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Towards creating a set of Battery Mineral Reference Materials

for Applied Mineralogy and Mineral Processing Research

Part 3: Cobalt Reference Materials

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Summary

This study documents the geochemical and mineralogical characteristics of several **Cobalt Reference Materials**, and forms part of **Work Package 5**, Circular Battery Materials Value System, as part of **BATCircle2.0 Project**, in collaboration with partners **Aalto University** and **VTT**. This is **Part 3** of four deliverables, with others covering similar reports on Lithium, Nickel and Reference Materials, along with recommendations for an e-Waste Reference Material.

The new **Reference Materials** reported here comprise **nickel-cobalt matte** (ex-Boliden), **gold-cobalt** bearing drill core samples from **Juomasuo** (ex-Latitude 66), and final **cobalt hydroxide** (ex-Zambia).

Together, they are not designed to be definitive mineral or rock standards, but rather represent samples that have been characterized using multiple methods (optical, e-beam, x-ray beam, laser-beam), at different scales (cm-micron), and in different forms (drill core, crushed and milled ore, thin-section, polished block).

It is the intention that the new data and physical sub-samples will be made available to all those within the **BATCircle2.0 Consortium** who are interested in battery mineral research. Typical end-users for the new materials might include geologists, mineralogists and material scientists interested in testing new analytical or experimental devices; or minerals engineers that require well-characterized materials for flotation, leaching or physical separation experiments.

A novel aspect of the study is that we have used both traditional geoanalytical techniques for battery mineral characterization (whole rock geochemistry, QXRD, SEM-EDS, EPMA, Automated Mineralogy), as well as new and emerging technologies (scanning micro-XRF, LIBS, FTIR, Raman), thus creating a unqiue set of data for the three sample types, including new spectral information which can be used for building mineral identification libraries. Some of the devices used are handheld and are sufficiently portable that they can be operated efficiently in the field, which opens-up the possibility of wider use, leading to new applications in earth and mineral sciences.

The results, whether they be chemical, mineral or textural in nature, largely correlate across the different techniques. This report aims only to document the findings rather than interpret them or compare them to previous work (published or unpublished), as this activity will form the basis of a planned scientific journal paper in 2024, which will compare the relative accuracy and precision of the results across all 4 commodities (Ni-Li-Co-eWaste).

A further planned output from the present study is a quick reference **Fact Sheet** that will accompany each **Reference Material** before they are dispatched to researchers. This will be published separately once the materials are ready for release.

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1 CONTEXT

This report summarises research carried out to date by the **Geological Survey of Finland** (**GTK**), within Work Package 5 (**WP5**), Circular Battery Materials Value System, as part of an on-going **Business Finland**-funded Project, known as **BATCircle2.0**, in collaboration with partners **Aalto University** and **VTT**. The specific and relevant objectives of **WP5** are as follows:

- Extensive characterization of battery materials from both **Primary** and **Secondary** sources
- Development of **Reference Materials** for **Li**, **Co** and **Ni**
- Assessment of how to develop an **e-waste** materials characterization reference material

In order to fulfill these objectives, the following tasks are underway:

- **Task 5.3.1**
  Development of **Reference Materials** for **Nickel**, **Lithium** and **Cobalt**

- **Task 5.3.2**
  Assessment to plan the development of characterization of **Reference Electronic Waste**

Four reports are planned, each covering one of the main topics within Tasks 5.3.1 and 5.3.2. The present report documents the results for new **Lithium Reference Materials**, and is labelled accordingly as **Part 3** (of 4).

2 CONCEPT

The original idea was to create a collection of well-characterized materials that could be used by researchers, whether they be geologists, mineralogists, geochemists, mineral processors, or any other professions linked to battery minerals, metals and materials. Ideally, we wanted to characterize ores (drill cores or hand samples, or run-of mine material), processed products (concentrates), and final materials (saleable products), and make sub-samples of these available to all those interested, along with a fact sheet.

3 STANDARD REFERENCE MATERIAL VS REFERENCE MATERIAL

At the commencement of the **BATCircle2.0 Project**, we wanted to clarify the meaning of the following terms, Standard, Standard Reference Material, and Reference Material.

A **Standard** is generally defined (at least in the world of analytical geomaterials) as a material (say crystal, mineral, rock type) with absolute known values that can be used for calibrating analytical techniques & instrumentation. It is usually available in the form of a fine powder, or a single crystal or

grain, which tends to limit the variability of the standard from sub-sample to sub-sample during manufacture.

On the other hand, a **Standard Reference Material** (again, in the context of analytical geomaterials) is a general term for a so-called *round-robin* material, which is specifically manufactured to be analysed by multiple laboratories in order to establish intra- and inter-laboratory variation, in terms of accuracy, precision, and general variance in results, especially when comparing the same technology (say ICP or XRF), or different technologies (say XRD, SEM and EPMA).

Our preferred terminology, and the one used in the present study, is simply to refer to these types of materials in this study as **Reference Materials**. By using this short descriptor, we imply that materials have been specifically created with scientific and engineering research in mind. These **Reference Materials**, although well-characterized (in terms of their bulk geochemical composition, known mineral content and textures, and other material properties), will display natural variation, from batch to batch, because of their very nature (drill cores, ore lumps, and processed mineral particles), and so cannot be considered as true **Standards**.

Multiple batches of **Reference Material** will be manufactured as aliquots from a Master sample, and made available, in the first instance at least, to members of the **BATCircle2.0 Consortium**, and then later to interested parties outside, depending on demand and availability of material. Each batch will be accompanied by a **Fact Sheet**, which we believe will be adequate to allow the recipient to plan and design their own experiments, and is certainly an excellent starting point for any further research on them. Ideally, additional analytical work on these batches would then be fed back to the GTK and incorporated into documentation of any future batches. The kinds of uses we envisage for these **Reference Materials** might include, but are not restricted to, the following: teaching, research, professional development, fingerprinting (tracking and tracing), general metallurgical testing, and technology testing.

4 GEOANALYTICAL TECHNIQUES USED TO CHARACTERIZE THE REFERENCE MATERIALS

There are a bewildering number of analytical techniques that are currently available to geologists when it comes to the characterization of drill cores, crushed core and particulate mineral products. These include: optical methods (petrographic microscopy); X-ray analysis (XRF, XRD, X-CT), electron-beam analysis (SEM, EPMA) and laser-based techniques (LA-ICP-MS, Raman, LIBS) and others (FTIR).

In the present report, we document many of these for a suite of **Cobalt-bearing Reference Materials** sampled from various deposits in Finland (see **Table 1** below) have been characterized using the META multidisciplinary geomaterial workflow developed by X-ray Mineral Services (XMS UK) to explore various Mineralogical, Elemental and Textural Analyses (META) to provide cross-validated analytical data. Specifically, the “gold-standard” techniques of XRD and Automated Mineralogy (AMICS) were used to characterise the samples.

5 DETAIL OF THE MASTER SAMPLES USED TO MAKE THE COBALT REFERENCE MATERIALS

Cobalt-bearing samples from different localities in Finland (and Zambia) were selected as potential sources for **Cobalt Reference Materials**:

- **Cobalt hydroxide** (ex-Zambia)
- **Nickel-cobalt matte** (from Boliden)
- **Cobalt-bearing drill core samples** (from Latitude 66)

The table below summarises the sample details:

Table 1. Samples analysed and their LIMS number identifier.

Sample Number	Description
Juomasuo 73	Gold-cobalt ore crushed drill core
Juomasuo 166	Gold-cobalt ore crushed drill core
Ni-Co matte	Harjavalta Boliden reference material
Co hydroxide	AHKZ Reference material

6 CHARACTERIZATION OF THE COBALT REFERENCE MATERIALS

Due to the potentially hazardous (and contaminating) nature of the nickel-cobalt matte and the cobalt hydroxide, only automated mineralogy analysis (**AMICS***) was performed on them. The drill cores, however, were analysed by **XRD**, **XRF** and **AMICS***.

X-ray diffraction is a robust whole-rock analytical technique for identifying minerals and phases present in a sample, based on their characteristic diffraction patterns, and when used in conjunction with specialised software, the **Rietveld method** allows for quantitative modal analysis (**XRD**). Minerals present in low quantities (5 vol% or less) can be problematic for XRD. Some minerals display overlapping diffractograms, leading to challenging identifications. The technique relies on the ability to determine the crystallinity of the mineral for a positive identification to be made, and therefore amorphous minerals are therefore problematic. Sample needs to be pulverized to a fine powder.

