Institution: Durham University

Unit of Assessment: Earth Systems and Environmental Sciences (UoA 7)

Title of case study: A Novel Geochemical Toolbox for the Petroleum and Mineral Industries

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

Innovative geochemical research led by Selby at Durham has permitted savings of up to $70M in global mineral and petroleum exploration programmes (e.g., Andes of S. America; West of Shetlands oilfields). Selby's research has developed a unique geochemical toolbox using rhenium, osmium, platinum and palladium that constrain more accurate geological models leading to better reserve predictions. The toolbox provides previously unavailable geological time constraints and source identification of resources (e.g., **copper, gold, crude oil**) that gives mineral and/or petroleum companies an enhanced economic advantage by improving reserve estimates and/or reducing exploration budgets and/or minimising the environmental impacts of exploration.

2. Underpinning research (indicative maximum 500 words)
[Bracketed numbers refer to papers listed in Section 3]

The underpinning research carried out by Selby (TOTAL Reader in Petroleum Geoscience, 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 oil and copper, form in rocks? Analytical and technological advances, developed in part by research at Durham, have permitted the use of previously challenging geochemical methods to help answer old, but critically important geological questions. Selby, his research group and international collaborations (6 PhD students, 2 post-doctoral researchers, United States and Canada Geological Survey research staff; Prof. Creaser [U of Alberta]; Dr Osborne [BP]; Dr Ellis [Statoil]; cf. [1-6]; and references therein – Section 3) have pioneered and refined application of the rhenium-osmium (Re-Os) radioisotope and platinum/palladium (Pd-Pt) methods to sulphide minerals, organic-rich rocks and petroleum. As a direct result, Selby's research has defined and enhanced the precision and understanding of Re-Os and Pd-Pt analytical protocols and elemental behaviour in rocks and minerals. This permits the determination of Re-Os ages for sulphide minerals [4-6], organic-rich sedimentary units and hydrocarbons [1-3], and the ability to use Os isotope compositions and Pt/Pd ratios to identify the source rock of petroleum accumulations [3]. This has improved our understanding of genetic models for both mineral and hydrocarbon systems [1-6]. In impact terms, the outcome yields critical necessary data required for exploration programmes [Section 4]. Ultimately Selby's research has shown that the Re-Os system can be applied much more widely than previously thought and has placed Durham at the forefront in the use of this novel research tool both academically and through industry. This leadership was recognised by the award of the William Smith Fund (2009) to Selby from the Geological Society of London for excellence in contributions to applied and economic aspects of the science and by the TOTAL petroleum company who fund Selby's position at Durham.

The underpinning research highlights are:

- Shown that the Re-Os chronometer is a reliable, precise chronometer for obtaining the *depositional age* of clastic marine and lacustrine sedimentary rocks.
- Illustrated the utility of Re-Os to define the *age of oil generation* from a source rock. [1, 2]
- Demonstrated how Re, Os, Pt and Pd geochemistry can be used to *characterise ('fingerprint') crude oils*. [2]
  Discovered that the Re-Os isotope system and Pt/Pd systematics can be used to ascertain the *timing of oil generation and identify an oil source rock age in sedimentary basins by analysis of oils alone*. [3]

- Developed an understanding of the optimal *use of molybdenite* and other sulphide minerals for precise Re-Os geochronology in ore systems. [4, 5, 6]
- Demonstrated independently that the rhenium decay constant is accurately and precisely determined, critical knowledge underpinning Re-Os geochronology.

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

[bracketed values in bold are the number of citations, Google Scholar]
= references best illustrating research quality

[1] **Selby, D.,** Creaser, R.A., 2005**.** Direct radiometric dating of hydrocarbon deposits using Rhenium-Osmium isotopes. *Science,* 308, 1293-1295. DOI: 10.1126/science.1111081 **[48]#**

[2] **Selby, D.,** Creaser, R. A., Fowler, M. G., 2007. Re-Os elemental and isotopic systematics in crude oils. *Geochimica et Cosmochimica Acta*. 71, 378-386. doi:10.1016/j.gca.2006.09.005 **[28]**

