Cobalt: Geology, Geomicrobiology, Geometallurgy

About the project

Aim and objectives

The principal aim of CoG^3 project is to understand the natural behaviour and biogeochemistry of cobalt in order to develop and apply novel bioprocessing strategies for cobalt extraction, recovery and the synthesis of targeted products using an integrated multi-institute and multidisciplinary approach.

The project will deliver:

- New knowledge about **cobalt residence and behaviour** in natural systems
- New **bioprocessing strategies** for cobalt ores
- **Bioengineered** and biomineral **products**
- **'Mine to product'** concept for cobalt
- Improvement of **supply chain**
- Promotion of **public understanding of cobalt** and its place in a modern society

The detailed objectives of the project are:

- To improve understanding of the **residence of cobalt** in reduced, sulfide-rich hydrothermal systems, to better characterise complex ore types and assess the differences in deportment between cobalt and other transition metals such as Ni and Cu.
- To study the behaviour of cobalt in the Critical Zone and in seafloor oxide deposits in order to develop a fundamental understanding of the **mineral residence at the atomic scale** within natural assemblages and synthetic analogues
- To understand the **natural biogeochemistry** of cobalt in both aerobic and anaerobic environments.
- To develop and apply **microbiological bioprocessing strategies** for extracting cobalt from primary ores and using **biomineralization processes** to recover cobalt from the process liquors and synthesise targeted downstream products
- To improve **cobalt recovery** from complex sulfide-oxide ores using a **'geometallurgy' approach** for orebody characterisation
- To improve **cobalt extraction and production** methods in order to accommodate current and future needs of the end user community in the cobalt supply chain

Consortium

Project Leader: Professor Richard Herrington, Natural History Museum London

The CoG^3 consortium comprises a group of 13 experienced researchers from **8 institutions** with the aim of training 5 PhD students and 7 early career researchers to become a new generation of multidisciplinary mineral resource scientists and engineers.

5 PhD projects will be delivered through research within the CoG3 consortium:

- Incorporation of Co into synthetic Fe oxyhydroxide systems - Implications for natural systems - PhD studentship Loughborough University - NHM
- Defining mineralogy and its structural evolution and reaction pathways during bioprocessing of Cobalt-bearing Fe and Fe-Mn oxides - PhD studentship Manchester -NHM
- Bio-reduction of Co and Ni bearing Manganese Minerals (STXM-focused) – PhD studentship Manchester-Diamond
- Optimisation of bio-mineral precipitation in chemoorganotrophic systems for Co recovery – PhD studentship Dundee
- Selective mineral processing and hydrometallurgical recovery processes for Co from Polish copper ore – PhD studentship Exeter

Project partners include:

Manchester University - leading **WP2** - Natural Biogeochemistry of Co http://www.manchester.ac.uk/research/jon.lloyd/

Bangor University - leading **WP3** - Bioprocessing of Co https://www.bangor.ac.uk/biology/staff/johnson.php

Exeter University - leading **WP4** - Improving the Supply Chain of Co http://emps.exeter.ac.uk/csm/staff/hjglass

Dundee University - **WP2**- Natural Biogeochemistry of Co http://www.lifesci.dundee.ac.uk/research/gmg

Loghborough University - **WP1** -The New Sources of Co http://www.lboro.ac.uk/departments/chemistry/staff/academic-research/caroline-kirk/

Southampton University- **WP1** -The New Sources of Co http://www.southampton.ac.uk/oes/research/staff/sr2

Diamond Light Source - **WP1**- The New Sources of Co http://www.diamond.ac.uk/Home.html

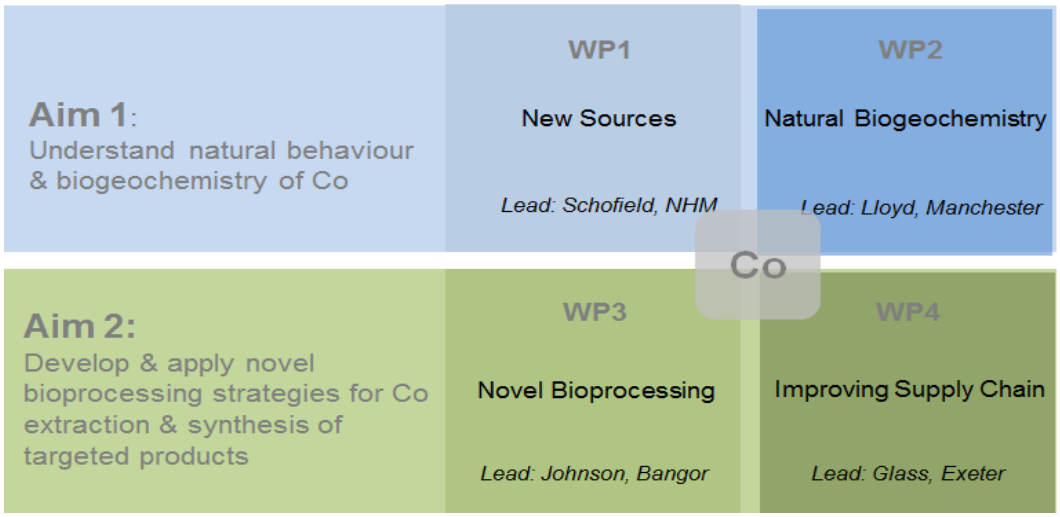
Cobalt Development Institute -**WP4** - Improving the Supply Chain of Co http://www.thecdi.com/