X-ray Fluorescence Spectrometry (**XRF**) is a standard method of analysis in order to gain a bulk geochemical analysis of any geomaterial. It is ideal for major elements, some minor elements, but is generally unsuitable for trace and ultra-trace elements, such lithium. The sample is typically required to be in the form of pressed powdered pellets or glass beads.

Automated Mineralogy is an established method to map 2D polished surface of samples by Scanning Electron Microcopy using Energy Dispersive Spectrometry (**SEM-EDS**) to determine micro-composition, and to create mineral maps with textural details that allow for quantification of grain sizes, shapes and associations. Grain boundaries, inclusions, and fractures can also be mapped. The sample is usually presented to the instrument in

the form of a thin section or polished block. Scanning resolution can be down to as little as 1 micron, but typically a stepping interval greater than this is used to speed up measurement time.

7. TECHNICAL INFORMATION FOR COBALT REFERENCE MATERIALS

7.1 XRD - Mineralogical analysis

X-Ray diffraction (**XRD**) is an analytical technique used for the quantitative determination of minerals present in crystalline material such as rocks. The method depends upon the unique structural properties of the analysed crystals and measures the intensities and scattering of the x-rays leaving the sample.

Two Latitude 66 drill core samples were analysed for XRD, details of which are provided in Table 1. All samples were prepared and analysed at X-ray Mineral Services Ltd, Colwyn Bay, UK.
and drying the filtrate on the filter paper. The samples were analysed as an untreated clay, after saturation with ethylene glycol vapour overnight and following heating at 380°C for 2 hours, with a further heating to 550°C for one hour.

The clay filters were scanned on a Philips PW1730 Generator with a CuKα radiation at 40 kV and 40 mA. from 3 to 35° (2θ) at a step size of 0.05° and 2 s step time.

7.2 XRF

X-ray Fluorescence Spectrometry (**XRF**) is a standard method of analysis in order to gain a bulk geochemical analysis of any geomaterial. It is ideal for major elements, some minor elements, but is generally unsuitable for trace and ultra-trace elements, such lithium. The sample is typically required to be in the form of pressed powdered pellets or glass beads.

7.3 Automated SEM-EDS Analysis

All four samples were prepared and investigated by Helford Geoscience LLP using automated SEM-EDS analysis to quantify the phases present.

On receipt, the samples were double sealed within plastic zip lock bags (**Figure 1**). Risk assessments were provided for the Ni-Co matte and the Co-hydroxide sample. The samples were digitally photographed. The two ore samples were examined using binocular microscopy. All four samples were subsampled and prepared as resin impregnated polished blocks and carbon coated prior to analysis. Care was taken to avoid any aerosol particles and skin exposure in the Co hydroxide sample.

The mineralogy and texture of the sample was quantified through automated SEM-EDS mineral analysis (Schultz et al., 2020). Analysis was undertaken using a Hitachi SU3900 scanning electron microscope fitted with two large area (60 mm²) Bruker SDD energy dispersive spectrometers and running the **AMICS*** automated mineralogy software package. Beam conditions were optimised for analysis and therefore an accelerating voltage of 20kV coupled with a beam current of approximately 15 nA were used. The sample was

measured with a segmented field image mode of analysis. This analytical mode subdivides the BSE image into domains (segments) of similar brightness which represent different mineral grains / crystals and then acquires a representative EDS X-ray spectrum from a point within the segment; the mineral identified is then assigned to the entire segment. Measurements were optimised to highlight both textural and modal mineralogical information and a resolution of 5 µm was achieved.

The EDS spectra acquired during the measurement are compared with a library of measured and synthetic standards and a mineral identification is made on a closest match basis. Phases which are not represented in the standards list at the time of measurement are added either by acquiring reference spectra directly from the sample, or by creating a reference spectrum from the measurement itself. As the standards list can comprise hundreds of reference spectra, the data are grouped into a final, reported mineral list (**Table 2**). It should be noted that the samples had previously been polished using Al powder, which may be present ingrained into fractures in the surface; the possible presence of this Al has been considered during the data processing. Modal data expressed as both area % and mass % are provided. During the Automated Mineralogy analysis full area SEM-BSE montages are also captured of the analysed areas.

***AMICS** is an acronym for Automated Mineral Identification and Characterization System by Bruker. This technology brings together a high-resolution BSE imaging (back scattered electron) with a high-throughput EDS (energy dispersive spectrometer) for a solution that automates the collection of data from the Scanning Electron Microscope (SEM) and provides tools for the identification of phases (mineral or synthetic). The technique provides a quantitative breakdown of sample mineralogy along with key textural information in a spatially resolved sample map. AMICS is the next generation characterization tool for detailed and quantitative analysis of samples incorporating innovative imaging and analysis.

Figure 1. Co reference materials submitted for AMICS mineral analysis.

8. RESULTS - AUTOMATED MINERALOGY

A general summary of the AMICS mineral list is provided in **Table 2, with modal results in Table 3**

Table 2. Mineral groupings used to process the data.

Mineral	Description
Quartz	Silica group of minerals (e.g., quartz, cristobalite, etc). Includes opal and chert.
K Feldspar	K-rich alkali feldspar including orthoclase, sanidine & microcline.
Plagioclase	Albite to anorthite solid solution. In this study, predominantly albite.
Muscovite	Muscovite and Al-rich white mica such as sericite.
Biotite	Biotite and phlogopite. May include Ti-bearing mica varieties.
Kaolinite	Kaolinite and dickite.
Chlorite	Chlorite group minerals such as chamosite and clinochlore etc. May include specific compositions of garnet and/or tourmaline If present.
Fe Al Silicates	Mg-bearing Fe Al Silicates such as orthorhombic amphibole and specific, Al-rich, compositions of chlorite.
Mg Silicates	Mg silicates such as olivine, talc, and serpentine.
Illitic Clays	Illite and illite-dominant illite-smectite. May include specific mixtures of kaolinite and illite.
Calcite	Calcite and ferroan calcite.
Dolomite	Non-ferroan dolomite.
Mg Oxide and Carbonate	Mg oxides, hydroxides and carbonates such as brucite and magnesite.
Fe Oxide and Carbonate	Fe oxides and hydroxides such as goethite and hematite.
Ti Oxide	Ti oxides such as ilmenite, rutile and anatase.
Pyrite	S-rich Fe sulphides such as pyrite and marcasite.
Pyrrhotite	Fe-rich Fe sulphides such as pyrrhotite and troilite etc.
Fe Sulphate	Fe sulphates and S-bearing Fe oxides and hydroxides.
Cu Sulphide	Cu sulphides such as chalcopyrite, bornite, and chalcocite.
Cu Oxide	Cu oxides, hydroxides and carbonates.
Sphalerite	Zn sulphides such as sphalerite.
Galena	Pb sulphides such as galena. May include cerussite.
Cobaltite	Cobaltite and Co-bearing arsenopyrite.
Ni Sulphide	Ni sulphides such as mackinawite, millerite, and violarite. Typically contains minor amounts of Fe and possibly traces of Co. May include pentlandite.
Ni Fe Sulphate	Ni-bearing Fe sulphates. May include S-bearing oxides and hydroxides.
Fe Ni Oxide	Fe-rich, Ni-bearing oxides and hydroxides.
Co Oxide	Co-rich Ni-bearing oxides and hydroxides. Often contains small amounts of Mn.
Co Sulphate	Co-rich sulphates. May include oxidised Co sulphide. Contains small amounts of Fe and Mn. Likely to be Co hydroxides
Co Mg Sulphate	Co- and Mg-bearing sulphates. May include finely intermixed Co sulphate and Mg oxide / carbonate.
Fe Co Phosphate	Fe- and Co-bearing phosphates. Often contains small amounts of Mn.
Co Mg Oxide	Co-bearing Mg oxide and hydroxide. May contain small amounts of Mn.
Molybdenite	Mo sulphide.
Ca Sulphate	Ca sulphates such as gypsum and anhydrite.
Barite	Ba and Sr sulphates such as barite and celestine.
Apatite	Ca phosphates such as apatite and francolite.
Zircon	Zircon, monazite and other HFSE or REE-bearing minerals.
Undifferentiated	Phases not included in the above categories.

