Section A

Institution: University of St Andrews

Unit of Assessment: UoA 07: Earth Systems and Environmental Sciences

Title of case study: Holistic geologic approaches for safeguarding a sustainable future of mineral resources

Period when the underpinning research was undertaken: 2000 - 31 December 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed:
Adrian Finch	Professor	01 October 2000 - present
William Hutchison	Research Fellow	23 May 2016 - present
William McCarthy	Senior Lecturer	05 January 2015 - present
Tony Prave	Professor	01 September 1996 - present
Tim Raub	Lecturer	12 September 2011 - present
Ed Stephens	Principal Research Fellow	01 October 1972 - present

Period when the claimed impact occurred: 01 August 2013 - 31 December 2020

Is this case study continued from a case study submitted in 2014? N

Section B

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

GeoBus *programme reaches the 50,000-pupil milestone in 2016*

Establishing Green Economies as a response to anthropogenic induced climate change is resulting in a currently unsustainable demand for natural (geologic) resources. The School of Earth and Environmental Sciences has addressed this on many fronts, from exploration, to building renewable capacity, to educating Scotland's children. This has been achieved by partnering with local communities, government and industry via collaborative, multidisciplinary research programmes that integrate field geology with state-of-the-art geochemistry and geophysics. The School has:

1. Created new methods to search for and increased exploration investment for rare-Earth elements, Au, Cu-Mo and sulphide copper at five sites in Greenland, Ireland, Kazakhstan and Finland by more than [text removed for publication]. This has resulted in: Greenland increasing its status as one of the most significant depositories of rare earth elements in the world; in a [text removed for publication] mine expansion in Kazakhstan; a doubling of the exploration target in Ireland; and the regional value increase by more than [text removed for publication] in Finland;

2. Influenced policy for the development of geothermal energy in Scotland, which led to Scotland launching the Geothermal Energy Challenge Fund as part of their Low Carbon Infrastructure Transition Programme;

3. Pioneered a new education initiative (*GeoBus*) for schools across Scotland, which has reached over 70,000 people (school pupils) to date. which led to a NERC-invested spin-out *GeoBus* programme based at University College London; and

4. Built local specialist training capacity in ODA country settings such as Kazakhstan, increasing the employability in Kazakhstan and reducing dependence on foreign labour.

2. Underpinning research (indicative maximum 500 words)

Since the seminal 1997 UN Meeting of Parties to the Kyoto Protocol, global leaders have recognised the need to reduce carbon outputs taking greenhouse gas emissions to net zero anthropogenic input during the second half of the 21st C. For example, the UK and Scottish Governments have set net zero carbon targets by 2050 and 2045, respectively. To achieve this will require a transition to alternative, renewable and low carbon power and heat sources with technologies that are fundamentally reliant on rare-Earth materials. Research within the School of Earth and Environmental Sciences has two complementary strands with a focus on resourcing the Green Revolution (that is the sourcing of key minerals needed for new green technologies) and on Earth derived sustainable energies.

Fundamental and applied research have utilised field geology expertise supplemented with geochemical analyses and geophysical techniques to inform exploration strategies targeting common and rare-Earth element minerals and precious metals including:

- Specific focus in the last 10 years on key minerals such as zirconium, niobium, tantalum and copper-, molybdenum- and gold-bearing rocks, all of which are central in renewable technologies. Research by Finch since 2000 on the mobility of rare-Earth elements, in alkaline igneous rocks such as those in Greenland and Namibia, has provided new models for the genesis of these metals and allowed for re-evaluations of global stock (**R1**).
- Fundamental research on both field and laboratory application of rock magnetic fabric analysis provided McCarthy with the tools to investigate aspects of the structural emplacement mechanisms of intrusive diapirs in copper-molybdenum porphyry ore bodies and allowed him to establish a generic model for distinguishing diapirs from plutons (**R2**).
- Over a decade of research by Prave on the Fennoscandian-Russian Archaean-Proterozoic crustal belt and its archive of ancient biogeochemical phenomena as part of an international drilling project provided the key data for him to create a geological model for critical Earth deposits in Finland (**R3**).
- In a series of projects, a team of researchers utilised the School's applied stable isotope geochemistry facility to devise new understanding of the genesis of sedimentary-hosted copper ores such as those in the northern part of the Midcontinent Rift system, USA as an exemplar (**R4**).

Research on geothermal energy began as an applied aspect of fundamental studies by Stephens, and later Raub, on granites across Scotland. Specifically, they demonstrated that evaluations of granite-related heat gradients had previously been seriously underestimated due to the lasting imprint of Quaternary glacial events (as exemplified by **R5**). Stephens and Raub built on this body of research to investigate the un-tapped geothermal potential of shallow aquifers in the Midland Valley, Scotland, and Hutchison's research has greatly improved our understanding of deeper and high temperature resources located in the African Rift Valley, which have helped identify suitable drilling targets for production wells on Aluto volcano (R6), Ethiopia.

