Institution: Durham University		
Unit of Assessment: UoA: 7, Earth Systems and Environmental Sciences		
Title of case study: Geological age relationships to define economic metal resource potential		
Period when the underpinning research was undertaken: Between 2014 and 2019		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): David Selby	**Role(s) (e.g. job title):** Professor	**Period(s) employed by submitting HEI:** 2005-present
Period when the claimed impact occurred: Between 2014 and 2020		
Is this case study continued from a case study submitted in 2014? Y – Only in part. Previous case dealt with >80% impact with the petroleum industry with only <20% with the mineral industry. This case demonstrates 100% impact with the mineral industry, supported by additional research published during this REF cycle		

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

The development of accurate exploration models for geological resources is a critical economic consideration for the mineral industry. Durham University led research by Selby has delivered impact worth 100s of millions of US Dollars to the global mineral (e.g., copper, gold, molybdenum) industry (e.g., Canada, Chile, Greece, Brazil). This impact has arisen through the development and application of rhenium-osmium (Re-Os) isotope geochemistry to determine the age and source of mineralisation. This Durham-delivered geochemical tool enables the development of more accurate geological models for industry and also permits improved reserve estimates, reduced exploration budgets and minimises the environmental impacts of global exploration.

2. Underpinning research (indicative maximum 500 words)

The underpinning research carried out by Selby (Professor, appointed 2005) and his research group at Durham University (from appointment to present) addresses longstanding academic (industry-related) issues concerning the development of subsurface Earth resources. Specifically, exactly when, how and where do resources, such as copper, molybdenum and gold form in rocks? Analytical and technological advances, developed by Durham-led research, have permitted the use of previously challenging geochemical methods to help answer old, but critically important geological questions – what is the geological age of the metal enrichment in the Earth's crust? Selby, his research group and international collaborations (10 PhD students, 4 post-doctoral researchers, and researchers worldwide: cf. **[R1-6]**; and references therein (Section 3) have pioneered, refined and applied the application of rhenium-osmium (Re-Os) radioisotope methods to sulphide minerals. The referred to underpinning research (Section 3) has demonstrated independently that the rhenium decay constant is accurately and precisely determined, critical knowledge underpinning Re-Os geochronology **[R1]**. It has also developed a mineral purification protocol permitting the isolation of ultrafine molybdenite (50-100 µm grain size) in rocks, thus extending the application to more mineralisation styles **[R2]**. Papers **R3-6** demonstrate the critical application of establishing the timeframe of geological events within various mineral systems, with a particular focus to porphyry type systems, which are explicit to this case study. Overall, the research culminates in developing an understanding of the optimal use of molybdenite for both accurate and precise Re-Os geochronology in ore systems. **[R1 - 6].**

This case deals specifically with the outcomes and impacts of molybdenite Re-Os geochronology for the mineral industry. Molybdenite (a molybdenum disulphide, MoS_2) is enriched in Re on formation and not Os. With time, the rhenium isotope ^{187}Re decays to form the osmium isotope ^{187}Os, and thus permits the age of the molybdenite formation to be determined by isotopic analysis. Selby and co-workers [e.g., **R1-6** and therein] have demonstrated the unique ability of

the Re-Os molybdenite geochronometer to yield a more accurate and precise determination of the absolute timing of metal precipitation compared to other radioisotope methods (e.g., Ar-Ar, Rb-Sr etc) and this precise determination allows companies to operate and search in new ways.
Selby's research has permitted a greatly enhanced understanding of the best Re-Os analytical protocols, age accuracy and precision, and elemental behaviour in rocks and minerals. This has allowed the determination of Re-Os *ages* for sulphide minerals (e.g., molybdenite) **[R1-6]**, and the ability to use Os isotope compositions (e.g., pyrite, chalcopyrite) to identify the *source* of ore metals [references therein of **R1-6**]. Moreover, this has improved our understanding of genetic models for mineral systems [e.g., **R1, 2, 4, 6** and references therein].
In terms of impact, the outcome yields critically necessary data required for exploration programmes [Section 4]. Ultimately Selby's research has shown that the Re-Os system, and specifically that related to dates obtained from molybdenite, can be applied much more widely than previously thought [**R2, 4-6]**. This has placed Durham at the forefront in the use of this novel research tool both academically and through industry as a fundamental exploration tool. Selby's Re-Os research leadership is recognised internationally through published literature that he has authored or co-authored since 2001. He is the recipient of the William Smith Fund (2009 from the Geological Society of London, and has been honoured as an elected Fellow of the Geological Society of America (2018) for excellence in contributions to applied and economic aspects of the science. He was also awarded the 2019 Impact and Engagement Technical and Commercial prize, by Durham University.