Table 3. Modal mineralogy for the four **Cobalt Reference Materials**, with minerals of interest highlighted.

Sample Name	Juomasuo 73	Juomasuo 166	Ni-Co matte	Co hydroxide
Pixel size (µm)	2	1.6	10	1.1
Quartz	43.15	31.03	0.01	1.45
K Feldspar	0.16	0.20	0.00	0.01
Plagioclase	11.80	26.92	0.00	0.03
Muscovite	12.38	23.57	0.00	0.02
Biotite	7.10	0.15	0.00	0.02
Kaolinite	0.02	0.00	0.00	0.00
Chlorite	3.48	1.51	0.00	0.01
Fe Al Silicates	11.77	0.16	0.00	0.00
Mg Silicates	0.11	0.02	0.00	2.75
Illitic Clays	0.32	0.55	0.00	0.05
Calcite	0.00	0.00	0.00	0.20
Dolomite	0.00	0.00	0.00	0.14
Mg Oxide and Carbonate	0.00	0.00	0.00	3.61
Fe Oxide and Carbonate	0.52	0.05	3.67	0.02
Ti Oxide	0.03	0.37	0.00	0.00
Pyrite	1.62	1.67	0.00	0.00
Pyrrhotite	7.11	12.49	0.00	0.00
Fe Sulphate	0.02	0.38	0.01	0.00
Cu Sulphide	0.02	0.10	7.53	0.00
Cu Oxide	0.00	0.00	0.64	0.00
Sphalerite	0.01	0.09	0.00	0.01
Galena	0.01	0.03	0.00	0.00
Cobaltite	0.17	0.33	0.00	0.00
Ni Sulphide	0.00	0.00	80.38	0.00
Ni Fe Sulphate	0.00	0.00	0.09	0.00
Fe Ni Oxide	0.00	0.00	7.60	0.00
Co Oxide	0.00	0.00	0.02	10.20
Co Sulphate (hydroxide)	0.00	0.00	0.00	60.47
Co Mg Sulphate	0.00	0.00	0.00	11.51
Fe Co Phosphate	0.00	0.00	0.00	3.74
Co Mg Oxide	0.00	0.00	0.00	4.57
Molybdenite	0.00	0.22	0.00	0.00
Ca Sulphate	0.00	0.00	0.00	1.03
Barite	0.00	0.00	0.00	0.00
Apatite	0.14	0.01	0.00	0.01
Zircon	0.04	0.02	0.00	0.01
Undifferentiated	0.00	0.10	0.04	0.15
Total	100.00	100.00	100.00	100.00

8.1 Sample Juomasuo 73

Figure 2. Binocular optical microscope images of sample Juomasuo 73. Scale bar is 5 mm.