Work plan and work packages

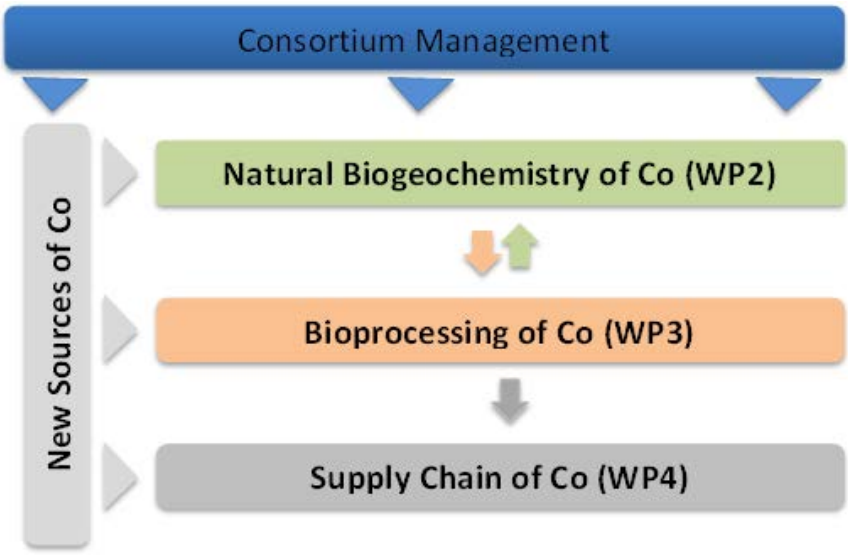
To deliver its objectives, CoG^3 will follow 4 carefully integrated packages (WP1-WP4)

WP No	Work Package Title	Work Package Leader	Institution
WP1	The New Sources of Cobalt	Dr P. F. Schofield	NHM
WP2	Natural Biogeochemistry of Cobalt	Prof J.R. Lloyd	Manchester
WP3	Bioprocessing of Cobalt	Prof D.B. Johnson	Bangor
WP4	Improving the Supply Chain of Cobalt	Prof H. Glass	Exeter

Work packages 1 and 2 will provide comprehensive data to address Aim 1 of the project while work packages 3 and 4 will deliver results to address Aim 2.



Research carried out within work packages WP2, WP3 and WP4 will be underpinned by extensive characterization data generated within WP1. WP2 and WP3 are closely interrelated and will both provide crucial data for WP4.



Work Package 1

The New Sources of Cobalt - Characterization of new ore types and ores for new types of processing

