PHD PROJECT: ORDOVICIAN PERI-GONDWANAN PALEOGEOGRAPHY AND CU-ZN-PB-AU MINERALISATION IN SE IRELAND

1. Principal Investigator

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2. Research Team & Associated Roles

Quentin Crowley: Associate Professor at Trinity College Dublin, Ireland; main PhD supervisor.

Seán McClenaghan: Assistant Professor in Economic Geology at Trinity College Dublin, Ireland; co-supervisor.

Brian McConnell: Senior Geologist (Head of Bedrock Programme) with the Geological Survey of Ireland; co-supervisor.

Stephen T. Johnston: Chair / Professor – Tectonics, Earth & Atmospheric Sciences, University of Alberta, Canada; co-supervisor.

3. Objectives

- Compile existing geological, geophysical and geochemical data for the Ordovician of SE Ireland.
- Characterise U-Pb detrital age spectra of sedimentary protoliths, ages of volcanic rocks and mineralised systems, εNd of volcanic rocks and Pb-isotopes of K-feldspars and sulphide minerals.
- Develop a genetic model for Ordovician mineralisation in SE Ireland with a context of peri-Gondwanan Ordovician paleogeography and tectonic development.

4. Project Description

Introduction: This project focusses on a suite of NE-SW trending Ordovician sedimentary, basic to acid volcanic and intrusive rocks and associated sulphide deposits from Rathnew [52.9946° N, 6.0828° W] in to Tramore [52.1614° N, 7.1493° W] in SE Ireland. The study area therefore encompasses the former Avoca Cu mine, as well as the Kilmacoo Au prospect, Ballymurtagh, Cronebane, etc. This includes the licensed areas TS3849, TS3850 and TS3857 currently held by IMC, as well as licensed areas held by other exploration companies.

SE Ireland has featured mining activity for over three hundred years. A considerable amount of geological data exists for the region, not all of which has previously been compiled. SE Ireland is host to a series of orebodies, including the well-known but enigmatic Cu - Pb - Zn - Au massive sulphide orebody at Avoca. Although mineralisation is generally considered to have been generated in a Middle to Upper Ordovician volcanogenic exhalative-style deposit (McConnell, 1991), there are considerable uncertainties over the tectonic setting, structural style and precise

timing of volcanism and mineralisation and a coherent genetic model is lacking (e.g. Rio Tinto or Koroko-type). Whereas similar aged massive sulphide deposits in Canada (e.g. New Brunswick 12) have been studied in detail since the 1980's (e.g. van Staal & Williams, 1984), such systematic and integrated approaches have yet to be applied to mineralized zones in SE Ireland. This project represents a new opportunity to apply modern field and analytical approaches to both archived and newly collected material (i.e. new cores and Tellus data). Providing new data and a more robust regional geological model will not only broaden our scientific knowledge of the area, but will also strengthen links with industry (IMC and Coza Gold) and help to develop the mineral exploration potential of SE Ireland.

Geological Background: In broad terms, the basement of SE Ireland (with the exception of the Rosslare Complex) is considered to form part of the Peri-Gondwanan Ganderia terrane (Pollock et al 2012; van Staal et al 2012) and is distinct from Avalonia in that it features a distinct 600 Ma and 2.1 Ga detritial / inherited zircon signature considered to represent derivation from Amazonia in west Gondwana (Waldron et al, 2014). Volcanic rocks from Ganderia generally display initial εNd values of -4.8 to +2.8 and TDM ages between 1.7 and 0.85 Ga indicating recycling of older, pre-existing crust (Nance et al 2008). U-Pb detrital zircon data from the Cambrian Bray and Cahore Groups which lie to the north and south of this study area respectively highlight several similarities between the Cambrian rocks of SE Ireland and similar aged rocks in Wales (Monian terrane of Anglesey; Waldron et al 2014). Comparison with equivalent rocks in Newfoundland and New Brunswick, however indicate that closure of Iapetus was diachronous, with an Ordovician Laurentia-Ganderia collision in the Appalachians and a subsequent Silurian (c. 430 Ma) collision in the Irish and British Caledonides. It should be noted that neither the detrital zircon age spectra from metasedimentary rocks or the εNd of igneous rocks from the study region of this project have been determined, so there are considerable uncertainities as to how these rocks fit into regional provenance and global geodynamic models. Reducing these uncertainties is crucial in terms of developing a coherent geological model for Ordovician mineralization in SE Ireland.