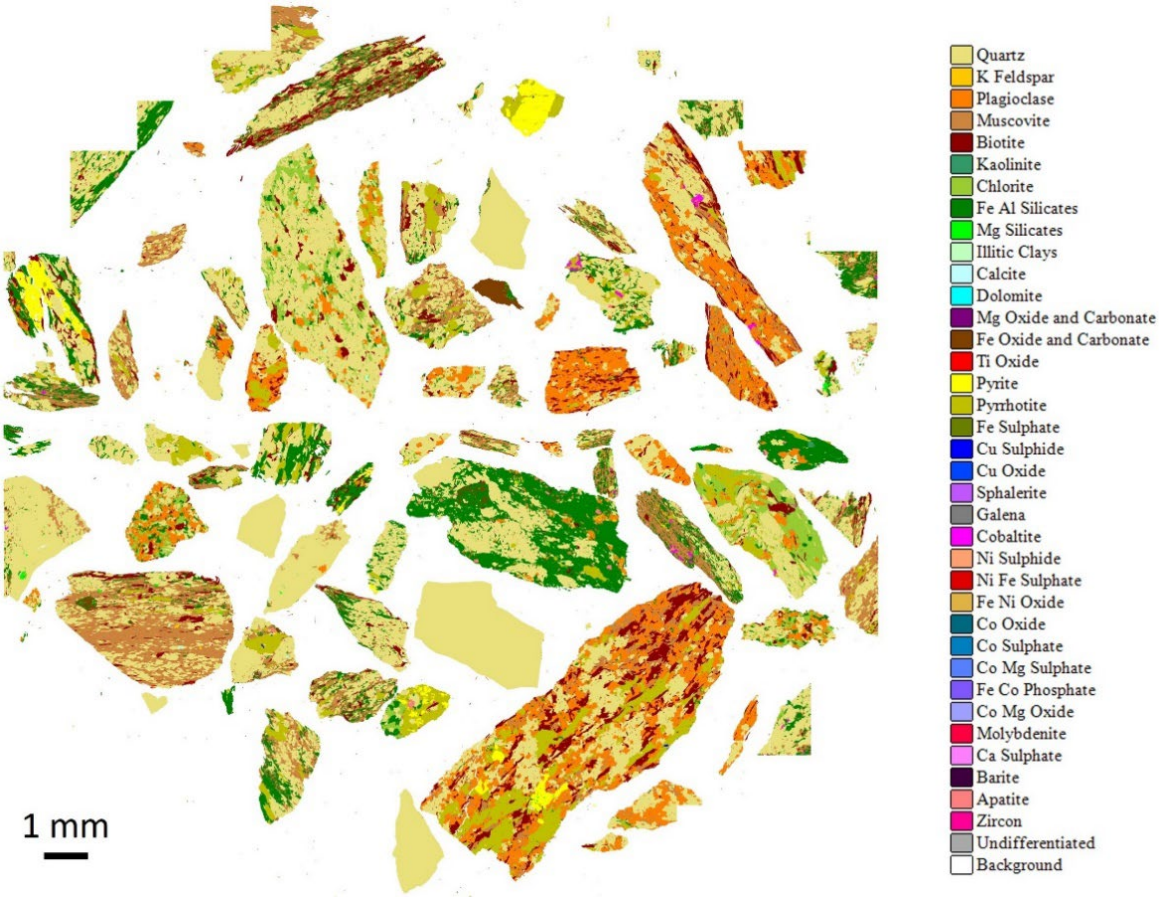

Figure 3. AMICS particle images for sample Juomasuo 73

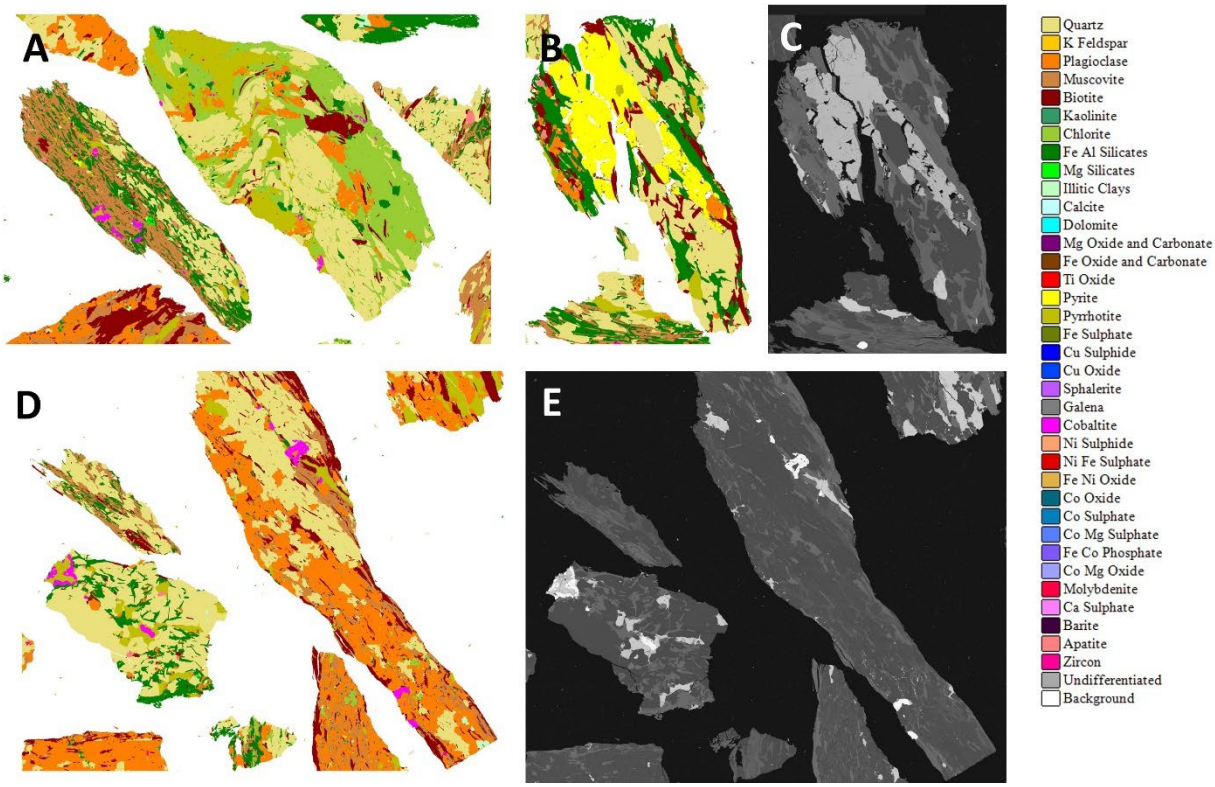

Figure 4. Enlarged area AMICS particle images (A, B, D) and corresponding SEM-BSE images (C, E), for sample **Juomasuo 73**. (A) Folding in AMICS particle image. (B, C) Pyrite and pyrrhotite parallel to the mineral fabric. (D, E) Cobaltite grains (fuchsia pink) in part associated with pyrrhotite.

Brief description of results

The sample is dominated by major quartz (43.15%), plagioclase (11.80%), muscovite (12.38%) and FeAl silicates (11.77%) along with minor biotite, chlorite, pyrite (1.62%) and pyrrhotite (7.11%). Trace phases are: K feldspar, kaolinite, Mg silicates, illitic clays, Fe oxide/carbonate, Ti oxide, Fe sulphate, Cu sulphide (0.02%), sphalerite (0.01%), galena (0.01%), cobaltite (0.17%), apatite (0.14%) and zircon. The AMICS mineral image is provided in Figure 3. The individual crushed rock fragments show well defined metamorphic fabrics. Sulphides (pyrite and pyrrhotite) tend to co-occur but are not uniformly distributed between the different fragments. Cobaltite typically occurs as discrete crystals or associated with pyrrhotite and quartz.

Enlarged AMICS images are provided in **Figure 4** highlighting the textural features. The full area SEM-BSE image is provided in **Figure 5**.

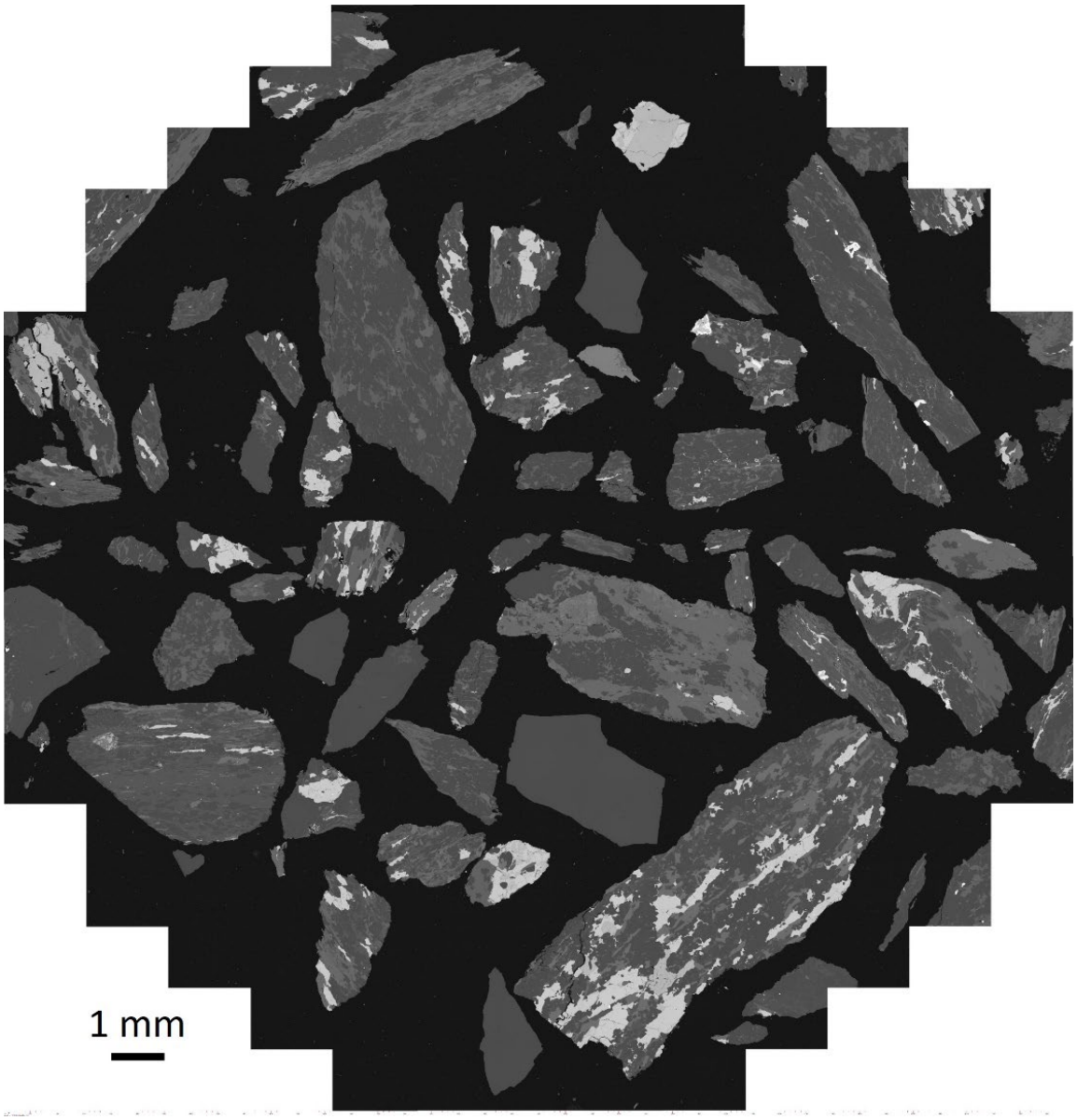

Figure 5. SEM-BSE particle images for sample **Juomasuo 73.**

8.2 Sample Juomasuo 166

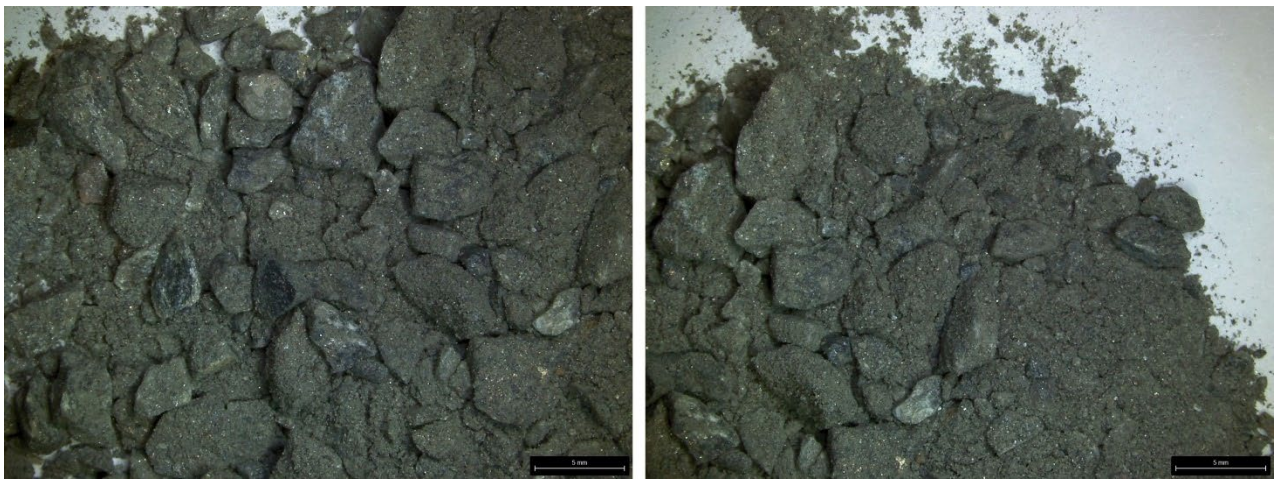

Figure 6. Binocular microscope images for sample **Juomasuo 166**. Scale bar is 5 mm.

