Institution: Cardiff University		
Unit of Assessment: Earth Systems and Environmental Sciences (7)		
Title of case study: Improved geological strategies for efficient and non-invasive discovery of magmatic ore deposits in Africa, Australia and Canada		
Period when the underpinning research was undertaken: 2007 – 2019		
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:**
W. Maier I. McDonald	Professor Reader	01/09/2013 – present 01/08/2001 – 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)

Magmatic ore deposits contain nickel (Ni), copper (Cu) and platinum-group elements (PGE) that are highly valued for industrial and commercial applications. Cardiff's geochemical vectoring and petrological strategies for mapping and prospecting these deposits enabled more efficient exploration, which were less invasive to the environment than drilling. This research benefited the following commercial and governmental organisations:

1. Ivanhoe Mines Ltd. in South Africa (PGE);
2. The Geological Survey of Western Australia (PGE, Ni, Cu);
3. Northern Shield Resources Inc. in Canada (PGE).

Use of Cardiff's exploration strategies created financial savings of over £23M and prevented disruption and immense costs of relocating communities, protecting culturally sensitive land and forming unique partnerships with local people in these areas.

2. Underpinning research (indicative maximum 500 words)

Magmatic ore deposits contain metals crucial to industry and trade, particularly Platinum-Group Elements (PGE) as well as Chromium (Cr), Vanadium (V), Nickel (Ni), and Copper (Cu). PGEs are used in auto catalysts, Cu in electric infrastructure, and Cr, Ni and V are used in the manufacture of steel and batteries. Global energy requirements and climate targets will significantly influence future metal demand and supplies. For example, building the infrastructure underpinning the green economy transition, including key areas of renewable energy production, storage, and electric vehicles, will trigger a >100% increase in demand for many key metals over the next decades (Vidal et al., 2013, Nature Geoscience, 6, 894-896). Similar demand growth is also likely for PGE, in view of their essential use in fuel cells.

Maier and McDonald, of the Economic Geology and Geoscience Africa research groups at Cardiff University, have worked with global exploration companies and geological survey organisations over the last 15 years to create new techniques for exploring magmatic ore deposits. This work focussed on mapping, sampling, petrologic-geochemical characterisation, and genetic interpretation of mineral prospective regions.

2.1 Bushveld Complex, South Africa – Ivanhoe Mines

In South Africa, several new PGE deposits were characterised within the Bushveld Complex, the largest ore belt on Earth, by Maier and McDonald. Specifically, Cardiff research **[G3.1]** led to a new model of fluid-based palladium mobilisation at the Aurora deposit **[3.1]**. The research also showed that strongly contaminated reefs at the margins of intrusions can be stratigraphically correlated with uncontaminated reefs within intrusions, and that both types are formed by hydrodynamic processes **[3.2]**.

The research supported by **[G3.2]** and **[G3.3]** led to a new exploration model for PGE reefs involving metal concentration in hydrodynamic traps and magma conduits **[3.2]**. The ore

model was confirmed by the discovery of the 'Flatreef' deposit, found beneath existing mine operations and deposits in 2012, and characterised by Maier and colleagues in 2018 **[3.2]**. Cardiff research was essential in the decision that further exploration should target hydrodynamic traps in the centre of intrusions **[3.2]**.

2.2 Musgrave and Albany Fraser ore deposit belts, Western Australia – Geological Survey of Western Australia

Cardiff's research was instrumental in the first detailed chemical and mineralogical characterisation, and interpretation of the ore forming processes in the Musgrave and Albany Fraser magmatic ore deposit belts (2012-2016). Both are vast, remote territories in Western Australia totalling around 60,000km^2 and are among the least understood and explored domains in the region. At Musgrave, Cardiff researchers were able to identify how long-lived mantle upwelling and relatively slow cooling rates created the Giles Complex, one of the world's greatest clusters of layered intrusions **[3.3]**. The Giles intrusions are rich in Ni, Cu, V and PGE, concentrated during subsidence of slowly cooling magma chambers and the sagging of cumulate mushes. At Albany Fraser, Cardiff researchers explored the composition of mafic-ultramafic rocks to determine the magmatic sulphide ore potential of the region **[3.4]**. The Fraser zone's potential as a significant new source for nickel, an essential metal in steel manufacturing and next generation high performance Ni batteries, was acknowledged following Cardiff's research.

2.3 Labrador Trough, Canada – Northern Shield Resources

Maier began working with Northern Shield Resources in 2007, starting in Ontario but expanding to northern Québec. Northern Shield began focussing their exploration for Ni-Cu-PGE in the Labrador Trough, namely the Huckleberry property, in 2014. Despite the apparent prospectivity of the province, exploration of the area remained at a formative stage until Cardiff's team joined the project. The Cardiff researchers (Maier and his PhD student Smith) interpreted the extensive geochemical data generated during the exploration programme, designed an ore deposit model, and proposed further drill targets based on geochemical vectors, also developed by Maier **[3.5]**.