3. References to the research

The listed research publications were supported by peer-reviewed grants and published in peer-review journals except for R3, which is a book with a highly regarded publisher. The publications listed are representative of a much larger body of work.

R1. Smith, M.P, Moore, K, Kavecsánszki , D, **Finch, A.A**, Kynicky, J & Wall, F. 2016. From mantle to critical zone: a review of large and giant sized deposits of the rare earth elements. Geoscience Frontiers, vol 7, no. 3, pp. 315-334. DOI: 10.1016/j.gsf.2015.12.006.

R2. McCarthy, W., Petronis, M.S., Reavy, R.J. and Stenenson, C.T. 2015. Distinguishing diapirs from inflated plutons: an integrated rock magnetic fabric and structural study on the Roundstone Pluton, western Ireland. Journal of the Geological Society, v. 172., pp. 550-565. DOI: 10.1144/jgs2014-067.

R3. Melezhik., V.A., **Prave, A.**, Fallick, A., Hanski, E., Lepland, A., Kump, L. and Straus, H. 2013. Reading the Archive of Earth's Oxygenation. Vols.1-3. Springer. ISBN 978-3-642-29670-3.

R4. Jones, S.M., **Prave, A.R., Raub, T.D.,** Cloutier, J., **Stüeken, E.E., Rose, C.V**., Linnekogel, S. and Nazarov, K., 2020. A marine origin for the late Mesoproterozoic Copper Harbor and Nonesuch Formations of the Midcontinent Rift of Laurentia. Precambrian Research, v. 336, 105510. DOI: 10.1016/j.precamres.2019.105510.

R5. Younger, P.L., Gluyas, J.G. and **Stephens, W.E.** 2011. Development of deep geothermal energy resources in the UK. Energy, v. 165 (1),19-32. DOI: 10.1680/ener.11.00009.

R6. Jolie, E., **Hutchison, W**., Driba, D. L., Jentsch, A. & Gizaw, B. 2019. Pinpointing deep geothermal upflow in zones of complex tectono-volcanic degassing: new insights from Aluto volcano, Main Ethiopian Rift. Geochemistry, Geophysics, Geosystems. V. 20, pp. 4146-4161. DOI: 10.1029/2019GC008309

4. Details of the impact

Mineral research conducted by the School of Earth and Environmental Sciences has addressed the challenge to society of securing Earth resources at a lower environmental cost. The interdisciplinary research has: 1. increased exploration investment for rare-Earth elements, Cu-Mo and sulphide copper in Greenland, Ireland, Kazakhstan and Finland [text removed for publication] mining expansion and valuation increases; 2. helped to guide the development of geothermal energy policy in Scottish government; 3. pioneered a new education initiative for schools across Scotland, which was later replicated with NERC funding in England; and 4. built local specialist training capacity in Kazakhstan.

1. Economic benefit through enhanced exploration for natural commodities stock evaluations

A step-change in mineral investigations began in the early 2000s with demand for rare-Earth elements for the globally expanding renewable energy market. A partnership with mining industries on Greenlandic resources led by Finch (2010-2016, as exemplified by **R1**) resulted in new prospects and development projects [text removed for publication] (Oct. 2014, **S1, p. 3**). The Chief Geologist for NunaMinerals wrote, "*We consider Dr Finch's input to the Qeqertaasaq project as a key part of its success in securing this major strategic partner, as well as facilitating more focused and cost effective exploration going forwards"* (**S1, p. 2**). NunaMinerals states that "*[i]t is our opinion that [Finch's] applied research in Greenland has been invaluable to the country in developing its status as the most significant depository of rare earth elements (and other critical metals) outside of China*." (**S1, p. 4**) Further development of novel field and laboratory analytical techniques on alkaline rocks by Finch (**R1**) yielded the identification of new exploration areas [text removed for publication], which resulted in [text removed for publication] exploration investment in the region by the Government of Korea through the Korea Resources Corporation (KORES) with NunaMinerals (**S1, p. 3**).

Approximately 60% of the world's copper and 95% of the world's molybdenum comes from porphyry deposits. While these have been the focus of investigation for centuries, understanding their formation is complex. Commissioned research by SLR Ltd in 2016 led McCarthy to develop new spectral and magnetic methods which proved "*highly useful in understanding the ore paragenesis and in guiding subsequent focused exploration drilling, which proved to be cost beneficial. Having completed significant new drilling after your work [**R2**], we developed a more* *in-depth understanding of the deposit which will aid our client, MOAG, in achieving its strategic goals*" (**S2**). As a result, MOAG invested [text removed for publication] in exploration and laboratory costs; it is now estimated that MOAG's exploration target for the Mace Head deposit (Ireland) is [text removed for publication] (**R2, S2**). In 2018 the application of similar methods was adopted by Kaz Minerals in Kazakhstan where research by McCarthy (stemming from **R2**) *"had direct impact… following recommendations of magnetic and hyperspectral reflectance… contributed to [text removed for publication], mine expansion programme"* which sees sulphide copper production increased to [text removed for publication]. KAZ Minerals employs 1,500 people and is the largest copper producer in Kazakhstan having generated 145,700t of copper as of 2019 (**S3**).