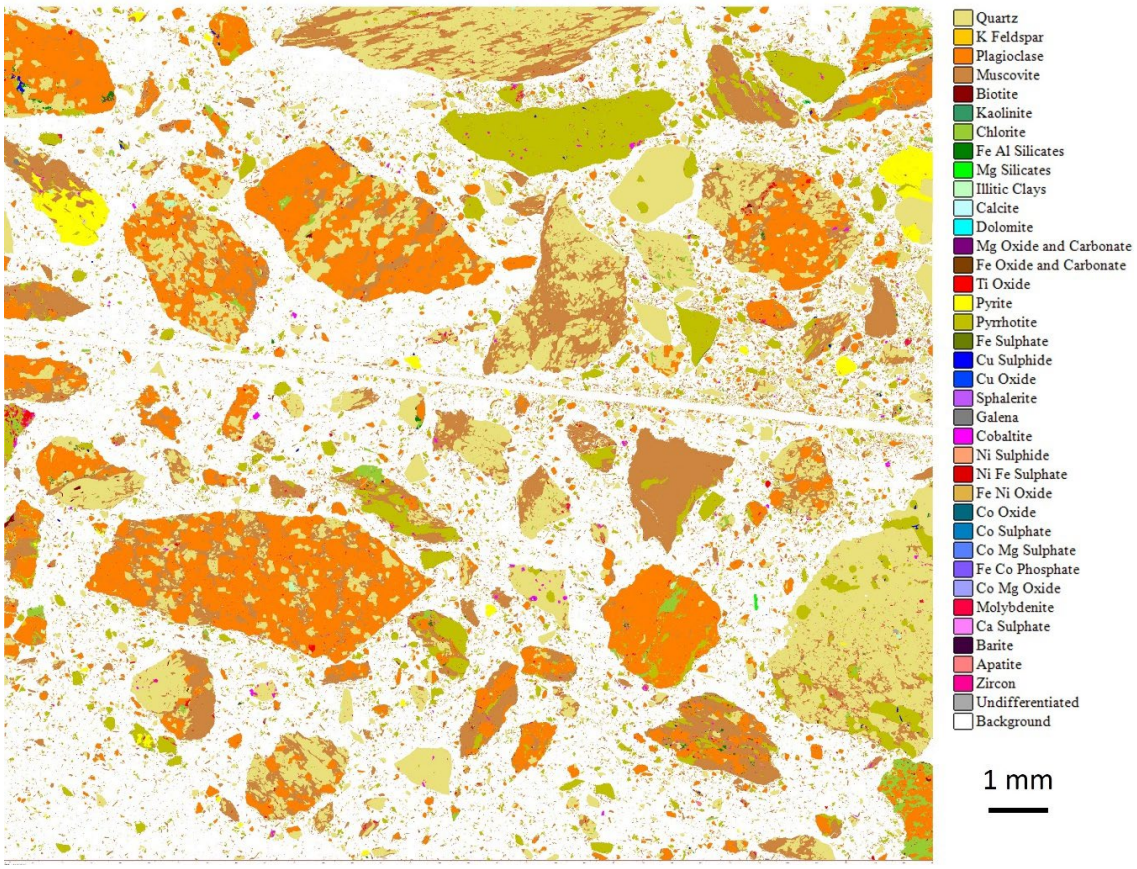

Figure 7. AMICS particle images for sample **Juomasuo 166**.

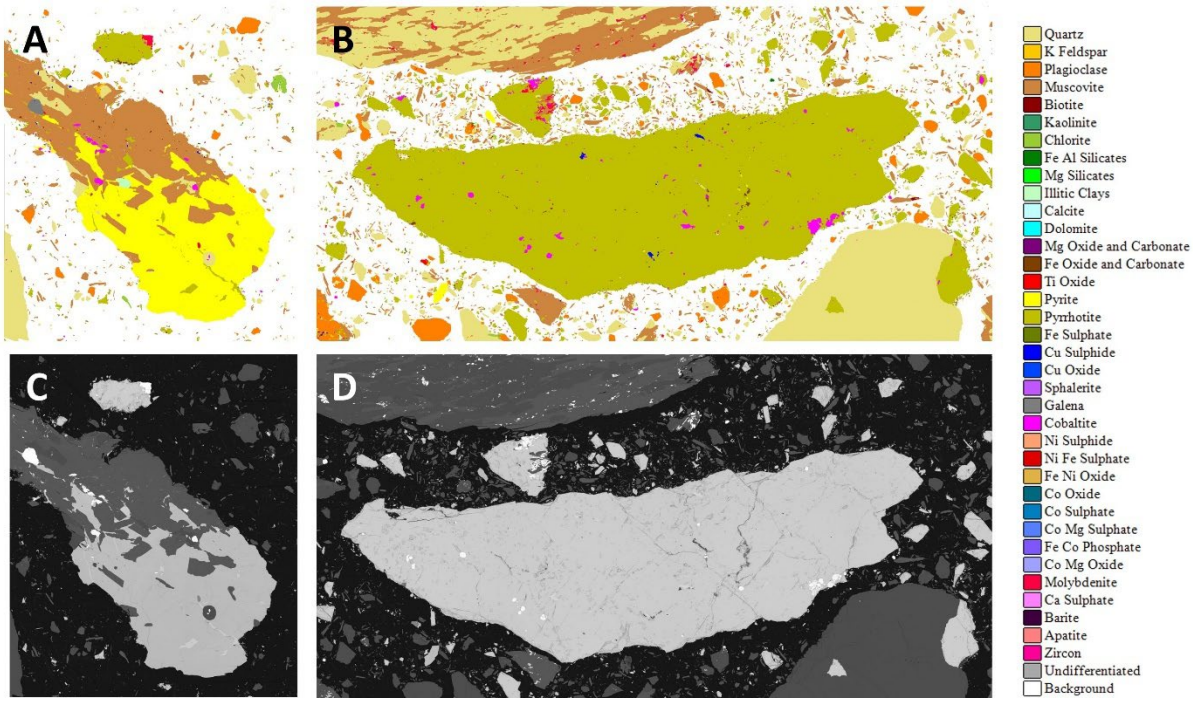

Figure 8. Enlarged area AMICS particle images (A, B) and corresponding SEM-BSE images (C, D), sample **Juomasuo 166**. (A, C) Pyrite and (B, D) pyrrhotite with small grains of cobaltite.

Brief description of results

The sample is dominated by major quartz (31.03%), plagioclase (26.92%), muscovite (23.57%) and pyrrhotite (12.49%) along with minor chlorite and pyrite (1.67%). Trace phases are: K feldspar, biotite, FeAl silicates, Mg silicates, illitic clays, Fe oxide/carbonate, Ti oxide, Fe sulphate, Cu sulphide (0.10%), sphalerite (0.09%), galena (0.03%), cobaltite (0.33%), molybdenite (0.22%), apatite (0.01%), zircon and undifferentiated. The AMICS mineral image is provided in **Figure 7**. The individual crushed rock fragments show well defined metamorphic fabrics. Sulphides (pyrite and pyrrhotite) appear coarse grained and are not uniformly distributed between the different fragments. Cobaltite typically occurs as small discrete crystals associated with pyrite and pyrrhotite; small, liberated cobaltite grains are also present. Enlarged AMICS images are provided in **Figure 8** highlighting the textural features. The full area SEM-BSE image is provided in **Figure 9**.

