineralized horizons within the stratigraphy; multiple sulphide bodies are arranged *en-echelon* within each horizon (Cook et al., 1993).

Sulitjelma ores are widely cited as spectacular examples of the effects of deformation on sulphide assemblages. These include *durchbewegt* textures, involving milling of refractory sulphides such as pyrite within matrices of ductile sulphides, plastic deformation of giant pyrite porphyroblasts and shearing along the ore horizons producing sulphide mylonites (Cook et al., 1990, 1993; Cook, 1996). There is evidence for sulphide recrystallization, remobilization, and local redistribution of trace elements, including precious metals, within the sulphide bodies (Cook, 1992, 1994, 1996). Chalcopyrite typically occurs, together with lesser sphalerite and pyrrhotite, in the sulphide matrix between coarse pyrite. Remobilized chalcopyrite is also observed filling fractures in refractory pyrite (Cook, 1994). Peak metamorphic conditions have been estimated at ca. 450-500 °C; see also Barrie et al. (2010).

KANMANTOO

The Kanmantoo Cu deposit (<http://www.hillgroveresources.com.au/section/Projects/Kanmantoo>) is hosted within metasedimentary rocks of the Cambrian Kanmantoo Group, Adelaide Fold Belt, South Australia; predominately psammitic schists with lesser aluminous pelites, black shales and calc-silicates (Oliver et al., 1998). Deposition occurred in the Kanmantoo trough about 520 Ma and rocks were deformed and metamorphosed at (~530-630 oC and 2.2-5.4 kbar during the ~500 Ma Delamerian Orogeny (Offler and Fleming, 1968; Sandiford et al., 1992; 1995). Although Thomson (1975), and several more recent authors attributed much of the mineralization to late-stage regional metamorphism, Jensen and Whittle (1969), Verwoerd and Cleghorn (1975), Seccombe et al. (1985), Both et al. (1995) and Spry et al. (2010) regarded the deposit, and others in the same belt, as having a syn-sedimentary (possibly VMS-style) genesis, albeit with substantial evidence for syn-metamorohic deformation and associated remobilization. The most common mineral assemblage in the Kanmantoo ore is quartz-chlorite-garnet ± pyrrhotite ± chalcopyrite. Mineralization is pipe-like and stratabound within a garnet-andalusite-biotite schist (Seccombe et al., 1985). At least three deformation events are recognised (e.g., Toteff, 1999).

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