Institution: Kingston University

Unit of Assessment: 17, Geography, Environmental Studies and Archaeology

Title of case study: Driving improved practice and associated economic benefits in the mineral exploration industry through development of integrated mineralogical and petrographic techniques.

1. Summary of the impact (indicative maximum 100 words)

Innovative application of fluid inclusion analysis led to the development of a novel technique for mapping mineral deposits. This has been developed into an exploration tool in collaboration with a leading mineral exploration company, Randgold Resources. Mapping different fluid pathways within potentially mineralised terranes through analysis of fluid inclusion chemistries enables definition of areas through which mineralising, as opposed to barren ore fluids, passed. Applying this has enabled Randgold Resources to increase efficiency and save costs in its exploration and mining activities. Kingston University research has changed the working practices of Randgold Resources, with consequent economic benefit to that company.

2. Underpinning research (indicative maximum 500 words)

An understanding of mineralogy, mineral textures, mineral chemistry and the nature and chemistry of inclusions (both fluid and solid) hosted within them underpins our comprehension of petrological principles and processes. Fluid inclusions represent tiny portions of fluids (ca. 5-20 micron) trapped in minerals. The only way to identify the passage of enriched fluids is through assessing the chemistry of fluid aliquots held in fluid inclusions because the transport of metals is dependent on the chemistry (salinity) and temperature of the hydrothermal fluids in which they are dissolved. The research methodology is based on the premise that rocks and minerals from different geological environments can be distinguished from each other on the basis of distinctive features of their fluid inclusion populations.

Researchers at Kingston University, led by Professors Treloar and Rankin, have advanced the understanding of these geodynamic and crustal processes by developing an innovative methodology that applies a number of integrated techniques including electron microscopy, micro-analysis, whole rock chemistry, fluid inclusion analysis, laser Raman analysis and cathodo-luminescence. Techniques used include heating-freezing methodologies, laser Raman identification of hydrocarbons and daughter minerals, and electron microscopy analysis of daughter phases in inclusions that have been cracked open [1][2][4]. The body of this work provides a remarkably robust basis for an instrument-based system for fluid inclusion analysis to map fluid chemistries and thus to inform exploration strategies for base and precious metal deposits. The knowledge and expertise associated with the research outlined here (together with associated expertise in mineral characterisation, largely through electron microscopy and micro-analysis) has been taken up and applied by professionals and organisations associated with mineral and hydrocarbon exploration and gemmology.

Rankin collaborated with Linkam Systems as they developed their prototype heating-freezing stage for fluid inclusion analysis during his career at Kingston University and he has continued this collaboration during the current assessment period in conjunction with Treloar in characterising high quality fluid inclusion standards. Evidence of this continuing collaboration with Linkam is in the provision of natural, as opposed to synthetic, standards based on freezing in the $CH_4 - CO_2$ system [2]. Treloar and Rankin have continued to develop methods of cracking inclusions to allow SEM analysis of daughter phases and of trace-element analysis of metals left remnant in the inclusions [5]. The benefits of integrating fluid inclusion microscopy and laser Raman analysis were demonstrated during research on the evolution of abiogenic methane and higher hydrocarbons in the alkaline rocks of the Kola Peninsula [1][4]. Much of the work outlined above is technical in nature and has led to protocols for analysis of fluid inclusions that are now routinely utilised worldwide in both industry and academia. The narrative here is that Kingston University, through the work of Rankin, Treloar and their co-workers, claims significant credit for the development of this methodology and its impact on mineral exploration industry. The techniques and analyses developed in this underpinning research underpin the impact on Randgold Resources.

Key researchers:

Treloar	Professor of Mineralogy and Petrology	01/11/1990-present
Rankin	Emeritus Professor (formerly Professor of Applied Geology)	09/1991-09/09
P J Murphy	Senior Lecturer	01/03/1999-present
D M Lawrence	Doctoral Research Student PDRA	01/10/2006-31/07/2010 01/10/2010 – 31/12-2011
B Beeskow	Doctoral Research Student	01/10/2003-31/07/2007
J Potter	Doctoral Research Student	01/10/2002-31/07/2004

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

Publications

The research has been published in peer-reviewed articles in internationally recognised high impact factor journals (2* and above).

[1] Potter, J, Rankin, AH and Treloar, PJ (2004). Abiogenic Fischer–Tropsch synthesis of hydrocarbons in alkaline igneous rocks; fluid inclusion, textural and isotopic evidence from the Lovozero complex, N.W. Russia. Lithos, 75, pp. 311-330. ISSN: 0024-4937. DOI: http://dx.doi.org/10.1016/j.lithos.2004.03.003. [Impact factor: 3.691 (five year). Citations: 130.]

[2] Beeskow, B, Rankin, AH, Murphy, P and Treloar, PJ (2005). Raman spectroscopy of the methane triple point in mixed CH4-CO2 fluid inclusions – natural low temperature calibration standards for microthermometric analysis. Chemical Geology, 233(1-3), pp. 5-15. ISSN: 0009-2541. DOI: http://dx.doi.org/10.1016/j.chemgeo.2005.01.028. [Impact factor: 4.063 (five year). Citations: 10.]

[3] Kodera, P, Lexa, J, Rankin, AH and Fallick, AE (2005). Fluid inclusion and stable isotope evidence for the genesis of epithermal Au-mineralization at Rozalia mine, Banska Hodrusa, Slovakia. Mineralium Deposita, 39(8), pp. 921-943. ISSN: 0026-4598 (print version). DOI: http:// dx.doi.org/ 10.1007/s00126-004-0449-5. [Impact factor: 1.684 (2011). Citations: 10.]