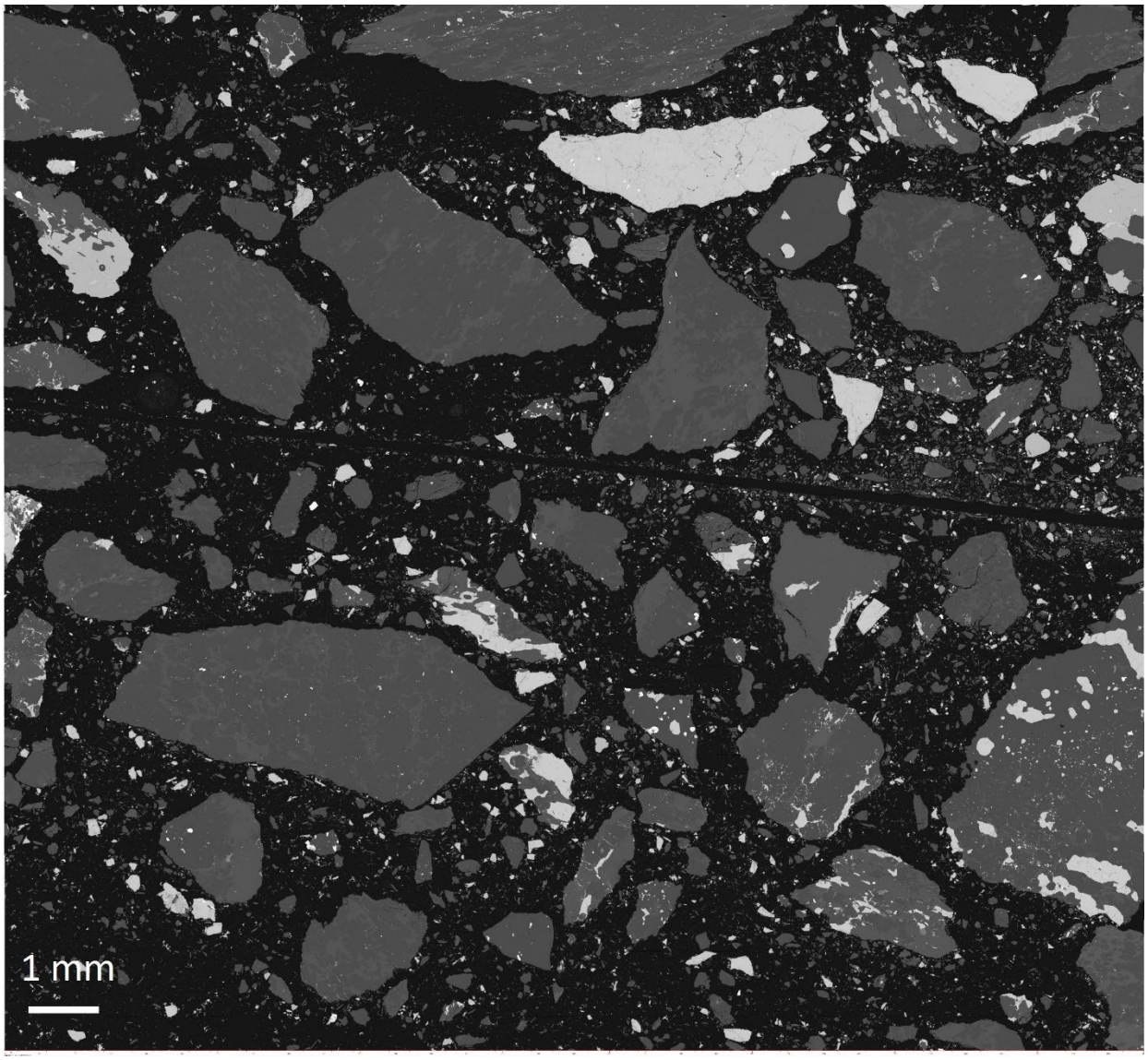

Figure 9. SEM-BSE particle images for sample **Juomasuo 166**.

8.3 Sample Ni-Co matte

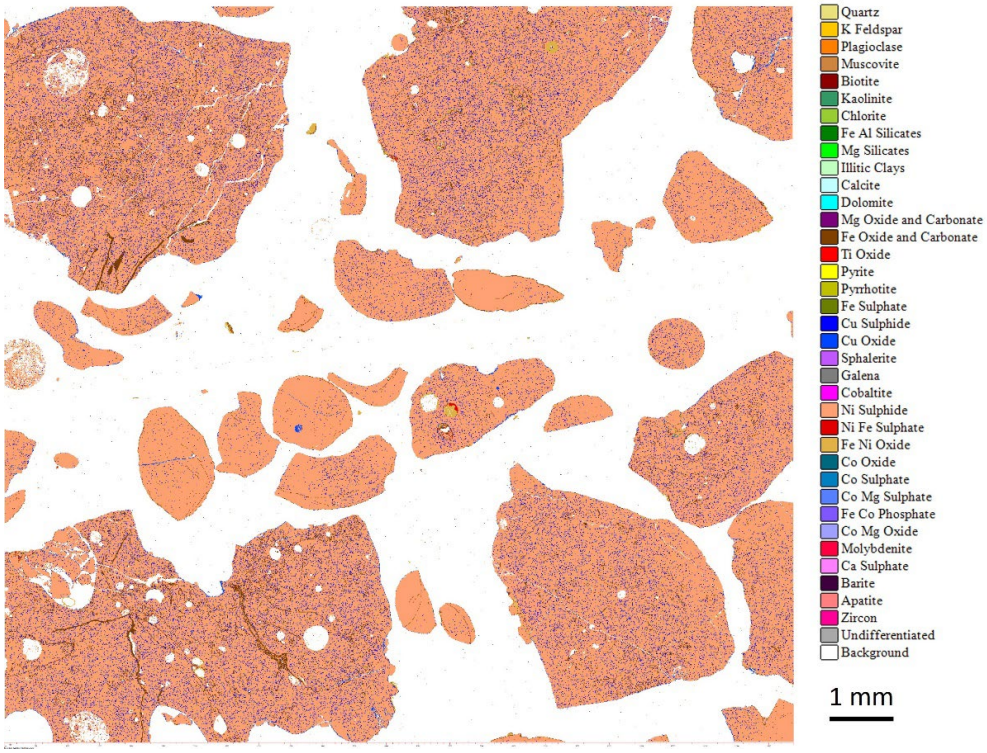

Figure 10. AMICS particle images, sample **Ni-Co matte**.

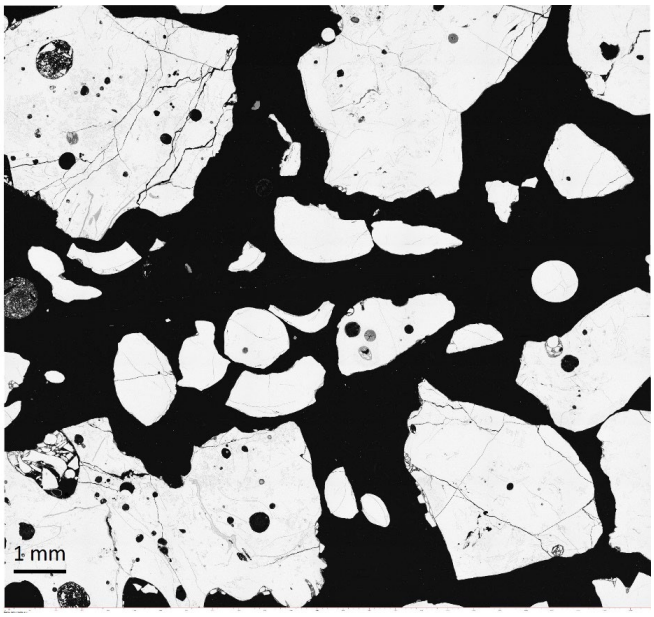

Figure 11. SEM-BSE particle images Sample Ni-Co matte.

