Institution: University of Bristol		
Unit of Assessment: 7 – Earth Systems and Environmental Sciences		
Title of case study: Improved copper-exploration strategies for mining industry based on new understanding of copper formation		
Period when the underpinning research was undertaken: 2006-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Stephen RSJ Sparks	Professorial Research Fellow	04/1989-08/2020
Jon D Blundy	Professorial Research Fellow	05/1989-06/2020
Alison C Rust	Reader	08/2006-present
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Period when the claimed impact occurred: 2015-2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

Global demand for copper will increase three-fold by 2050 if electrification is part of the solution to keep global warming below the target of ≤2°C. BHP, the world's largest mining company, approached the University of Bristol (UoB) to overcome the industry's difficulties in locating new world-class copper resources. Using their world-leading expertise in volcanology, magma petrology and landscape evolution, the UoB researchers fundamentally changed the understanding of how copper ore deposits are formed and used these insights to identify the most likely locations to find high-value copper deposits, as well as which areas to avoid.

The resulting models and tools have improved BHP's copper-exploration strategies and have saved the company > USD10 million, while also avoiding environmental damage and safety risks through drilling. The savings comprise USD5 million-USD10 million for narrowing exploration areas in northern Chile, USD5 million for evaluation at a specific site with copper mineralisation in Chile, and 'millions of USD' related to exploration in western USA.

The UoB scientists are now advising BHP on new, more sustainable extraction methods that could substantially increase copper reserves and fundamentally change the copper mining industry.

2. Underpinning research (indicative maximum 500 words)

Bristol PCD is a long-term collaborative project (since 2010) between UoB and the global mining company BHP, triggered by the mining industry's difficulties in locating new world-class copper resources. Working closely with BHP has given UoB researchers access to datasets and industrial contacts that ensure effective and timely research that is aligned with the challenges of the copper exploration industry.

Copper comes from magmas with copper concentrations of just parts per million. It is only economically and environmentally affordable to extract copper from rocks where natural processes have concentrated copper into ore deposits that, despite forming at depth, are today not very deep underground. Research into fluid-mediated processes that transport metals from the magmas to ore bodies helps us understand how viable ore deposits (with economic concentrations of around 1% copper) are formed. An improved understanding of the parental magmatic systems and the subsequent landscape evolution that can expose and enhance the copper concentration of ore deposits are, thus, central to the discovery of valuable copper reserves. This lies at the core of the Bristol PCD project, which has focussed on the formation of porphyry copper deposits (PCDs). These account for 75% of the world's copper production.

Hypogene PCD: The transcrustal magmatic framework and gas-brine models

PCDs form as a result of magmatic processes that discharge hot metal-bearing fluids into the roots of volcanoes to form hypogene, sulphide-rich ore deposits. Conventional wisdom is that these critical fluids primarily come from large, shallow melt-rich magma chambers. However, over the last 15 years, through a series of highly cited papers starting with [R1], UoB researchers have challenged the magma chamber paradigm, invoking instead a vertically extensive 'transcrustal' magmatic system in which liquid silicate melt is mostly distributed along solid crystal boundaries and can become connected even when it comprises just a few percent of the partially molten rock. This paradigm shift is influencing conceptual models of magma fluxing through the crust, the formation of intrusive rocks, volcanism and PCD generation.

An important consequence of transcrustal magmatic systems is that the buoyant silicate melts and aqueous fluids needed to form PCDs can rise separately throughout the crust [R1]. In particular, metal-sulphide ores containing copper can precipitate when metal-bearing saline fluids (brines) derived from magmas react with sulphur-rich gases derived from deeper portions of the same magmatic system. Related hydrolysis reactions lead to the distinctive patterns in the alteration of rocks around PCDs that are widely used as an exploration tool to assess the direction and distance to an ore deposit [R2, 2015].