[3] Finlay, A. J., **Selby, D.**, Osborne, M. 2011. Re-Os geochronology and fingerprinting of United Kingdom Atlantic Margin oil: Temporal Implications for regional petroleum systems. *Geology*, v. 39, 475-478. doi:10.1130/G31781.1 *(PhD research)* **[7]#**

[4] **Selby, D**., and Creaser, R.A., 2004. Macroscale NTIMS and microscale LA-MC-ICP-MS Re-Os isotopic analysis of molybdenite: Testing spatial restrictions for reliable Re-Os age determinations, and implications for the decoupling of Re and Os within molybdenite. *Geochimica et Cosmochimica Acta,* v. 68, p. 3897-3908. doi:10.1016/j.gca.2004.03.022 **[104]#**

[5] 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. doi:10.2113/econgeo.107.7.1499 *(PhD research)*

[6] **Selby, D**., Kelley, K.D., Hitzman, M.W., Zieg, J. 2009. Re-Os sulfide (bornite, chalcopyrite and pyrite) systematics of the carbonate-hosted copper deposits at Ruby Creek, southern Brooks Range, Alaska. *Economic Geology*, 104, 437-444. doi:10.2113/gsecongeo.104.3.437 **[15]**

Quality of Research:

Paper 1: Pioneering paper showing the application of Re-Os isotopes to constrain the absolute age of oil generation. Published in Science (impact factor 31.4). Paper received media attention, e.g., radio interviews (CBC) and articles written in international newspapers, e.g., Toronto Sun, Washington Post. Entered by Selby as research output for RAE 2008 of which 97.3% of the Durham UoA 17 Research outputs were rated 2* or above, with 71.2% rated 3* or above. This paper also provided the founding support for the successful application for a *Royal Society Industrial Fellowship* to Selby held between 2008 and 2012.

Papers 1, 2, 4 and 6 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.

All papers are published in an international peer reviewed journal with an impact factors between 2.6 and 31.4.
The underpinning research has also been presented through several invited keynote conference presentations at major leading conferences, e.g., AGU Fall Meeting 2011 **;** GSA 2011; Pardee Symposium to Honor Arthur Holmes (1890-1965) for Contributions to Geochronology, Plate Tectonics, & the Origin of Granite, and Venezuelan Symposium On Applied Earth Science in Hydrocarbon Exploration (2008).

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

[bracketed numbers refer to papers listed in section 3 and corroborated sources in section 5]

The Re-Os and Pt/Pd methodology has been commissioned through focused industry-based research projects at Durham by BP, Statoil and Rio Tinto to establish geological ages and source information for petroleum and sulphide mineralization. BP and Statoil conducted proprietary Re-Os and PGE research concerning global petroleum systems with particular emphasis on offshore Angola and Faroes-West of Shetland (F-WoS) fields because it can be used to establish a chronological framework for a petroleum system. This data has provided critical data to evaluate exploration models (see below). In the mineral exploration sector, Rio Tinto needed to establish if their preliminary stage investigations had located economic or sub-economic copper mineralization. The specific impacts detailed below are, in summary, that the Re-Os and Pt/Pd data has permitted petroleum and mineral companies to devise accurate resource estimates and exploration programmes and save exploration expenditure and thus reduce any industry-related environmental impact.

Petroleum Sector

For Statoil and BP, Re-Os and Pt-Pd research was used to underpin exploration frameworks in four areas:

[A] Oil geochronology: In the F-WoS basin, Re-Os research provided evidence that oil generation was pulsed and originated from the same source rock strata between 70 and 40 Ma [3]. This finding contradicted existing models that invoked a single Cretaceous age (~80Ma) of generation and a complex history of oil migration. Given the greater age assumed by these models, they incorrectly predicted that the present-day basin plays should be dominated by gas. The multiple younger generation ages identified from the Re-Os data presented Statoil with a solution to this conundrum: the heat flow values used in their basin modelling could simply be reduced leading to an oil-dominated system in the F-WoS basin. Oil is economically easier and more environmentally friendly to develop than gas. For example, the development of the F-WoS region would cost ~$9B for oil vs $27B for gas. If the resource had been gas, then the F-WoS basin would have been considered uneconomic and abandoned. The basin has ~17-20% of current UK resources at ~3.5 BBOE recoverable worth ~£**350**B. The ability to predict the chance of oil vs gas using Re-Os geochronology [1-3] has therefore been critical to Statoil's economic assessments of future oil exploration and extraction development in the F-WoS region. Testimony from a Leading Geoscientist at Statoil states: '*This is a significant result in that it has a major impact on future exploration activity, particularly on evaluating trap charge and hydrocarbon type (oil vs gas). Accurate prediction of hydrocarbon type impringes on pre-drill economic assessments'* [8].

