

Institution: Cardiff University		
Unit of Assessment: Earth Systems and Environmental Sciences (7)		
Title of case study: Enhanced geological strategies improve gold and copper exploration for world-leading mining companies		
Period when the underpinning research was undertaken: 2013 – 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:
T. Blenkinsop	Professor	19/08/2013 – present
J. Lambert-Smith	Lecturer	04/04/2017 – present
Period when the claimed impact occurred: 01/08/2013 – 31/12/2020		
Is this case study continued from a case study submitted in 2014? No		
1. Summary of the impact (indicative maximum 100 words)		
<p>Increased global demand for gold and copper resources requires improved detection of ore bodies. Cardiff University research into ore formation and drill core analysis advanced exploration methods for world-leading mining companies including [text redacted], Barrick Gold Corporation, AngloGold Ashanti and Kinross Gold Corporation. Models of ore formation were developed and applied to redirect annual exploration budgets worth over £15.9M in West Africa and led to the commitment of over £1.6M for exploration in Australia. Improved drill core analysis changed professional practice in major and junior mining companies across the world and was formally adopted into [text redacted].</p>		
2. Underpinning research (indicative maximum 500 words)		
<p>Global demand for mineral resources is greater than ever. Discovery rates for gold and copper are declining and both may reach peak production within the next 20 years. This resource crisis demands more predictive exploration techniques, and superior expertise and training for exploration geologists. Research led by Blenkinsop and Lambert-Smith in the Economic Geology research group at Cardiff University improved exploration strategies for mining companies by modelling the formation of ore deposits, and by developing new methods of analysing drill core.</p>		
2.1 Modelling the formation of ore deposits		
<p>Major deposits of gold and copper in the Earth's crust form when fluid carrying these metals flows through structures (such as faults) and reacts with rocks and different fluids. Cardiff research concentrated on two critical and complementary factors that regulate the mineralising process: the geometry of the structures that control the fluid flow (Blenkinsop) and the nature of the fluids and the chemical reactions that cause metal precipitation (Lambert-Smith). These two factors govern where mineral deposits form in the crust, as well as their quality and size. The relative importance of each factor varies in different mineralising systems and at different spatial scales.</p>		
<p>Cardiff research showed that networks of structures controlling fluid flow have fractal properties [3.1], allowing this characteristic to be used to locate the most favourable sites for fluid flow and mineral deposits along faults. [Text redacted]. Cardiff research on the hydrothermal system around Loulo showed, however, that volatile elements in the gold systems were derived from both metamorphic reactions in the lower crust and from local magmatism [3.2], completely changing the exploration strategy by correctly identifying the origin of the metalliferous fluids, and highlighting the importance of areas where magmatic rocks are present.</p>		
<p>Detailed studies were also made on more local scales by Cardiff at some of the largest hydrothermal gold and copper deposits in the world. These enabled a greater understanding of fluid flow pathways and controls on the locations and geometry of individual ore deposits, leading to more cost-efficient exploration at the mines. Key deposits studied included:</p>		

- Tropicana gold mine in Australia [3.3];
- Geita gold mine in Tanzania [3.4 G3.2];
- Mount Isa copper mine in Australia [G3.3];
- Kainantu copper mine in Papua New Guinea [3.5];
- Kupol and Dvoinoye gold mines in Russia [G3.4].

In each case, the specific geometry of the structures that controlled the formation of the ore bodies at the deposit scale was identified. When combined with inferences about the stress field and fluids in the crust during mineralisation, Cardiff's research assisted in mining the gold or copper resources.

2.2 Improved analysis of drill cores through the Cor! tool

Ore deposits can be delineated by measuring the geological structures within drill cores extracted from exploratory drilling. Historically, vital structural information from these cores has been overlooked (especially from linear structures), partly because many mine geologists lack a coherent suite of tools to measure the structures and to determine their original orientation within the ground. Information is also lost in the process of removing one half of the core for assaying.

Blenkinsop developed new and simplified algorithms, and an associated workflow that systematically documents the structures and re-orientates the core sample. The workflow unifies previously diverse ways to handle full and half cores, and ensures that structures in cores are comprehensively analysed, including linear structures [3.6]. The algorithms were integrated into a tool named 'Cor!', developed in collaboration with industry geologists at AngloGold Ashanti, which allows mine geologists to implement the straightforward workflow based on simple measurements. Since the initial launch in 2013, Cor! has been updated with the ability to measure important linear structures such as fold hinges, vorticity vectors, and slip directions, including a challenging subset of linear structures that are awkward to deal with because they do not pass through the centre of the core [3.6]. It also includes both half core and full core methodologies. The workflow of Cor! has now been embedded globally [text redacted].