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

[bracketed values in bold are the number of citations, Google Scholar]

[R1] Selby, D., Creaser, R.A., Stein, H. J., Markey, R. J., Hannah, J. L., 2007. Assessment of the ^{187}Re decay constant accuracy and precision: Cross calibration of the ^{187}Re-^{187}Os molybdenite and U-Pb zircon chronometers. *Geochimica et Cosmochimica Acta,* 71, 1999-2013. **[125] DOI:** 10.1016/j.gca.2007.01.008
[R2] Lawley, C.J.M., and **Selby, D**. 2012. Re-Os Geochronology of Quartz Enclosed Ultra-fine Molybdenite: Implications for Ore Geochronology, *Economic Geology*, v. 107, p. 1499-1505. **[25] DOI:** 10.2113/econgeo.107.7.1499
[R3] Li., J, Bi, S., **Selby, D**., Chen, L., Vasconcelos, P., Thiede, D., Zhou, M., Zhao, X., Li., Z., Qiu, H., 2012. Giant Mesozoic gold provinces related to the destruction of the North China craton, *Earth and Planetary Science Letters, v. 349-350, 26-37.* **[183] DOI:** 10.1016/j.epsl.2012.06.058
[R4] Lawley, C.J., **Selby, D.,** Imber, J., 2013. Re-Os Molybdenite, Pyrite, and Chalcopyrite Geochronology, Lupa Goldfield, Southwestern Tanzania: Tracing Metallogenic Time Scales at Midcrustal Shear Zones Hosting Orogenic Au Deposits. *Economic Geology*, v. 108, p. 1591-1613. **[39] DOI:** 10.2113/econgeo.107.7.1499
[R5] Buret, Y., von Quadt, A, Heinrich, C., **Selby, D.** Walle, M., 2016**.** From a long lived upper crustal magma chamber to rapid porphyry copper emplacement: Reading the geochemistry of zircon crystals at Bajo de la Alumbrera (NW Argentina). *Earth and Planetary Science Letters,* v. 450, p. 120-131, **[61] DOI:** 10.1016/j.epsl.2016.06.017
[R6] Li, Y., **Selby, D**., Condon, D., Tapster, S., 2017. Cyclic magmatic-hydrothermal evolution in porphyry systems: High-precision U-Pb and Re-Os geochronology constraints from the Tibetan Qulong porphyry Cu-Mo deposit. *Economic Geology*, *v. 112, 1419-1440.* **[33] DOI:** 10.5382/econgeo.2017.4515

Quality of Research Evidence:

All papers are published in international peer reviewed journals.

Paper R1: A critical and highly cited paper than provides an assessment of the accuracy and precision of the decay constant of the rhenium. Critical for the application of the rhenium-osmium geochronometer, which is fundamental for the geochronology of molybdenite.

Papers R2 – 6: Discusses analytical advancements to further the applications of rhenium-osmium molybdenite geochronology and our understanding of mineral resource formation processes.

Paper R1: Led to the award of the *William Smith Fund* (2009) to Selby from the Geological Society of London. This award is made for research excellence in contributions to applied and economic aspects of the science.

Papers R2 – 6: This body of work is recognised by Selby election as a Fellow of the GSA, noting his career to date in being one the leading geochemists.

