Institution: Cardiff University

Unit of Assessment: 7

Title of case study: Platinum-Group Element mineral deposits: exploration, evaluation and beneficiation

1. Summary of the impact

Platinum Group Elements (PGE) are critical strategic metals because of their unrivalled applications in catalysts, fuel cells and electronics and cancer therapies. Research and analytical methods developed at Cardiff have impacted on exploration for new PGE deposits, and more efficient processing of PGE ores by international mining companies. A key milestone between 2009 and 2012 was the discovery of a 3 billion year old giant impact crater in West Greenland. This discovery is of major economic significance because all craters previously found in this size class are associated with multi-billion dollar mineral and/or hydrocarbon resources. It led to an intellectual property transaction worth CDN$ 2.1 million and discovery of nickel and PGE deposits in Greenland by North American Nickel Incorporated.

2. Underpinning research

PGEs are among the rarest elements in the Earth's crust. All current major world minable PGE resources, and likely future potential resources, occur in mafic igneous rocks. Almost all exploitable PGE ore deposits form when an immiscible sulphide liquid scavenges PGE from a silicate melt, then separates and concentrates them. Depending on the extent of sulphide melt fractionation, its trace element chemistry and any post-magmatic alteration, the PGE may be distributed between different base metal sulphide (BMS) minerals or form their own platinum-group minerals (PGM) in the final ore. Since 2000, research on the distribution of PGE in ores has changed focus from PGM studies using electron microscopy to include laser ablation ICP-MS analysis that measures trace PGE concentrations in sulphide minerals. Drs Prichard and McDonald have been based at Cardiff from 1996 and 2001 respectively. They are recognized as experts with established track records in PGE studies using electron microscopy[3.1, 3.2] and laser ablation mass spectrometry techniques[3.4]. This work is crucial in evaluating the economic potential of PGE mineral deposits, since the distribution of PGE between BMS and PGM in the ore strongly influences the type of ore processing and its cost (e.g., at Aguablanca mine in Spain). Research by Prichard and McDonald in 2010[3.2] on the redistribution of PGE during low temperature alteration at Aguablanca has provided significant insights into the potential for processing oxidized supergene ores that are a presently under-exploited PGE resource.

In addition to characterizing ore and improving extraction efficiency at known deposits, research at Cardiff has revealed new targets for PGE exploration. In 2009-2010, as the Cardiff lead, McDonald's work on the World's third largest PGE deposit, the Platreef, resulted in a fundamentally new exploration model involving highly efficient concentration of PGE in staging chambers[3.3, 3.4]. The points where these chambers feed into the Platreef are prime targets for high grade mineralization[3.3] and in 2011 this research won the Wardell Armstrong prize from the Institution of Materials, Minerals and Mining. Major extra-terrestrial impact structures are potential hosts for PGE deposits and the Sudbury Basin, long known to host a range of magmatic sulphide deposits that are the subject of Prichard's research[3.1], is such an impact structure. Prichard's research at Sudbury since 2009 has been described as part of a number of "landmark contributions to the science of nickel deposits" by Peter Lightfoot, chief geologist of the mining company Vale[5.2]. Research by McDonald in collaboration with the Geological Survey of Denmark and Greenland and Lund University, led to the discovery of a 3 billion year old giant impact crater at Maniitsoq in West Greenland[3.5, 3.6]. McDonald led the geochemical and economic geology

aspects of the project. Prior to this study the oldest known crater was the 2.02 billion year old Vredefort crater in South Africa. Giant (>150 km diameter) craters have major exploration significance because all of the craters previously known in this size class are associated with multi-billion dollar mineral and hydrocarbon resources (gold and uranium at Vredefort; nickel and copper at Sudbury; and hydrocarbons at Chixculub). Identifying old eroded craters such as Maniitsoq is extremely difficult, and it took from 2009 until 2012 to compile enough evidence to validate the discovery[3.5]. The earliest version of the impact model was exploited in an intellectual property transaction in 2011 is now being used by North American Nickel Incorporated, to guide exploration for nickel and PGE at Maniitsoq[3.6].