8.4 Sample Ni-Co matte

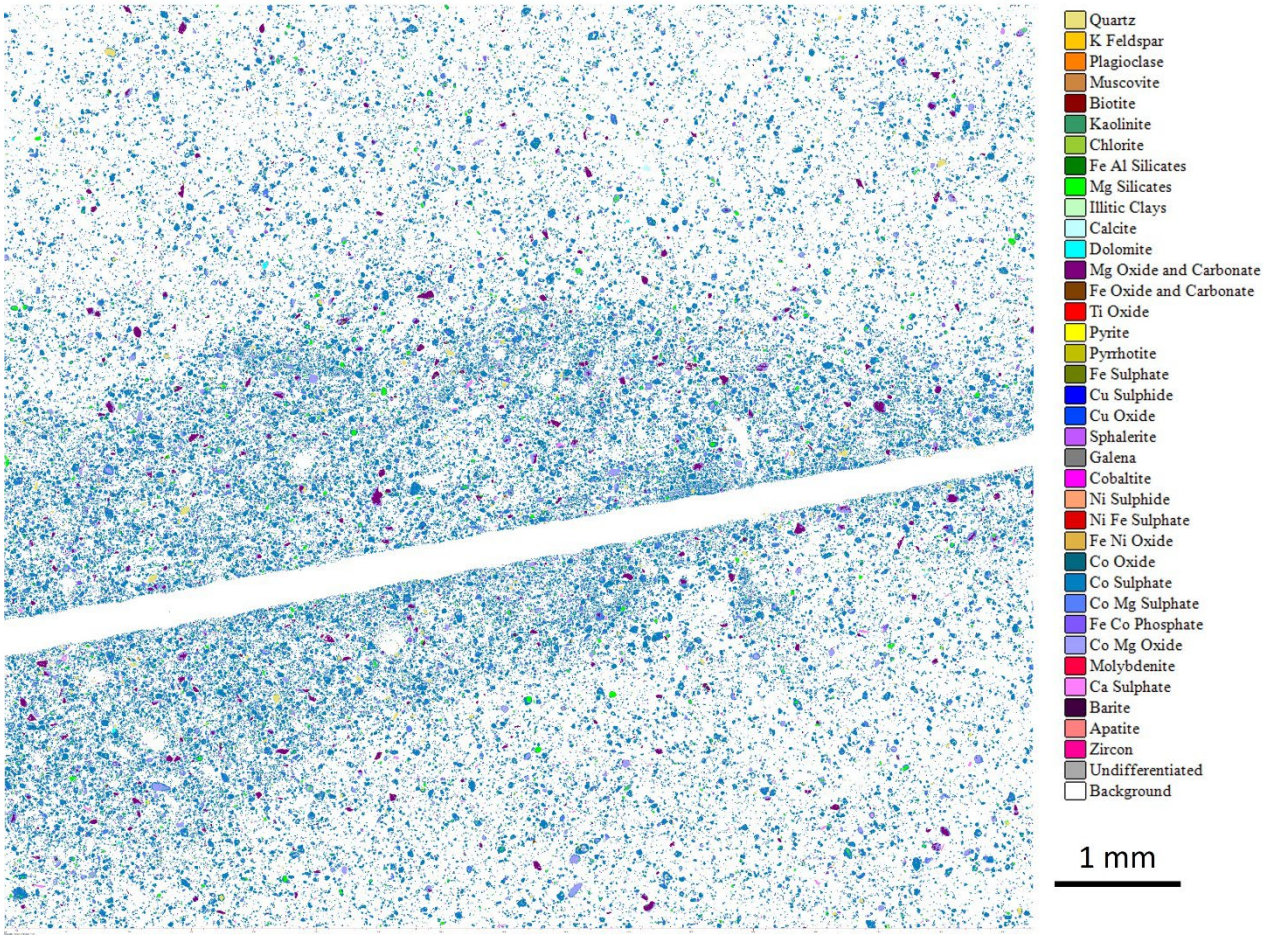

Figure 12. AMICS particle images for sample Co-hydroxide.

Brief description of results

Sample Ni-Co matte is dominated by a major Ni sulphide phase (80.38%) which contains trace Co along with minor FeNi oxide (7.60%) and Cu sulphides (7.53%), Fe oxide/carbonate (3.67%) and trace Cu oxides (0.64%). Other trace phases present are quartz (0.01%), Fe sulphate (0.01%), NiFe sulphate (0.09%), Co oxide (0.02%) and undifferentiated (0.04%). The AMICS mineral image is provided in Figure 10 with the full area SEM-BSE image in **Figure 11**. The AMICS image shows that the phases are intergrown.

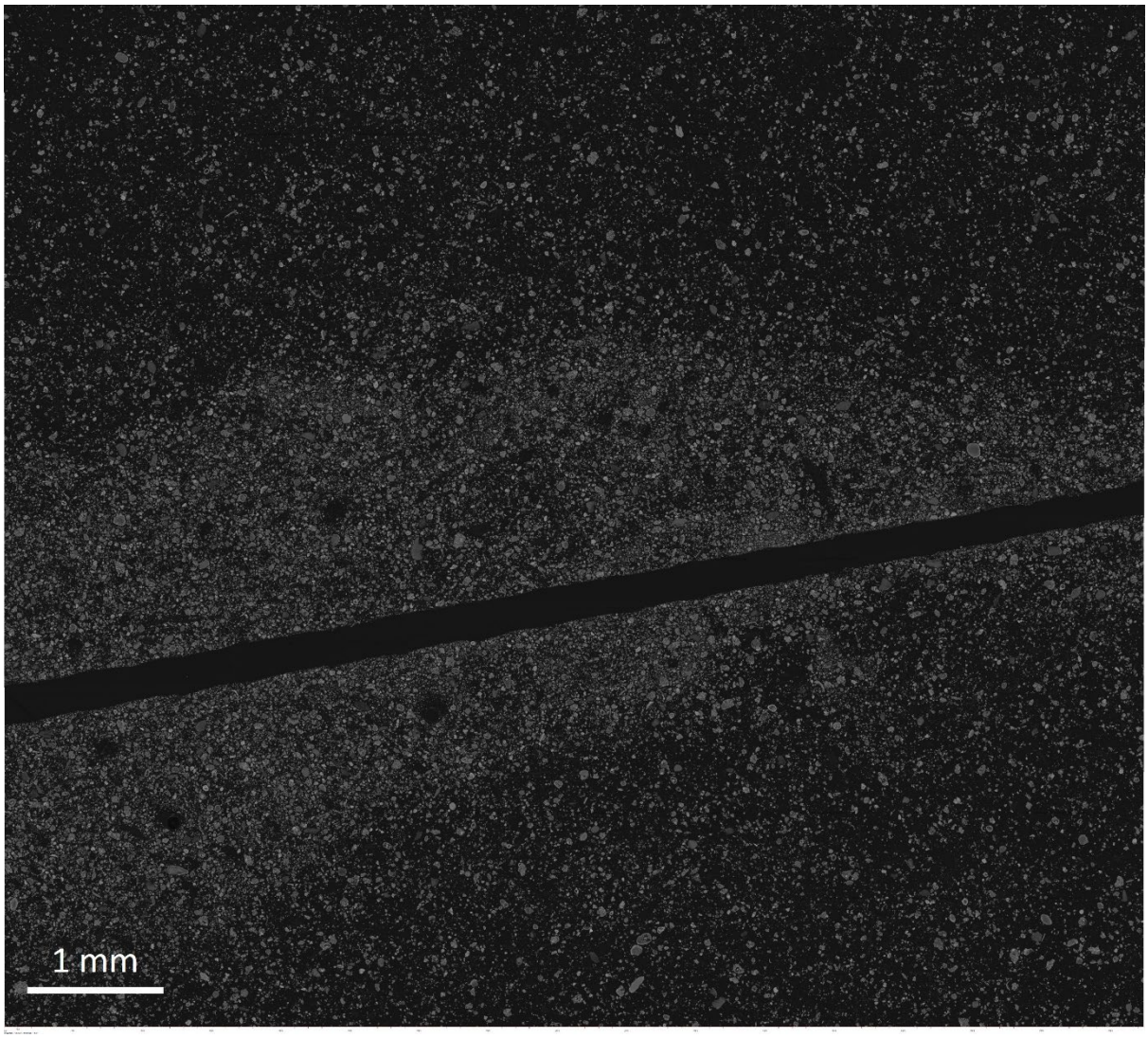

Figure 13. SEM-BSE particle images, sample **Co-hydroxide**.