Papers R1 – 6: Were recognised in 2019 award for Impact and Engagement Technical and Commercial prize by Durham University.

Papers R1 – 6: The underpinning research has also been presented through several invited keynote conference presentations at major international conferences, e.g., AGU Fall Meeting 2011**;** GSA 2011, 2012, 2013, 2015, 2019; EGU 2013; Goldschmidt 2015; Mineral Deposits Studies Group 2011-16; IGC 2016; Pardee Symposium to Honor Arthur Holmes (1890-1965) for Contributions to Geochronology, Plate Tectonics, & the Origin of Granite.

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

A metallogenic belt is typically formed by multiple geological events that have led to the Earth's crust being endowed in metals that are associated with different formation mechanisms as well as ages. As such, for economic exploration, it is critical to establish the geological age of the metal (e.g., copper, gold, molybdenum) enrichment in the Earth's crust that a company is targeting. Herein lies the power of the application of the Re-Os molybdenite chronometer based on Durham-led research [e.g., **R1 – 6]** and why companies such as Rio Tinto and MMG, as part of their exploration program want to establish the chronology of the mineral enrichment targeted in their exploration programmes**.** Commissioned through focused industry-based (Rio Tinto, MMG, Eldorado, Sun Metals – see below) research projects at Durham, Re-Os molybdenite ages (hereafter referred to as Durham-led Research - DLR) have provided critical data to evaluate exploration models. This allows mineral companies to devise accurate resource estimates and exploration programmes and save exploration expenditure and thereby reduce any industry-related environmental impact. Although due to confidentiality exact figures cannot be given, the total impact claimed here is worth hundreds of millions of US dollars.

In the cases discussed below, the impact has occurred since August 2013 and is on-going, as is the nature of impact with mineral exploration. Companies will not divulge the specific details of their explorations to maintain their competitive market position, but they have provided testimony that falls within the REF period.

*Rio Tinto and MMG Impact cases **[E1, 2]***

The DLR has provided Rio Tinto and MMG data that has permitted reassessment of mining activities and exploration in the REF period, respectively. The DLR has resulted in plans to increase the life of mine operations at one of the World's major copper producers for another 20 years. This yielded a revenue of hundreds of millions of US dollars.

Both Rio Tinto and MMG are major explorers for porphyry-related copper reserves (supply ~75 % of the world's copper) that typically also contain significant reserves of molybdenum and gold. Porphyry deposits are a major geological manifestation of where the Earth's crust has been repeatedly intruded by small porphyry plutons that also channel metal-rich fluids, resulting in a local enrichment of metals (e.g., copper), with the younger events often overprinting the older events **[R2 – 6** and industry-led research at Durham**]**, or occurred spatially close together (< a few kms) or at deeper crustal levels. Over the last decade, it has been shown that the youngest magmatic-hydrothermal event is typically the major carrier of the economic resource. As such,

knowing the age of the sequence of the magmatic-hydrothermal events **[R2 - 6]** is of paramount importance in determining the likely economic value during preliminary exploration.

DLR Outcome 1 – During the REF period the MMG case highlights how the Re-Os molybdenite ages obtained by DLR have specifically aided in providing the understanding that the economic mineralisation occurred in a very short time interval (0.5 millions of years), and is only specifically related to one intrusion event (the youngest), although the prospect geology includes igneous activity that spans nine million years. This has benefited MMG by permitting the company to focus their exploration accordingly. The company state that, whilst it is difficult to put an absolute financial figure on the impact, direct savings in terms of drilling (USD 100,000 per drill hole – exploration at this scale involves 100+ drill holes) and time (e.g., mapping, assay analysis, geophysics, etc) had enormous impacts. Specifically: '*Constraining the timing / geological formation of metal enrichment is fundamental to not only the scientific understanding of how economic concentration of copper and molybdenum (Cu-Mo) form, but also to develop financially effective exploration programme and deposit models. The geological dating of the Mo bearing mineral molybdenite by the Re-Os radioisotope tool is the most accurate and precise methodology to achieve this, with the laboratory at Durham University led by David Selby being world leading in its development and application.'* Principal Exploration Geologist, MMG Las Bambas **[E1].**