Using computer models of fluid flow, high-temperature and pressure experiments, and petrological data, Bristol PCD developed and refined a 'gas-brine' reaction model for hypogene PCDs [R2, 2015]. The formation of lenses of metal-rich brines beneath volcanoes is a key component of this model for generating PCDs. It also represents a hugely significant new frontier in copper resources, since it means that there is potential to tap reservoirs of hot brines rich in dissolved metals by drilling with co-recovery of geothermal power [Patent R3, 2019]. The transcrustal magmatic system and new gas-brine concepts developed at UoB have been refined and tested through applications to natural ore-forming systems [R4, 2017].

Supergene PCD deposits: Landscape evolution maps and deposits 'under cover'
Supergene deposits with higher concentrations of copper can form when oxidising groundwater remobilises copper from a hypogene deposit and re-precipitates it at the water table where conditions are more reducing. Bristol PCD developed novel landscape evolution maps [R5, 2017] to quantify the interplay between rock uplift (tectonics) and climate, which affect processes that are key to the formation of valuable supergene deposits: exhumation of the hypogene deposit, interaction of arid-climate groundwater with the hypogene deposit, and deepening of the water table. These landscape evolution maps are a new visualisation tool that can be used to identify areas with the optimum conditions for supergene enrichment.

Volcanic deposits can impede supergene enrichment if they bury hypogene ore deposits and so inhibit the required interaction with oxidised groundwater. Establishing the timing and distribution of such burial events is critical to the development of exploration strategies for deposits that are buried 'under cover'. Bristol PCD studied one such giant volcanic deposit in northern Chile, the Cardones Ignimbrite [R6, 2016], to show how the pre-eruption landscape affected the volcanic current and so the distribution and thickness of the resulting ignimbrite deposits. The researchers proposed that, and demonstrated how, copper exploration for supergene deposits under cover should target ancient elevated ground where the ignimbrite deposit is significantly thinner.

3. References to the research

R1. Annen, C, **Blundy, JD**, & **Sparks, RSJ**, 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. *Journal of Petrology*, **47**, 505-539. DOI: 10.1093/petrology/egi084.

R2. Blundy, J, Mavrogenes, J, **Tattitch, B, Sparks, S, Gilmer, A**, 2015, Generation of porphyry copper deposits by gas-brine reaction in volcanic arcs, *Nature Geoscience*. **8**, 235–240, DOI: 10.1038/ngeo2351

R3. Blundy, J, **Afanasyev, A**, 2019. Patent. *Metal Extraction Method and System*, WO2019081892 (A1)

R4. Gilmer, A, Sparks, RSJ, Rust, A, Tapster, S, Webb, AD, Barfod, D, 2017. Geology of the Don Manuel igneous complex, central Chile: Implications for igneous processes in porphyry copper systems. *Geological Society of America Bulletin*. **129**, B31524. DOI: 10.1130/B31524.1

R5. Evenstar, LA, Mather, AE, Hartley, AJ, Stuart, FM, **Sparks, RS, Cooper, FJ**, 2017, Geomorphology on geologic timescales: evolution of the late Cenozoic Pacific paleosurface in Northern Chile and Southern Peru. *Earth-Science Reviews*, **171**, 1-27. DOI: 10.1016/j.earscirev.2017.04.004.

R6. Van Zalinge, M, Sparks, S, Evenstar, L, Cooper, F, Condon, D, 2016, Early Miocene large-volume ignimbrites of the Oxaya Formation, Central Andes, *Journal of the Geological Society.* **173**, 716-733. DOI: 10.1144/jgs2015-123.