3. References to the research (indicative maximum of six references)

[3.1] **Blenkinsop, T.** (2014) Scaling laws for the distribution of gold, geothermal, and gas resources. *Pure and Applied Geophysics*, 172, 2045–2056. doi.org/10.1007/s00024-014-0909-5

[3.2] **Lambert-Smith, J.S.**, Allibone, A., Treloar, P.J., Lawrence, D.M., Boyce, A.J., Fanning, M. (2020) Stable C, O, and S isotope record of magmatic-hydrothermal interactions between the Falémé Fe Skarn and the Loulo Au systems in Western Mali. *Economic Geology*, 115, 1537-1558. doi.org/10.5382/econgeo.4759

[3.3] **Blenkinsop, T.G.**, Doyle, M.G. (2014) Structural controls on gold mineralization on the margin of the Yilgarn craton, Albany–Fraser orogen: The Tropicana deposit, Western Australia. *Journal of Structural Geology*, 67, 189–204. doi.org/10.1016/j.jsg.2014.01.013

[3.4] Dirks, P.H.G.M., Sanislav, I.V., Ryt, M.R. Van, Huizenga, J., **Blenkinsop, T.G.**, Kolling S.L., Kwelwa S.D., Mwazembe, G. (2020) Chapter 8 The world-class gold deposits in the Geita Greenstone Belt, Northwestern Tanzania, in: *SEG Special Publications*, 23, 163–183. https://www.segweb.org/store_info/SP/SP-23-Additional-Product-Info.pdf

[3.5] **Blenkinsop, T.**, Tripp, G., Gillen, D. (2017) The relationship between mineralization and tectonics at the Kainantu gold–copper deposit, Papua New Guinea, in: *Geological Society, London, Special Publications*, 453, 269-288. doi.org/10.1144/SP453.11

[3.6] **Blenkinsop, T.**, Doyle, M., Nugus, M. (2014) A unified approach to measuring structures in orientated drill core, in: *Geological Society, London, Special Publications*, 421, 99-108. doi.org/10.1144/SP421.1

Selected grants

[G3.1] [Text redacted]

[G3.2] **Blenkinsop, T.G.**, Geita gold mine, AngloGold Ashanti, 17/01/2015-26/01/2015, £12,702.

[G3.3] **Blenkinsop, T.G.**, Exploring for Copper at Mount Isa, Mount Isa Mines - CASE contribution and Sponsorship, 01/10/2018-31/03/2022, £66,719.

[G3.4] **Blenkinsop, T.G.**, Kupol and Dvoinoye epithermal vein deposits, Kinross Gold Corporation, 08/06/2019-30/09/2019, £35,924.

4. Details of the impact (indicative maximum 750 words)

Cardiff collaborated with the top four gold mining companies in the world, as measured by output, to develop more efficient exploration strategies and methods for locating mineral resources. Working with [text redacted], Barrick Gold Corporation (merged with Randgold in 2019), AngloGold Ashanti and Kinross Gold Corporation, the research delivered the following impacts:

- 1) directed exploration strategies through modelling the formation of ore deposits in Australia, Africa and Russia;
- 2) defined industry best practice through global professional training in Cardiff's Cor! tool;
- 3) [text redacted]

4.1 Directing exploration strategies through modelling the formation of ore deposits

[Text redacted]

Cardiff University also collaborated with Barrick to investigate the genesis of gold deposits at Loulo Mine Complex in the Kédougou-Kéniéba Inlier (KKI) in Mali, Africa. Cardiff's isotopic analysis of gold formation within the complex was described by Barrick as vital evidence that "*changed quite fundamentally our regional targeting model for the eastern Kédougou-Kéniéba Inlier*" [5.2]. These insights enhanced the exploration strategy within the KKI, saving considerable resources.

As stated by Joel Holliday, Senior Vice President Global Exploration at Barrick: "*We now know why there are no deposits in the north of the KKI between Kofi/Loulo and Sadiola, whereas before there was still a concern that we should be exploring in this area*" [5.2]. The scale of the change in strategy is evidenced by the fact that Barrick's total exploration budget of US\$21 million (£15.9M) was influenced by the research: "*Our revised regional model... has allowed us to direct this budget away from high-risk ground that we now consider less prospective and focus on areas which meet the criteria outlined above*" [5.2].