[B] Oil-source correlation [2-3]: the identification of the correct source rock of migrated hydrocarbons is essential for all oil companies exploring in the subsurface. Re-Os and PGE are inorganic elements that are resistant to biodegradation. The elements are concentrated in source rocks and oils, and yield radiometric dates. This property allowed BP to directly date the source rocks from which oils were generated from plays located in Angola and the North Sea. Such information has helped to reduce exploration risk and improve capital efficiency, e.g., avoiding one dry hole reduces costs by $70M.

[C] Shale gas play chemostratigraphy and geochronology: determining the absolute age of source rocks and stratigraphic correlation is often challenging due to a lack of reliable biostratigraphy. Accurate stratigraphic correlation is essential in shale gas plays in order to define the 'staying in zone', i.e. keeping the horizontal well in the best horizon for gas/oil production. Re-Os and PGE techniques [2-3] are proving a very valuable technique for such correlation purposes, e.g., Angola (BP) [7].

[D] Oil field compartmentalisation: Before production data is available, it is critical to design the optimum extraction plan for an oil reservoir. Establishing compartmentalisation from organic geochemistry data alone is challenging because petroleum-related fluids can have a very similar organic composition. However, combining organic with PGE and Re-Os geochemistry [1-3], the detection of fluid compartments is more readily achieved, allowing a better idea of the number of wells required and their optimal positions to exploit an oil field. This has saved BP $10'sM of well development costs [7].

Mineral Sector

Porphyry copper-systems host and supply ~75% of the world's copper and are an important target for major mining companies (e.g., Rio Tinto). A metallogenic belt typically comprises several porphyry systems that formed at different geological times, e.g., 10 to 250 Ma. Commonly the most economic porphyry systems form during similar time periods in the geological evolution of a metallogenic belt. Thus, the age of copper porphyry mineralization in magmatic arcs is of paramount importance in determining the likely economic potential resource of a porphyry system located during preliminary exploration.
Molybdenite located near a regional fault zone in the Andes was sampled by Rio Tinto for Re-Os geochronology. The fault juxtaposes two geological terranes of different age: Permian-Triassic and Tertiary. For the exploration programme, it was necessary to know the age of the mineralization to quickly assess the likely value of the exploration target potential prior to an extensive drilling programme. The Re-Os molybdenite age obtained by the Durham Group [3-6] was Triassic and as a direct result of the Re-Os age the exploration was abandoned. The senior geologist testimony states, '*In the Andes, Triassic porphyry systems are known to be sub-economic for major mining companies* (such as Rio Tinto)*. As a consequence, this target was dismissed'* [9]. The Re-Os dating resulted in saving the company approximately US$300,000 in drilling, rock geochemistry and employee-related costs and avoided additional environmental impact through the mining exploration programme. As a result, the company was able to allocate resources to other projects with greater economic potential [9].

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 petroleum and 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.

[7] **Testimony:** Acting Team Leader, ISDM team. Unconventional Reservoirs & Fluid R&D programme Manager. BP International Centre for Business & Technology, Building H, Chertsey Rd., Sunbury-on-Thames, Middlesex, UK, TW16 7LN.

[8] **Testimony:** Leading Geoscientist, EXP INT EA Europe, Statoil (U.K.) Limited

[9] **Testimony:** Senior Geologist, Rio Tinto, Presidente Riesco 5435, Oficina 1302, Las Condes, Santiago, Chile

Web article: Mary Guevara & Joanna Lumley (PGS) *"New Era Of Understanding For Faroe Shetland Basin"* E&P http://www.epmag.com/Exploration/New-Era-Understanding-Faroe-Shetland-Basin_103966