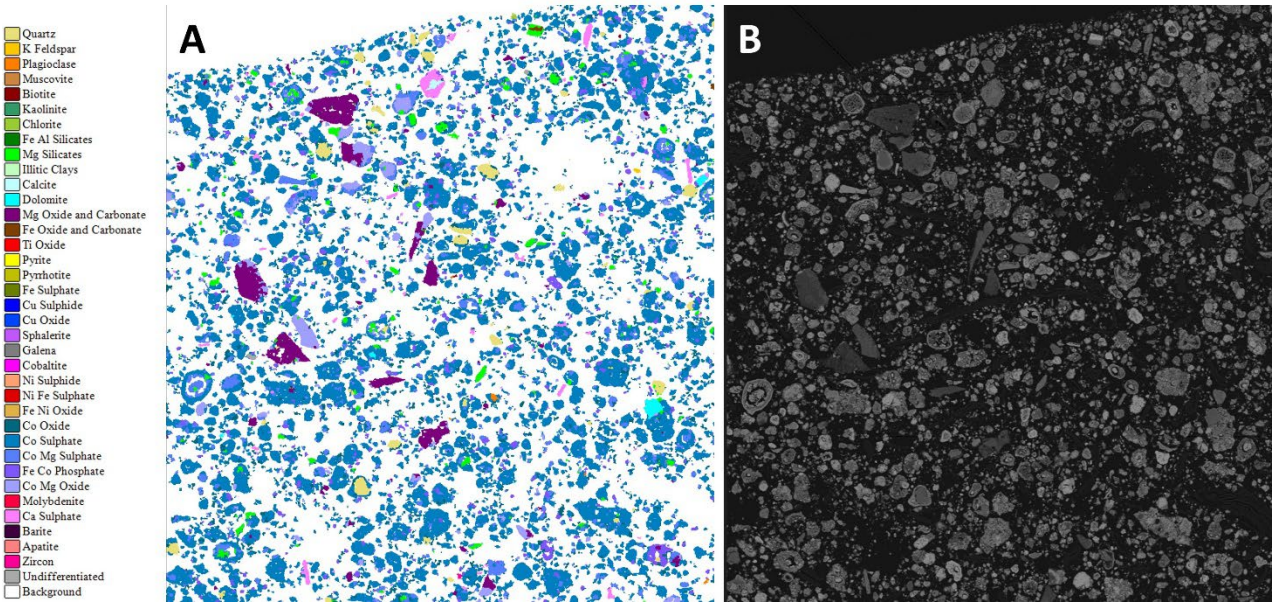

Figure 14. Enlarged area (A) AMICS particle images and (B) corresponding SEM-BSE particle images, sample **Co-hydroxide**.

Brief description of results

The sample described as Co hydroxide is dominated by a major Co sulphate (hydroxide) phase (60.47%) along with minor major CoMg sulphate (11.51%) and Co oxide (10.20%) along with minor quartz, Mg silicates, Mg oxide/carbonate, FeCo phosphate (3.74%), CoMg oxide (4.57%) and Ca sulphate. Other trace phases present are K feldspar, plagioclase, muscovite, biotite, chlorite, illitic clays, calcite, dolomite, Fe oxide/carbonate, sphalerite, apatite, zircon and undifferentiated. The AMICS mineral image is provided in Figure 12 with the full area SEM-BSE image in **Figure 13**. The AMICS and SEM-BSE image shows that whilst the phases are typically separate, they are commonly complexly intergrown at a fine scale (**Figure 14**).

9. RESULTS – XRD and comparison of AMICS vs XRD

Brief Summary

Juomasuo 73 and **166** drill cores have only trace **molybdenite** present, but it is surprisingly challenging to quantify because it has a very distinctive peak by XRD. It is only present at 0.5 wt%, but its peak is as big as the pyrrhotite peak that is present as a major phase (16 wt.%), resulting in a very low LOD for molybdenite, probably 0.05-0.1%.

The **Ni-Co Matte** sample produced very good XRD analysis. Pentlandite may be present in two forms, they are both cubic with the same space group, but they have different formulas: Fe_5Ni4S_8 and $(Fe,Ni)_9S_8$. By using both pentlandite varieties, all of the peaks can be matched in the diffractogram. Argentium-pentlandite or cobaltian-pentlandite are not present.

The **Cobalt Hydroxide** sample by XRD does not produce useful results as it is poorly crystallized. The software database is unable to find a perfect match with the material, and the only match is with a **Cobalt Nickel Arsenate Hydrate** (honzaite or burgessite). It seems that AMICS has identified more phases and is probably more correct.

A comparison of **AMICS** (modal area %) and **XRD** is good for all samples, except **Cobalt Hydroxide**.

Table 4. Comparison between AMICS mineralogy and XRD mineralogy.

Modal area (%)								
	AMICS	XRD	AMICS	XRD	AMICS	XRD	AMICS	XRD
Laboratory Code	**HG-23-16a**	**HG-23-16a**	**HG-23-16b**	**HG-23-16b**	**HG-23-16c**	**HG-23-16c**	**HG-23-16d**	**HG-23-16d**
Sample Name	**Jumasuo 73**	**Jumasuo 73**	**Jumasuo 166**	**Jumasuo 166**	**NiCo matte**	**NiCo matte**	**Co hydroxide**	**Co hydroxide**
Pixel Size (µm)	2		1.6		10		1.1	
Quartz	43.15	37.10	31.03	31.33	0.01		1.45	TR
K Feldspar	0.16	0.00	0.20	3.52	0.00		0.01	
Plagioclase	11.80	12.30	26.92	23.49	0.00		0.03	
Muscovite	12.38	14.40	23.57	18.86	0.00		0.02	
Biotite	7.10	10.00	0.15	TR	0.00		0.02	
Kaolinite	0.02		0.00		0.00		0.00	
Chlorite	3.48		1.51		0.00		0.01	
Fe Al Silicates	11.77	15.90	0.16	4.92	0.00		0.00	
Mg Silicates	0.11		0.02		0.00		2.75	
Illitic Clays	0.32		0.55		0.00		0.05	
Calcite	0.00		0.00		0.00		0.20	
Dolomite	0.00		0.00		0.00		0.14	
Mg Oxide and Carbonate	0.00		0.00		0.00		3.61	
Fe Oxide and Carbonate	0.52		0.05		3.67	1.6	0.02	
Ti Oxide	0.03		0.37		0.00		0.00	
Pyrite	1.62	1.30	1.67	1.44	0.00		0.00	
Pyrrhotite	7.11	9.20	12.49	15.96	0.00		0.00	
Fe Sulphate	0.02		0.38		0.01		0.00	
Cu Sulphide	0.02		0.10		7.53	5.0	0.00	
Cu Oxide	0.00		0.00		0.64		0.00	
Sphalerite	0.01		0.09		0.00		0.01	
Galena	0.01		0.03		0.00		0.00	
Cobaltite	0.17		0.33	TR	0.00		0.00	
Ni Sulphide	0.00		0.00		80.38	81.9	0.00	
Ni Fe Sulphate	0.00		0.00		0.09	11.5	0.00	
Fe Ni Oxide	0.00		0.00		7.60		0.00	
Co Oxide	0.00		0.00		0.02		10.20	
Co Sulphate (hydroxide)	0.00		0.00		0.00		60.47	100
Co Mg Sulphate	0.00		0.00		0.00		11.51	
Fe Co Phosphate	0.00		0.00		0.00		3.74	
Co Mg Oxide	0.00		0.00		0.00		4.57	
Molybdenite	0.00		0.22	0.48	0.00		0.00	
Ca Sulphate	0.00		0.00		0.00		1.03	
Barite	0.00		0.00		0.00		0.00	
Apatite	0.14		0.01		0.00		0.01	
Zircon	0.04		0.02		0.00		0.01	
Undifferentiated	0.00		0.10		0.04		0.15	
Total	100.00		100.00		100.00		100.00	

10. RESULTS – XRF

Table 5 Summary of XRF data for the two Latitude 66 core samples, namely **Juomasuo 73** and **Juomasuo 166**.

Sample	Na2O	MgO	Al2O3	SiO2	P2O5	SO3	K2O	CaO	TiO2	V2O5	Cr2O3	MnO	Fe2O3	NiO	CuO	ZnO	SrO	ZrO2	BaO	HfO2	PbO	Co	Ga	Ge	As	Se	Rb	Y	Nb	Mo	Sn	Sb	Cs	La	Ce	Nd	Ta	Th	U
Units	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Jumasuo 73	ND	2.34	12.9	48.2	0.31	8.52	3.37	0.49	0.38	ND	0.014	0.042	22.9	0.014	0.027	0.002	0.002	0.042	0.049	ND	ND	**2070**	6.68	ND	**846**	82.7	77.8	38	5.23	52.8	ND	ND	ND	ND	510	863	ND	ND	ND
Jumasuo 166	1.7	0.63	12.9	42.4	0.15	17.6	2.86	0.17	0.72	0.010	0.010	ND	19.6	0.021	0.082	ND	0.003	0.009	0.071	ND	ND	**4170**	ND	ND	**2960**	241	33.1	15.3	ND	2760	ND	ND	ND	264	400	601	ND	ND	ND

Brief summary of the results

The two drill core samples are quite different, especially in terms of their cobalt, nickel and molybdenum levels, suggesting that they could be classed as different ore types. Gold content was not determined in this study.

11. REFERENCES

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End of Report