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

[3.1] McDonald I., Harmer R.E., Holwell D.A., Hughes H.S.R., Boyce A.J. (2017) Cu-Ni-PGE mineralisation at the Aurora Project and potential for a new PGE province in the Northern Bushveld Main Zone. *Ore Geology Reviews*, 80, 1135-1159. doi.org/10.1016/j.oregeorev.2016.09.016

[3.2] Grobler D.F., Brits J.A.N., **Maier W.D.**, Crossingham A. (2019) Litho- and chemostratigraphy of the Flatreef PGE deposit, northern Bushveld Complex. *Mineralium Deposita*, 54, 3-28. doi.org/10.1007/s00126-018-0800-x

[3.3] Maier W.D., Howard H.M., Smithies R.H., Yang S.H., Barnes S.-J., O'Brien H., Huhma H., Gardoll S. (2015) Magmatic ore deposits in mafic-ultramafic intrusions of the Giles Event, Western Australia. *Ore Geology Reviews*, 71, 405-436. doi.org/10.1016/j.oregeorev.2015.06.010

[3.4] Maier W.D., Smithies R.H., Spaggiari C.V., Barnes S.J., Kirkland C.L., Yang S., Lahaye Y., Kiddie O., MacRae C. (2016) Petrogenesis and Ni-Cu sulphide potential of mafic-ultramafic rocks in the Mesoproterozoic Fraser Zone within the Albany-Fraser Orogen, Western Australia Albany Fraser. *Precambrian Research*, 281, 27–46. doi.org/10.1016/j.precamres.2016.05.004

[3.5] Smith W.D., **Maier W.D.**, Bliss I. (2019) Contact-style magmatic sulphide mineralisation in the Labrador Trough, northern Québec, Canada: Implications for regional prospectivity. *Canadian Journal of Earth Sciences*, 57, 867-883. doi.org/10.1139/cjes-2019-0137

Selected grants:

[G3.1] McDonald I. (2015): TeaSe (Te and Se Security of Supply) - NERC NE/M011615/1, £446,848.

[G3.2] Maier W.D. (2018): Geochronology of Flatreef, NERC Isotope Geoscience Facility IP - 1763-1117, £35,000.

[G3.3] McDonald I. (2015): The Platreef magma event at Turfspruit - Ivanhoe Project 508122, £68,409.

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

The findings of Maier and McDonald resulted in identification of high-value exploration sites and enabled new ore discoveries, generating exploration cost savings of over £23M. Furthermore, Cardiff research helped minimise societal and cultural impacts for landowners and indigenous groups within these prospective areas, removing the need to relocate or disrupt communities in these provinces. Cardiff's work was applied across the world, benefiting the following mining organisations:

1. Ivanhoe Mines Ltd. in South Africa;
2. The Geological Survey of Western Australia;
3. Northern Shield Resources Inc. in Canada.

4.1 Geological modelling in South Africa

Ivanplats (a subsidiary of Ivanhoe Mines) are exploring the northern Bushveld Complex of South Africa, an area estimated to hold 75% of the world's supply of platinum. In 2014, the company was granted mining rights to a deposit named "Flatreef", with indicated mineral resources of 41.9 million ounces of PGE and gold (*in situ* value currently >£40B), and an additional 52.8 million ounces of PGE and gold in inferred resources.

Since 2012 Ivanhoe worked with Maier and McDonald to develop a clearer geological definition of the Flatreef and wider area. Dr Danie Grobler, Head of Geology and Exploration, Ivanhoe Mines confirmed that Cardiff's assessment and validation of the stratigraphic interpretation "*enabled Ivanhoe Mines (and our competitors on adjacent properties) to better understand the internal structure of the Flatreef orebody*" **[5.1]**.

Cardiff's geochemical prospectivity vectoring and petrological mapping of the Flatreef area generated significant economic and strategic benefits: "*As a company, Ivanhoe has derived enormous value from the results of these studies and from the ideas and independent scrutiny offered by Dr McDonald and Professor Maier that have helped to test and refine our geological model*" **[5.1]**. Specifically, Cardiff's independent assessment and validation of the stratigraphic interpretation used by Ivanhoe to plan development of mine locations "*enabled Ivanhoe to better predict the occurrence and economic potential associated with these rocks*" **[5.1]**.

Ivanhoe Mines estimated that: "*Considering that total exploration expenses in the last few years has been US$100M, this work translates into at least US$30M [£23.1M] in exploration cost savings*" **[5.1]** and further notes that the research enabled Ivanhoe Mines "*to identify 3 new high priority exploration targets in Southern Africa and globally"* **[5.1]**.

Improved exploration increased social welfare for local people "*by reducing the amount of drilling required to identify new ore resources and by making drilling unnecessary on ground judged to be non-prospective*" **[5.1]**. The northern Bushveld Complex is densely populated and Cardiff's research delineated non-prospective areas within these community neighbourhoods. Ivanplats stated that "*The area of ground affected by these developments is approximately 4km^2, on which at least 20,000 people are currently living and will therefore not need to be relocated. The potential cost of this relocation would have been approximately US$ 100M [£77.6M]"* **[5.1]**.

The research further enhanced professional methods used by Ivanplats across the world: "*Specific guidelines for exploration in the Bushveld and elsewhere that are now applied as best practice by Ivanplats exploration teams"* are *"used regularly by the Ivanplats geological teams, comprising at least 15 employees*" **[5.1]**.