DLR Outcome 2 - During the REF period, one case from Rio Tinto, at Escondida, Chile, highlights how DLR has permitted the company to restructure its mine site to access and maximise exploitation of the greatest endowment of copper in the region. In a development costing hundreds of millions of dollars, DLR has permitted the company to expand their exploration to locate the most economic concentration of copper. This will ultimately lead to revenues far exceeding the initial development expenditure for the company. The mine restructuring will result in an increase in the lifespan of the mining at Escondida yielding enhanced employment security for hundreds of Chileans and revenue for Chili. The Principal Geologist, at Rio Tinto states: *'For Rio Tinto, the recognition of the value Re-Os molybdenite geochronology that is provided by Prof Selby at Durham University has changed the way in which we explore for resources over the last five years'* **[E2**].

Eldorado Gold Corporation Impact cases **[E3]**
For Eldorado Gold, DLR has aided in steering the company's exploration program which runs in to CAD10sMillion.

DLR Outcome 3 - During the REF period, in Brazil, DLR identified an age that is genetically associated with the copper and not gold mineralisation. As Eldorado Gold is a gold-focused company, this allowed the company to re-evaluate their exploration program, which in this case, involved leaving the prospect area that, although economic for copper, was not economic for gold. This was an important decision as halting exploration resulted in savings that would have run into several millions of Canadian dollars (CAD). Chief Geoscientist, Eldorado Gold states*: 'The Re-Os molybdenite date allude to the fact that the molybdenite was genetically associated with the Cu-Mo system and not the gold-bearing IRGS system. This was critical in guiding our exploration in the region because as a gold-focused company the IRGS were the most attractive target and thus allowed the company to pull back on the Cu-Mo exploration. As a result, potentially saving several millions of dollars in exploration costs.'*

DLR Outcome 4 - During the REF period, in Turkey, a Tertiary geological age has been established to be the key timing interval for gold mineralisation. The DLR has been critical in confirming or denying the age of gold-related mineralisation, which has as a result guided the company's exploration programs where approximately CAD20million have been spent on exploration.

DLR Outcome 5 – Similarly during the REF period, in Greece, where the key geological ages are 33 to 23 and 23 to 5 million years ago, with the geological characteristics of each age of mineralisation being similar, the DLR has confirmed the timing of gold mineralization and directly guided the company's exploration strategy that has a budget of up to CAD10million. The Chief

Geoscientist, Eldorado Gold states: *'We have used Re-Os dating of molybdenite on our prospects to determine which generation the mineralisation is related to, and the results have helped guide our exploration strategy in the region where we typically have an exploration budget of CAD5-10million.'*

In summary, during the REF period, the outcome of DLR for several international mining companies working in several countries has provided critical data to strategically refine their exploration programs, and in one case revise the location of a principal mining site. Financially, this has permitted companies to maximise expenditure in terms of explorations that totals hundreds of USD and minimise environmental impact. Moreover, in the case of mine redevelopment, DLR has led to further security in terms of employment and country revenue.

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

Note that in general it is difficult to provide copies of internal technical documents / reports from mining companies who consider such material to be highly confidential, especially at the early exploration stages, and thus commercially very sensitive. We therefore provide testimony from industry end-users to corroborate impact of the Re-Os research.

[E1] **Testimony:** *Principal Exploration Geologist,* Minera Las Bambas, Av. El Derby 055 Torre 3 Piso 9, Santiago del Surco, Lima, Peru

[E2] **Testimony:** *Principal Geologist*, Rio Tinto, *Rio Tinto Exploration, 1 Research Ave, Bundoora, Victoria, Australia*

[E3] **Testimony:** *Chief Geoscientist*, Eldorado Gold Corporation, *550 Burrard Street, Vancouver, BC, Canada, V6C 2 B5*