In 2019, Blenkinsop was asked by Kinross to advise on their Kupol and Dvoinoye properties in north-eastern Russia, using the research described in Section 2. Evan Lapointe, Regional Director for Exploration at Kinross, said: "*Professor Blenkinsop's 2019 work has yielded important new insights into the structural character of the Kupol and Dvoinoye districts and has generated a number of targets and areas of interest for consideration in future field evaluations and potential subsequent drilling programs*" [5.3].

4.2 Defining industry practice by teaching and applying the Cor! tool

The new Cor! tool for structural analysis of drill core samples produced widespread changes in exploration practice, including adoption of the tool within mining companies across the world. A Cor! workshop at a meeting on mineral deposits around the Pacific Rim (PACRIM 2015) motivated changes in practice across multiple high-profile commercial and government mining companies. Specifically citing output [3.6], a representative of multinational resource company ENRC Africa Holdings Ltd stated: "*There is an on-going effort within our group to review all the structural logging procedure, methods and measurements we currently have integrating the lessons I got from this workshop*" [5.4]. Another attendee commented: "*We'd*

take a paper like [Cardiff's] and show it to ~20 odd students / junior geologists to demonstrate to them the sort of thing that can be done structurally with core" [5.4].

In July 2015, training on Cor! and related structural and economic geology was delivered by Blenkinsop at Mount Isa Mines, Australia, and for exploration geologists from Australia, Papua New Guinea and the Philippines. A Senior Geologist from Mount Isa Mines observed that *"using Cor! was seen as critical, as previously these measurements have been difficult to perform with existing skill sets. This has had immediate impact on the data collected from drill core" [5.5].* Other attendees highlighted practical benefits of the training: *"the course taught me a lot on the techniques for quick and effective mapping"*, with another emphasising lessons learnt from guidance in the field: *"which were much more valuable in the areas of mineral identification, and detailed geological mapping in identifying contacts, lithology, structures, alteration, and mineralization" [5.6].*

The principles behind Cor! have been further delivered globally through an online course, Structural Geology for Exploration and Mining (SGEM), produced and run by Blenkinsop based on Cardiff research [3.6]. Beginning in March 2020, 334 geologists from 91 organisations across 34 countries have registered, with 163 completions so far. This intense interest continues at present. Impact is documented by participants and senior managers:

- Andrew du Toit, participant and Managing Director of Canister Resources, Zimbabwe, said: *"From a management perspective, the deeper understanding of structural geology and structural core logging achieved through the SGEM course has been important in order to direct the drilling program and select the appropriate additional downstream activities...Structural interpretation, based on the principles of SGEM, is vital for generating correct and effective resource models for Canister Resources...The financial implications of incorrect resource models run into tens of millions of dollars" [5.7].*
- Mike Erickson, Senior Vice President of AngloGold Ashanti, the world's third largest gold producer, said: *"There is a unique opportunity to develop an on-line training program in structural geology for the exploration and mining industry that will fill the current gap. We strongly support [Cardiff's] initiative" [5.8].*
- [Text redacted]

[Text redacted]

4.4 Summary

Cardiff University research into ore formation and drill core analysis enabled collaboration with leading gold and copper mining companies, with improved models of ore formation facilitating redirection of annual exploration budgets worth over £17.5M (£15.9M in West Africa and £1.6M in Australia). Cardiff-led training updated professional practice in exploration across four continents, enabling field professionals to maximise opportunities for locating ore deposits via use of the Cor! tool. [Text redacted].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[5.1] [Text redacted]

[5.2] Testimonial: Joel Holliday, Senior Vice President Global Exploration, Barrick Gold Corporation (merged with Randgold in 2019).

[5.3] Testimonial: Evan Lapointe, Regional Director for Exploration (Kinross).

[5.4] Testimonials: attendees at the PACRIM short course.

[5.5] Testimonial: Alex Brown, Senior Geologist, Mount Isa Mines.

[5.6] Testimonials: attendees at Advanced Field Training short course.

[5.7] Testimonial: Andrew du Toit, MD Canister Resources.

[5.8] Testimonial: Mike Erickson, Senior Vice President, AngloGold Ashanti.

[5.9] [Text redacted]

[5.10] [Text redacted]