3. References to the research

[3.1] Dare, S. A. S., Barnes, S.-J., **Prichard H. M**. and **Fisher P.C.** (2010) The timing and formation of platinum-group minerals from the Creighton Ni-Cu-PGE sulfide deposit, Sudbury, Canada: early crystallization of PGE-rich sulfarsenides. Economic Geology 105, 1071-1096.
DOI: http://dx.doi.org/10.2113/econgeo.105.6.1071

[3.2] Suárez S**., Prichard H.M.**, Velasco F., **Fisher P.C.**, and **McDonald I.** (2010) Alteration o platinum-group minerals and dispersion of platinum-group elements during progressive weatherin of the Aguablanca Ni-Cu deposit, SW Spain. Mineralium Deposita, 45, 331-350.
DOI: http://dx.doi.org/10.1007/s00126-009-0275-x

[3.3] **McDonald I**., Holwell D.A., and Wesley B. (2009) Assessing the Potential Involvement of an Early Magma Staging Chamber in the Generation of the Platreef Ni-Cu-PGE Deposit in the Northern Limb ofthe Bushveld Complex: A Pilot Study of the Lower Zone Complex at Zwartfontein. Applied Earth Science (Trans. IMM section B) 118, 5-20
DOI: http://dx.doi.org/10.1179/174327509X434902

[3.4] Holwell D.A., **McDonald I**., and Butler I.B. (2011) Precious metal enrichment in the Platreef, Bushveld Complex, South Africa: evidence from homogenized magmatic sulphide melt inclusions. *Contributions to Mineralogy & Petrology*, **161**, 1011-1026.
DOI: http://dx.doi.org/10.1007/s00410-010-0577-0

[3.5] Garde A.A., **McDonald I.,** Dyck B., and Keulen N. (2012) Searching for giant, ancient impact structures on Earth: the Mesoarchaean Maniitsoq structure, West Greenland. *Earth & Planetary Science Letters*, **337-338**, p.197-210.
DOI: http://dx.doi.org/10.1016/j.epsl.2012.04.026

[3.6] Garde A.A., Pattison J., Kokfeld T.F., **McDonald I**., and Secher K. (2013) The norite belt in the Mesoarchaean Maniitsoq structure, southern West Greenland: conduit-type Ni-Cu mineralisation in impact-triggered, mantle-derived intrusions*? Geological Survey of Denmark and Greenland Bulletin* 28, 45–48. http://www.geus.dk/publications/bull/nr28/nr28_p45-48.pdf

Additional Information
Institution of Materials, Minerals and Mining – Award Winners 2011 (Wardell Armstrog Prize for [3.3] to McDonald and co-authors). http://www.iom3.org/content/award-winners-2011 (accessed on 9th July 2013, archived as PDF)

4. Details of the impact

Understanding the fundamental controls on mineralization and locating the host phases that control the distribution of the PGE in ores provide key insights for companies carrying out exploration and/or mineral processing of PGE. The combination of specialist knowledge and analytical facilities at Cardiff allows the total distribution of PGE within ores, metallurgical products or other samples to be mapped and quantified; impacting both on exploration efficiency and reducing costs at deposits such as Aguablanca and Sudbury[5.1,5.2]. The evolution of these research-led technologies has led to collaborations with major PGE producers and junior exploration companies. Examples of these industrial impacts include:

Collaboration with Anglo Platinum Ltd (McDonald) resulted in the identification of staging chambers below the world's third largest PGE deposit (the Platreef) where highly PGE-rich sulphide liquids were concentrated[3.3]. Evidence for this sulphide liquid is preserved as inclusions trapped in the earliest Platreef minerals[3.4]. This new understanding has been used by Anglo Platinum to understand the development of the Platreef orebody and the underlying factors that affect the distribution of mineralisation in areas being mined and explored by the company[5.3].

Periodically, certain PGE deposits have been revisited to apply new analytical methods to solve long-standing problems. Prichard's research on PGM at the Aguablanca Ni-PGE deposit in Spain began in 2000 and since 2009 this work has been extended through a study of PGE behaviour in the gossans (siliceous iron oxide caps developed from weathering) in collaboration with the mine operators, Rio Narcea Recursos S.A[3.2]. This research has helped Rio Narcea Recursos S.A understand the ore mineralogy in a way they would not have been able to do themselves and has helped the company "add value to the base metal product through the processing of precious metals within our ores and helped us deal with smelter credits for precious metals in the ores" [5.1].

In recent years there has been strong activity in the mining sector for exploration at craters, formed via the impact of asteroids or comets with the Earth. This is due to the high probability that medium-giant sized craters will host significant mineral or hydrocarbon resources. For example, in 2005 it was estimated that in North America alone over US$ 18 billion worth of natural resources were extracted from crater sites each year. The research carried out by Prichard on the behaviour of PGE in the sulphide ores at the Sudbury impact crater[3.1] has been used by nickel company Vale to improve extraction efficiency of PGE in their ore[5,2].