Gold and copper are two elements that are crucial to society, the former for economic stability and the latter essential to electronics industry. Prave's research on Archaean-Proterozoic systems (**R3**) led to the creation of a geological framework that informed Mawson Gold Ltd's exploration strategy in its Finnish Au-Co prospect (Rajapalot Project). His contribution was central in guiding Mawson's exploratory activities such that, at the start of Mawson's Rajapalot project in 2014, the known Au-Co value of the region was increased in 2018 [text removed for publication] (**S4**). The President of Exploration writes *"[Prave] made an early and one of the most significant academic contributions to Mawson's Rajapalot gold-cobalt discovery and the continuing exploration success*" (**S4**).

In the United States, Raub, Stüeken and Prave developed a new geologic model to enable more precise targeting of sedimentary-hosted Cu deposits (**R4**). First Quantum Minerals Ltd subsequently hired the St Andrews' PhD graduate (supervised by Prave & Raub) to help implement the methodology where this change in strategy has resulted in a cost saving for the company in 2020 [text removed for publication] (**S5**).

2. Pathways to low-carbon futures through geothermal policy introduction in Scotland

Moving to a lower carbon and sustainable energy future was also at the heart of deep geothermal energy research by Stephens and the amassing of the UK's largest granite data base that included geothermal properties (**R5**). In August 2013, the Scottish Government verified the importance of this work as part of the new policy for the future of geothermal energy in Scotland, in which Stephens' data were highlighted as key to unlocking the potential for such an energy source (Aecom/Scottish Government 2013, 'Study in the Potential for Deep Geothermal Energy in Scotland') (**S6, pp. 234-5**, cites Stephens' work exemplified by **R5**) and from which, in 2016, the Scottish Government developed a new set of regulatory guidance 'Geothermal heat in Scotland'. As a result, in 2015 the Scottish Government launched the Geothermal Energy Challenge Fund as part of the Low Carbon Infrastructure Transition Programme (LCITP) at 5 sites in Scotland with the Guardbridge (St Andrews University) Geothermal Technology Project being selected as one of the top locations (**S7, p. 5**).

3. Educating school pupils on Earth resources in the UK

Research-led education programmes (**R2, R5,** see for example SoS RARE, 'Technology Metals for a Green Future' based on **R1**) have been developed for delivery in UK since the formation of *GeoBus*, an initiative to provide free educational outreach to schools in Scotland. This has delivered (mobile) geological St Andrews' research-informed teaching on a range of geo-topics since August 2013 to 71,167 people (school pupils) in more than 270 schools in Scotland (**S8, p. 4**). Nearly 70 of these schools have greater than 50% of pupils from the most deprived areas (SIMD Q1)*. The 50,000th student *GeoBus* milestone was recognised in November 2016 by an Earth Day motion in UK Parliament (**S8, p. 5**). In 2015, the success of the programme was recognised by NERC who invested in a spin-out sister *GeoBus* programme based at UCL to ensure impact from their funded projects in SE England. This *GeoBus* spinout has subsequently grown and between 2019 and 2020 delivered workshops to over 9,000 people (school pupils) at schools in London and the Southeast (**S8, p. 9**).

4. Building local specialist capacity in Kazakhstan

A *GeoBus*-style approach delivered McCarthy's research (**R2**) through the St Andrews in Kazakhstan Research Hub, a joint venture with environmental, engineering and mining company Wardell-Armstrong Russia. The Wardell-Armstrong Regional Director in Kazakhstan wrote that St Andrews "…*has provided unique and critical technological training and research opportunities to industry, government, and university graduates*". As of July 2020, the Regional Director stated, *"end result has been increasing the employability of young graduates in Kazakhstan and reducing overdependence on foreign labour with 15 [people (professionals)] new graduates trained each year on these new techniques"* (**S3**). Further, through collaboration with the Scythian Mining Group Ltd, a UK gold exploration/development company operating in Kazakhstan has *"…increases the employability of young graduates in Kazakhstan and reducing overdependence on foreign labour*" (**S9**).

* SIMD - Scottish Index of Multiple Deprivation. Q1 – 20% most deprived areas to Q5 – 20% least deprived areas.

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

S1. Letter from the Chief Geologist at NUNA Minerals A/S and company report

S2. Letter of support from the Technical Director, SLR Consulting, Ireland

S3. Letter of support from the Regional Director, Wardell-Armstrong, Russia 24/8/20

S4. Letter of support from the President Exploration, Mawson Gold Ltd.

S5. Letter of support from the Director Exploration, First Quantum Minerals Ltd., 1/9/20

S6. Scottish Government 'Study in the Potential for Deep Geothermal Energy in Scotland'

S7. Scottish Government policy 'Renewable and low carbon energy' actions

S8. *GeoBus* Scotland webpages, pupil records, UK Parliament motion and UCL *GeoBus* records

S9. Letter from the Managing Director at the Scythian Mining Group Ltd