4.2 Prospectivity of culturally sensitive Western Australian sites

The Western Australian government is responsible for natural resources within the largest state in Australia, approximately ten times the area of the UK. The Geological Survey of Western Australia (GSWA) oversees geological exploration for the state and, as stated by Dr Hugh Smithies, Project Manager of Geoscience Mapping, has "*routinely requested Prof. Maier's help in various aspects of nickel- and copper-mineralised systems throughout central Australia and southern Western Australia*" **[5.2]**. Of specific importance is the evolution of nickel and copper-mineralised systems in the Albany-Fraser Orogen region and West Musgrave Province of Western Australia **[5.2]**.

Cardiff's work within the Albany-Fraser Orogen area "*identified geochemical and isotopic discriminators of high- and low- prospective ground and these have been incorporated into current exploration models for that region"* **[5.2]**. In addition, the GSWA stated that Cardiff's research "*provided perhaps the most significant body of data and of interpretations relating to the nickel- and copper-prospectivity of the west Musgrave region in central Australia*" **[5.2]**.

Cardiff's research is currently directing exploration into the Musgrave region and within the Albany-Fraser Orogen where Smithies notes the economic and material potential "*cannot be understated*" **[5.2]**.The GSWA has a unique policy of publicly releasing all prospectivity maps to encourage private exploration, which is estimated to deliver a return on investment of AUS$23.7 for each AUS$ spent through granted mineral rights, taxes, and employment **[5.3]**. Through collaborative research and mapping, Cardiff's input "*has been a critical component to the success of GSWA programs in these regions*" and *"significantly advanced the understanding of the geological evolution of these regions and their economic potential*" **[5.2]**.

A priority for the GSWA is working alongside indigenous traditional landowners, and the Musgrave and Albany Fraser ore deposit belts are some of the most culturally sensitive regions in Australia, home to a wide range of indigenous groups. The GSWA emphasised how the research "*provided a firm geological base, including detailed mapping and geological interpretations, upon which all land-use activities could be better planned and executed – providing clear benefits in terms of minimising potential disturbance of culturally and environmentally sensitive land*" **[5.2]**. As a result, Cardiff's research in the west Musgrave region "*formed part of a unique cooperative agreement between the Western Australian State Government and the indigenous Traditional Owners of that region (represented by the Ngaanyatjarra Council)*" **[5.2]**.

4.3 Discovery of Canadian magmatic ore deposits through non-invasive methods

Northern Shield Resources is a Canadian company that aims to conduct non-invasive exploration, using geochemical tools that reduce risk in early-stage exploration. Since 2006, Northern Shield collaborated with Maier on the implementation of geochemical vectoring. These methods now underpin the company strategy. Ian Bliss, the President/CEO of Northern Shield, notes that Maier "*was largely responsible for developing Northern Shield's methodology to discriminate prospective from non-prospective mafic-ultramafic intrusions and once prospective targets were defined, utilizing geochemistry as a vectoring tool, both on property and drill-hole scale*" **[5.4]**.

Northern Shield's application of Cardiff's geochemical prospecting strategies "*led directly to the Huckleberry discovery in 2014*" a Nickel-Copper-PGM site being actively explored under a joint venture between Northern Shield and South32 Ltd., with an estimated CDN$3M (£1.75M) spent on exploration **[5.4]**. Although Northern Shield cannot provide a definitive monetary value on Cardiff's expertise, Bliss estimated that "*contributions at Huckleberry resulted in cost savings of CDN$300,000 (two drill-holes, [£172,000]) and $400,000 [£230,000] for regional exploration and project generation*" **[5.4]**.

Maier's knowledge and application of non-invasive geochemical prospectivity vectors in remote regions of Québec was equally critical: "*Beyond dollar values our exploration methods, based on Dr Maier have positive social and environmental impact*" **[5.4]**.

Northern Shield's operations in the area are near local indigenous First Nation and Inuit communities. Bliss stated that by using Cardiff's *"prospectivity discrimination and vectoring*

methods based on rock geochemistry, unnecessary damage to the environment, no matter how light, is avoided by reducing the amount of drilling required" **[5.4]**.

4.4 Summary

Cardiff research resulted in delineation of highly prospective exploration tracts and the discovery of new magmatic ore deposits of PGE, nickel and copper in Africa, Australia and Canada. Equally importantly, the research identified areas of lower ore potential, reducing detrimental societal and cultural impacts for landowners and indigenous groups. In total, exploration cost savings of at least £23M were generated.

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

[5.1] Testimonial: Dr Danie Grobler, Head of Geology and Exploration, Ivanhoe Mines Ltd.

[5.2] Testimonial: Dr Hugh Smithies, Project Manager, Geoscience Mapping, Geological Survey of Western Australia, Government of Western Australia.

[5.3] ACIL Allen Consulting, Exploration Incentive Scheme Economic Impact Study: Geological Survey of Western Australia, p.55, 2015.

[5.4] Testimonial: Ian Bliss, President/CEO, Northern Shield Resources Inc.