A major research milestone during the REF period has been the discovery of the giant Maniitsoq impact crater in West Greenland[3.5]. Due to the highly eroded nature of the crater it took three years from 2009-2012 to establish the validity of the Maniitsoq crater among the scientific community[3.5]. However the mineral exploration industry was quicker to grasp the significance of the discovery and exploit it before the research was formally published. The opportunity was taken up in late 2010 by two mining consultants, John Ferguson and John Rowntree, who recognized the potential of the impact model and used it to prepare an outline programme for a mining company to acquire a licence and carry out exploration for nickel and PGE at Maniitsoq[5.4]. They recognised that the key targets were supercooled magmas (termed norites) carrying nickel and copper sulphides (with by-product PGE) that were produced shortly after the impact and which invaded the fractured target rocks. Modelling carried out by McDonald and his colleagues in 2011 identified the likely size of the crater and the limits of shock metamorphism, which could be used to optimise the size and geographical spread of the likely licence area. The size of the crater predicted by the impact model indicated that there should be many more of these mineralized norites than had been discovered by ground surveys in the 1970s and by fixed wing aeroplane geophysical surveys in the 1990s. In August 2011 North American Nickel Incorporated (NAN) acquired the intellectual property rights for the Ferguson-Rowntree exploration plan[5.6] for cash and share warrants worth

CDN$ 2.1 million plus a 1.25% net smelter royalty each – reducible to 0.5% upon payment of CDN$ 1 million each to Ferguson and Rowntree[5.8]. NAN committed $CDN 7.7 million in 2011-12 to prospecting the site and in late 2011 a helicopter-supported electromagnetic survey discovered 17 new norite targets for test drilling, consistent with the model. This had risen to 102 targets by June 2013[5.9]. NAN management have fully incorporated the impact model[5.7,5.9], been involved in follow-up research[3.6] and have expressed the view that now the science is confirmed[3.5, 3.6], they stand the best chance of success if they explore "from an impact point of view"[5.5].

5. Sources to corroborate the impact

[5.1] Confirmation by Chief Geologist for Aguablanca mine, Rio Narcea Recursos SA, of the impact of research by Prichard and McDonald (reference [3.2]) at the Aguablanca nickel-PGE deposit.

[5.2] Confirmation by Chief Geologist (Nickel) for Vale on the impact of Prichard's research at Sudbury , including reference [3.1].

[5.3] Confirmation by Former Head of Platinum Geology, Anglo Platinum Ltd on the impact of improved understanding of the Platreef through research by McDonald, including references [3.3] and [3.4].

[5.4] Confirmation by Director of Spar Resources Pty Ltd and advisor to North American Nickel Incorporated on the impact of the discovery of a giant impact crater at Maniitsoq by Garde, McDonald and others and its exploration potential (references [3.5] and [3.6]).

[5.5] Confirmation by Chief Geologist for North American Nickel on the usefulness of the impact model for Maniitsoq on the company's exploration strategy (reference [3.5])

[5.6] Confirmation of acquisition of exploration licence by North American Nickel http://www.northamericannickel.com/news/news-details/2011/North-American-Nickel-Acquires-Large-Mineral-Exploration-Licence-in-Greenland1126311/default.aspx (accessed 24th September 2013, archived as PDF)

[5.7] Confirmation that North American Nickel has recognised and appreciated the exploration significance of impact model developed by McDonald and his colleagues http://www.northamericannickel.com/news/news-details/2012/Earths-Oldest-Meteor-Impact-Site-Discovered-at-North-American-Nickels-Maniitsoq-Ni-Cu-PGE-Project-Southwest-Greenland1130135/default.aspx (accessed 24th September 2013, archived as PDF)

[5.8] North American Nickel's Full Financial Statement (12 months ended December 2012). Confirmation of expenditure (p.16 and section10d), share warrant agreements and intellectual property rights (p.22) for Maniitsoq. http://www.northamericannickel.com/files/doc_financials/Q4%202012%20Dec%2031%2012%20Financial%20Reports%20Complete_v001_p11272.pdf(accessed 24th September 2013, archived as PDF)

[5.9] North American Nickel investor presentation with geology based on the impact model (slides 10, 11, 16 and 30), including 102 conductive targets recognised for follow-up work (slide 18). http://www.northamericannickel.com/files/doc_presentations/NAN%20Maniitsoq%20Sept%205%202013.pdf (accessed 24th September 2013, archived as PDF)