Lead Dr P. F. Schofield, NHM

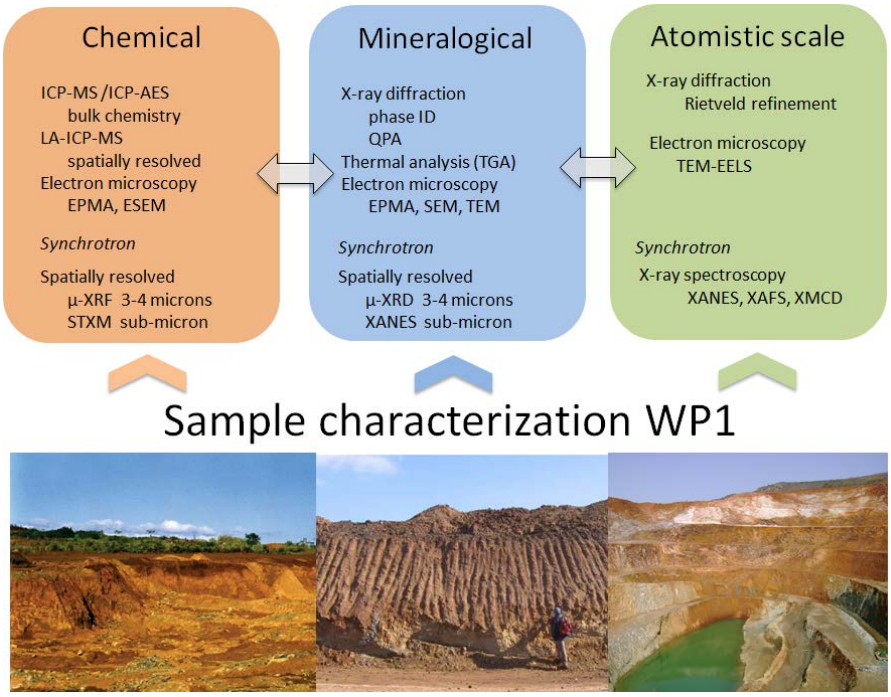
The aim of this work package is to provide detailed **mineralogical**, **chemical** and **atomistic-scale characterization** (NHM, Diamond Light Source, Loughborough University and Southampton University) of natural Co-bearing concentrations that represent potential new sources of the element. This comprehensive characterization will underpin the proposed research of WPs 2-4 that are examining novel techniques for Co extraction, enrichment and processing in order to provide tailored materials as required by the end users of this critical E-tech element.

Sampling sites - COG3 project

Cobalt from four contrasting recoverable reserves will be studied:

- **Cobalt-rich laterites** that currently provide 20% of the world's cobalt despite the fact that most of the hydrometallurgical technologies are optimized for Ni extraction leaving much of the Co unrecovered
- **Seafloor Fe-Mn crusts** and nodules which represent a huge potential future and strategic resource of Cobalt
- **Reduced sediment-hosted** Co ores. The Central African Copperbelt, (Zambia/DRC) is the world's largest cobalt producing region, yielding 57% of world production. The Kupfershiefer (central/northern Europe) is currently a resource for metals such as Cu, Au, and Ag but the viable Co remains unrecovered

- **Chalcogenide** mineralogy of Bou Azzer, Morocco, is the only mixed sulfide-arsenide deposit in which cobalt is the primary target metal. Bou Azzer provides 8% of the world's Co, which is recovered using intensive pyrometallurgical techniques



Graphical representation of work within WP1

Work Package 2

Natural Biogeochemistry of Cobalt: Biotic and Abiotic Constraints on Cobalt Mineral Formation and Transformation

Lead Prof J R Lloyd, Manchester

The focus of this work package is to further our understanding of the **natural biogeochemistry** of cobalt in **aerobic and anaerobic environments** by studying potential interactions with **prokaryotic and eukaryotic microbiota** and their effects on cobalt speciation and mobility using field samples and extant microbial communities.

The work will aim to: 1) increase our knowledge of trace element cycling and the formation of Co-rich ores and 2) provide underpinning information to help develop options for bioprocessing.

The fate of Co will be explored in a series of microcosm experiments constructed by the Manchester Geomicrobiology Group and Dundee Geomicrobiology Group partners using field samples collected and characterized in WP1. These experiments will use samples from mineralogically and lithologically contrasting horizons of laterite deposits. In addition to monitoring geochemical and microbial changes in these experiments, crucially we will also look at the evolution of Fe(III) mineral phases in the microcosms using a combination of XRF, EPMA, ESEM, HRTEM and dynamic, in situ

XRD while the oxidation state and coordination environment of the Co (Fe, Mn, and Ni) will be assessed using X-ray spectroscopy and microscopy techniques at Diamond Light Source.

The combination of geochemical, microbiological and mineralogical analyses will give a unique dataset illustrating the phase associations of Fe, Mn, and Co during microbial redox progressions catalysed by extant microbial communities and will complement more targeted experiments using high density pure cultures of the well-studied model laboratory Fe(III) and Mn(VI)reducing bacteria used for bioprocessing in WP3.

Work package 3

Bioprocessing of Cobalt: Abiotic and Biotic Leaching and Production of New Biomineral Products

Lead: Prof D.B. Johnson, Bangor

This WP will focus on modified and novel environmentally-benign biological strategies **for extracting cobalt** from primary ores**, recovering cobalt** from the process liquors, and **biomineralization** of cobalt to synthesise targeted products. These biological strategies for metal recovery will be compared with existing technologies which to date have focused on abiotic leaching for recovery of metals of interest including cobalt. Further **abiotic chemical leaching** experiments using both organic and inorganic solvents using the batch and column facilities will be conducted.