Research Grants

G1. *Scoping study on Porphyry Copper Deposits*. BHP Billiton. 2010-2011. GBP10,000

G2. *New perspectives on porphyry copper deposits (Phase I).* (L1725XV00) BHP Billiton 2012-2016 GBP1.73 million

G3. *New perspectives on porphyry copper deposits (Phase II).* (L1725XV00) BHP Billiton 2015-2020 GBP1.94 million

G4. *In situ mining of magmatic brines*. BHP Billiton 2018-2020 (8500066324 MA/CC 8100039670) GBP0.62 million

G5. J D Blundy (PI) *From arc magmas to ores (FAMOS): A mineral systems approach*. NERC Strategic Grant 2017-2021 (NE/P017371/1) GBP0.92 million

4. Details of the impact

Challenges facing the copper industry

Copper is an essential component of electric motors and power cables. As we transition to a low-carbon economy, demand for copper will grow rapidly, reflecting greater use of electric vehicles, wind turbines and photovoltaic cells. Global demand for copper will increase three-fold by 2050 if a target of ≤2 °C global warming is to be achieved [S1]. The increase in demand cannot be met by recycling alone, thus discovery of new world-class copper ore deposits is critical.

Most near-surface PCDs have already been discovered. The grand challenge for the mining industry is "*locating* [world class copper] *resources when such deposits occur at depth, potentially buried by post-mineralisation cover. New tools and new understanding are required to reduce exploration cost and risk and to minimise environmental impacts*" (Chief geologist - Technical support & technology development, Rio Tinto Exploration) [S2]. To achieve this requires a "*combination of economic geology, geochemistry, igneous petrology and volcanology … to make transformational advances in understanding these complex ore systems*" (independent geological consultant) [S3].

Copper exploration is further blighted by many 'false positives'; sites suspected of containing copper reserves often prove fruitless. A better understanding of where to drill and, thus, where *not* to drill, will improve the efficiency of exploration strategies and minimise environmental damage caused by drilling.

BHP collaboration

BHP, the world's largest mining company, approached UoB's Earth Sciences in 2010 to establish a research collaboration [G1-G4] to address the challenges facing the copper exploration industry. The goal was to develop new perspectives on copper deposit formation by engaging UoB researchers with world-class expertise in the fundamentals of volcanology and igneous petrology. Collaborating with BHP has given UoB researchers access to key datasets and facilitated knowledge exchange to enable improvements to copper exploration on a timescale of years. This working relationship with BHP is ongoing and, in return, BHP has had first-mover advantage on new models, tools and strategies resulting from the research. Moreover, the valuable knowledge co-developed between UoB and BHP stands to benefit the wider mining industry through a RCUK-funded consortium, FAMOS [G5], which runs 2017-22 to develop exploration tools for PCDs with partners from the major copper exploration and mining companies.

The UoB-BHP collaboration has already led to BHP's commercial adoption of the 'transcrustal magmatic system' [R1] and 'landscape evolution' [R5, R6] concepts. The UoB-BHP collaboration has already led to BHP's commercial adoption of the 'transcrustal magmatic system' [R1] and 'landscape evolution' [R5, R6] concepts. BHP's VP for Geoscience praises this "*valuable working relationship*", with strong, aligned research interests on Porphyry Copper systems and further comments that new developments in "*the fundamental understanding of the processes of mineralization associated with arc magmas* [are valuable] *to mineral discovery*" [S4]. In his presentation on BHP's copper strategy at London Metals Exchange Week (an annual meeting for the global metals community) in 2017, a BHP President of Operations announced: **"***Knowledge-sharing between our teams at BHP is important, but another valuable part of our exploration strategy is our academic ties. Our partnerships with the likes of Bristol University… has helped us tackle the geoscience issues our explorers face*." [S4].

Application of Bristol PCD's research has impacted BHP's exploration pipeline for both hypogene and supergene PCDs through: priority shifts in expenditure profile, reallocation of corporate budgets, decisions not to explore in certain areas and so freeing up budget to explore more promising areas, and new thinking on exploration targets.

Hypogene PCD deposits: Predicting PCD locations and copper fertility evaluation

The transcrustal [R1] and gas-brine models [R2] provide a new conceptual framework to understand the 4-D structure of ore-forming magmatic systems. This has transformed BHP's thinking for predicting locations in arcs that are most amenable to PCD formation. BHP's Head of Geoscience Excellence writes [S5]: "*… the interaction with Bristol has caused me to look very differently at the architecture and dynamics of magmatic systems and PCD formation, and how we can build these new perspectives into exploration strategies*".