[4] Beeskow, B, Treloar, PJ, Rankin, AH, Vennemann, J and Spangeberg, TW (2006). A reassessment of models for hydrocarbon generation in the Khibiny nepheline syenite complex, Kola Peninsula, Russia. Lithos, 91, pp. 1-18. ISSN: 0024-4937. DOI: http://dx.doi.org/10.1016/j.lithos.2006.03.006. [Impact factor: 3.691 (5 year). Citations: 30.]

[5] Lawrence, DM, Treloar, PJ, Rankin, AH, Boyce, A and Harbidge, P (2012). A Fluid Inclusion and Stable Isotope Study at the Loulo Mining District, Mali, West Africa: Implications for Multi-Fluid Sources in the Generation of Orogenic Gold Deposits. Economic Geology. 108. 229-257. doi:10.2113/econgeo.108.2.229 [Output from grants (1) and (2) below.]

Grants

The underpinning research described in output [5] was carried out with the benefit of the following grants received after peer review and competitive tender:

(1) Treloar, PJ 2010-12 Locating Gold in the Senegal-Mali Shear Zone: an integrated approach using regional structural, fluid inclusion, geochemical and geophysical data sets. Randgold Resources (£42,000)

(2) PJ Treloar. 2011. Locating gold in the Senegal-Mali Shear Zone: an integrated approach using regional structural, fluid inclusion, geochemical and geophysical data sets. NERC (Natural Environment Research Council) IP-1163-0510 (£21,000).

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

Developing and refining techniques of fluid inclusion analysis and embedding these into industry have been an underpinning theme of the mineralogy group at Kingston. Part of this has been through enhancing the robustness of the primary analytical technique, and part has been through

developing new application strategies. In particular, mapping the distribution of different fluid chemistries within potentially mineralised terranes through analysis of fluid inclusion chemistries has impacted on the economics of mineral exploration in companies using these techniques. End-user beneficiaries are companies working in the minerals and petroleum exploration and mining sectors. A specific beneficiary company, and the focus of this case study, is Randgold Resources (a FTSE100 company).

Rankin's pioneering early work in the use of fluid inclusion mapping as a tool in mineral exploration geology opened up the novel possibility that exploration geologists can collect quartz veins in the field and map their fluid chemistries. These fluid chemistries can now be embedded into Geographical Information Systems, thus developing a grid of mineralisation potential. This has proved to be a powerful exploration tool, and has been developed in collaboration with Randgold Resources through a long-term collaboration aimed at knowledge transfer. During this collaboration, Treloar and Rankin further developed the technique of cracking open fluid inclusions so that daughter minerals and their chemistry can be identified using SEM analysis. These data can also be embedded into GIS maps and serve to reinforce the picture painted by the fluid inclusion chemistries.

Using this tool, Randgold Resources and Kingston University researchers have mapped different fluid types over a wide region in West Africa (west Mali and east Senegal, 2010-2011), and the success of this has enabled the company to move away from a traditional empirical exploration philosophy towards one with a more scientific base built around routine fluid inclusion work.

This work is supported by detailed mineral chemistry using a combination of electron microprobe, LA-ICP-MS, and portable XRF analysis, which provides the minerals industry with critical metallurgical detail for ore processing. As a result of this engagement (see cited reports in section 3) with Kingston University, Randgold Resources has fundamentally changed its systems: the company now prefers to identify minerals by electron microscopy and microanalysis rather than by reflected light microscopy, and uses microanalysis to identify potential metallurgical problems in the initial stages of exploration. The resulting data has allowed the company to assess gold deportment and issues of gold liberation as well as environmental toxicity issues which might arise from mine waste storage at an earlier stage of resource evaluation. This analysis will lead to a long term reduction of the environmental impact of Randgold Resources' mining operations.

The Kingston University research has enabled this company to benefit from a more targeted approach in its exploration and mining activities, thus reducing costs and increasing profitability. Randgold has stated (April 2013) that "fluid inclusion mapping to constrain potential prospectivity ... has enabled a map of the distribution of different fluids to be developed"; and "detailed electron microscopy and micro-analytical analysis of ore minerals and the phases associated with them" has enabled "the company ... to seek to embed these techniques in its exploration and metallurgical testing strategies".

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

Corroborating testimonial:

1. Testimonial from Exploration Manager, Randgold Resources: corroborates Use of fluid inclusion mapping by Randgold; benefits to Randgold of electron microscopy and microanalysis; embedding of these techniques in exploration and metallurgical testing strategies.

The following petrographic studies undertaken for Randgold Resources Ltd demonstrate the impact claimed in Section 4 above. These reports corroborate the impact and can be supplied to the panel on request.

D.M. Lawrence and P.J. Treloar. June 2011 Quartz-molybdenite veins, Massawa gold deposit, Eastern Senegal Report to Randgold Resources Ltd 8 pp

D.M. Lawrence and P.J. Treloar May 2011 Preliminary petrographic and geochemical studies on the Kibali gold deposit, NE Democratic Republic of Congo (J. Robson 2010 sample suite) Report to Randgold Resources Ltd 24 pp

D.M. Lawrence and P.J. Treloar April 2011 Recovery problems at Gounkoto Report to

Randgold Resources Ltd 36 pp

D.M. Lawrence and P.J. Treloar Dec 2010 Petrography studies at Gounkoto (GGD sample suite) Report to Randgold Resources Ltd 77pp

D.M. Lawrence and P.J. Treloar October 2010 Petrography studies at Gounkoto (GGD029) Report to Randgold Resources Ltd 14 pp