Bioprocessing will involve using microorganisms (bacteria, archaea and fungi) to bioleach Co-containing ores and mineral concentrates and to selectively remove Co from pregnant leach solutions (PLS). The bio-leaching experiments will be conducted by the Bangor Acidophile Research Team and Dundee Geomicrobiology Group. By combining these two components, novel integrated approaches will be devised to facilitate the recovery of Co from primary ores. Both reduced (sulfidic; Co(II)) and oxidized (lateritic oxide deposits and marine nodules; Co(III)) reserves will be bioleached. Reduced ores will be subjected to oxidative dissolution catalysed by defined consortia of acidophilic sulfide mineral-oxidizing prokaryotes in pH-, temperature- and redox potential-controlled bioreactors, operated under different conditions in order to optimize Co extraction.

Biomineralization options used to selectively capture Co from PLS will include:

- Precipitation as a **sulfide phase**, using H_2S generated by sulfidogenic bacteria either in-line or off-line.
- Precipitation by fungal metabolites, to form **oxalates**. Oxalates are very important industrial substances used in e.g. nuclear reprocessing, nanotechnology, catalysis, superconductor and laser technology. Cobalt oxalate is already known as an important component in cobalt hydrometallurgy. It is possible that oxalate formation can be manipulated to nanoscale dimensions, providing further applications in biomineral technology
- Nutritional manipulation of geoactive cultures in bioreactors to produce supernatants laden with carbonate or phosphate to effect Co precipitation as the **carbonate** (high purity and can be of nanoscale dimensions) or **phosphate**

Finally, direct **bioconversions** of oxidized Co-rich lateritic Fe(III) minerals to potentially **useful bio-nanomaterials**, will also be explored in the Manchester laboratory. This approach has been shown to work on synthetic Fe(III) minerals, with fine grained **biomagnetite nanoparticles** formed with tuneable magnetic and catalytic properties. The Manchester Geomicrobiology group will investigate if such approaches can also be used for the bioconversion of naturally occurring Co-rich Fe(III) minerals.

Work package 4

Improving the Supply Chain of Cobalt

Lead: Prof H. Glass, Exeter

Research within WP4 will focus on improving the cobalt supply chain through investigation into the **geometallurgy of cobalt** with direct **engagement of industry**. It has long been recognized that the hydrometallurgical extraction of cobalt as a by-product of copper and/or nickel production is inefficient in Co recovery due to non-optimal selectivity of flotation and/or leaching conditions. Geometallurgy holds promise as a planning and assessment tool which attempts to harness the influence of geotechnical variables, such as rock hardness and fracture toughness, on the preferred mining and processing schedule. It considers the entire mining value chain, with integrated process monitoring and control and safeguarding of the environment. **Geometallurgy** of cobalt-bearing sulfide ores from the **Polish Kupferschiefer** and deposits in the **Central African Copperbelt** (CAC) will be studied in order to develop **environmentally-friendly extraction of cobalt** from these resources. Experimental laboratory work will be conducted to develop **a geometallurgical model** which integrates the effect of mineralogical and geotechnical properties of characteristic ore types, flowsheet design, process variables such as grind size and reagent type and dosage. Laboratory experiments will investigate the effect of ore types, leaching conditions (atmospheric versus pressure leaching, effect of temperature) and selection of environmentally-benign lixiviants.

A major **industry-science technology forum,** brokered by Cobalt Development Institute will be organized as one of the key tasks in WP4. The forum will aim to drive technology transfer, increase stakeholder engagement and promote awareness of security of supply. Specifically, it will seek to establish the implications of CoG3 project findings towards improving the geo- and bio-geoengineered recovery of cobalt. Session focused on mineral processing will be organised with CoG3 industry partners. There will also be a session focussed on downstream users of cobalt specifically addressing the issue of how bioengineered cobalt compounds (produced in WP3) can be tailored to specific industrial and biomedical needs

Finally, WP4 will integrate the results of WP1, WP2 and WP3 with a view to refining and extending the geometallurgical modelling of cobalt recovery. New information on cobalt deportment in key mineral phases, as gained from WP1, will be integrated with geotechnical and bulk assemblage mineral data and assessments obtained from WP4, in order to develop more sophisticated **ore assessment models**. The use of geometallurgical analysis for the screening of the types of the other potential ores suitable for bioleaching, as defined in WP3, will be investigated. This will provide a valuable insight into where **future cobalt supplies** may be recovered using more sustainable processing methods.