The benefits of combining this new understanding of PCD formation with detailed studies of rock samples was demonstrated in BHP's evaluation of the Don Manuel PCD prospect in Chile which began in 2013 [R4]: "*In essence, the University of Bristol research demonstrates that what remains of the Don Manuel system was too hot to host an economic copper porphyry deposit*" (VP Copper Exploration, BHP). Further, '[this work] *has impacted the final* [evaluation] *stage of the exploration process, where most of the expenses are generated and the decisions of moving forward are taken*. *This research was key to our decision not to drill further, which we estimate saved BHP approximately 3 to 4 drill holes or approximately $US 5,000,000* [09-2019]*."* (VP Copper Exploration, BHP) [S6].

In 2017, application of Bristol PCD's understanding of the architecture and dynamics of PCD forming systems [R1, R2] enabled BHP to reinterpret old exploration data and to locate quickly areas with good potential [S7]. BHP's Head of Exploration in North America writes: "*Thanks to* [Bristol PCD's] *work, BHP has refined its North American copper exploration strategy… bringing forward not only areas to explore but, critically, areas to no longer explore*" [S7]. Quantifying the value of avoided exploration is difficult, but BHP believe it to be millions of USD, as well as years of exposure to health and safety hazards [S7].

Supergene PCD deposits: Identification of prospective terranes including areas under cover

Bristol PCD's landscape evolution maps completed in 2017 [R5] have directly influenced BHP's ability to define areas unlikely to host supergene deposits. *"Based on this map, the company was able to avoid specific areas to explore. Reducing the search space allowed BHP to focus on other key areas, not spend unnecessary funds, and time in areas of lesser prospectivity. This work saved the company at least USD5-10 million* [09-2019] *in drilling fees and associated costs. It has also refined our exploration strategy to focus on areas that are predicted to have experienced the right conditions for* [supergene] *enrichment."* (VP Copper Exploration, BHP) [S8]. This work has been particularly important in northern Chile where much of the area has been buried beneath volcanic deposits. Further research on volcanic deposits by Bristol PCD, finished in 2016 [R6], demonstrated the importance of using cutting-edge volcanology to detect under-cover targets. "*It* *is only with* [such] *regional analyses that BHP is able to keep a competitive edge in their exploration programme*." (VP Copper Exploration, BHP) [S8].

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5. Sources to corroborate the impact

S1. World Bank Group, 2017. *The growing role of minerals and metals for a low carbon future*. World Bank report outlining future resources demand.

S2. Rio Tinto, 2016. Support letter for FAMOS grant application [G5] - Chief Geologist, Rio Tinto Exploration

S3. Leading independent consultant to mining industry, 2016. Support letter for FAMOS grant application [G5], Richard Sillitoe – independent geological consultant

S4. BHP, 2016. Support letter for FAMOS grant application [G5] - Vice President of Geoscience; Malchouk, D. (2017) *Copper's time has come.* LME Week Bloomberg Forum, London, 1 November 2017.

S5. BHP, 2020. Factual statement regarding the nature of the Bristol-BHP relationship [G1-G4] and the commercial impact of conceptual and scientific advances [R1,R2] made by the BristolPCD group and new initiatives around green mining [R3] - Principal Geoscientist, Technical Centre of Excellence and Legacy Assets

S6. BHP, 2019. Factual statement regarding research on Don Manuel prospect (Chile) [R4], - Vice President Copper Exploration

S7. BHP, 2019. Factual statement regarding work on legacy exploration data by BristolPCD PhD student Rebecca Perkins - Head of Exploration – North America

S8. BHP, 2019. Factual statement regarding importance of research on northern Chile paleosurfaces [R5, R6] to the BHP copper exploration programme - Vice President Copper Exploration

S9. BHP, 2020. Factual statement regarding 2020 developments on the green mining initiative including potential for commercialization – Principal New Copper Resources, BHP