Local Geology: Mineralisation in is hosted by Ordovician volcano-sedimentary rocks These predominantly acid (peralkaline) volcanic rocks were most likely generated on an active continental margin above a subducting Iapetus Ocean (southeast facing), and volcanism initiated during a period of extension within the arc (Stillman and Williams, 1979; McConnell, 1991). The volcanic pile sits conformably to unconformably on the Ribband Group, a continentally derived turbidite sequence of Cambro-Ordovician carbonaceous (graphitic) sediments derived from a peri-Gondwanan margin of the Ganderia. Closure of the Iapetus Ocean (Late Ordovician to Late Silurian) and westward-directed subduction resulted in the development of an accretionary wedge, with subsequent obduction onto the continental margin and associated polyphase deformation and lower to middle-greenschist metamorphism.

A detailed account of all mineralized areas of Ordovician strata in SE Ireland is beyond the scope of this proposal. In order to illustrate typical mineralization types and assemblages, we focus here on what is currently known for the Avoca Mine Sequence. The oldest volcanic lithologies, those of Unit 1 are unique to the Rathdrum area and are not present in the Avoca region. Unit 2 consists of rhyolites and lithic-dominated tuffs lying within the structural hanging wall of the mineralized sequence to the southeast and east of the mine. A younger sericite altered sequence of crystal-dominant volcanic rocks termed Unit 3 is best developed to the northwest and west of the mine and dominates the structural footwall of the mineralized sequence.

Avoca mineralization has been interpreted to lie stratigraphically atop Unit 3 and comprises a 2 to 4 km-wide and 15 km-long zone (McArdle 1993) of disseminated to massive pyrite with variable contents of chalcopyrite, sphalerite, and galena, as well as a wide range of trace accessory phases among these: pyrrhotite, arsenopyrite, native bismuth, bismuthinite, bournonite, magnetite and hematite. Three classic VMS hydrothermal facies have been

recognized: 1) Stockwork pyrite-chalcopyrite (Sliliceous); 2) Sub-massive to massive pyrite-chalcopyrite; and 3) banded pyrite-sphalerite-galena (Wheatley 1971; Platt 1973 and Williams 1984), suggesting a deposit genesis similar to other VMS deposits along the Appalachian-Caledonian Orogen. It is uncertain whether auriferous quartz veins of the Kilmacoo deposit occurring northeast of the mine area are related to the primary VMS mineralization. Within the mine area, massive sulphides are overlain by Unit 4, a sequence of upward-fining, lithic and crystal volcaniclastic rocks passing up into black shale. A post-mineralization cycle of volcanism consisting of intermediate lava flows comprise Unit 5, and represents the terminal stages of extension prior to the Caledonian Orogeny.

Central Research Questions:

1. What are the chemo- and litho-stratigraphic characteristics of Ordovician sedimentary and volcanic protoliths in SE Ireland?

2. What is the structural geometry of the lithologies, including that of the polydeformed mineralized zones? Does further potential exist for mineralization on unidentified fold limbs (sheaths), or is local shearing a more important control?

3. Are the provenance characteristics of the region compatible with being part of Ganderia? What do the U-Pb zircon age spectra tell us about the timing of amalgamation with Laurentia in this sector of the Caledonides?

4. What is a suitable genetic model for mineralization and how does the timing relate to known tectonic framework and associated volcanic activity along the Avoca Belt and wider Caledonian Orogen?

Research Methodologies:

1. Compilation and analysis of archived and new data from field work and core material.

2. Whole rock geochemistry by ICP-OES and ICP-MS. This is to be carried out at a commercial laboratory.

3. SEM and EDS analysis of representative assemblages from mineralized zones.

4. LA-ICP-MS U-Pb zircon and U-Pb dating of available phosphates (e.g. monazite and apatite) and silicates (e.g. hydrothermal zircon) associated with mineralization.

5. LA-ICP-MS elemental mapping of pyrite, chalcopyrite and galena.

6. Whole rock Nd isotopes by TIMS, LA-ICP-MS Pb isotope measurements.

Links with existing projects: Knowledge transfer of methodological advances made from four existing projects. These existing projects are: (1) “3D modelling of the Irish Carboniferous Basin – links between structure and mineralization”, (2) “Characterizing orogenic vein systems to promote gold exploration across Irish terranes”, (3) “Precious and energy critical metals in Zn-Pb deposits: from mine to mill” and (4) Abundance of the full range of ECE in Cu and Zn ores”. Aspects of the field, laboratory and modelling methodologies of will provide a basis for peer-to-peer learning and knowledge transfer.

Links with other research: This project will benefit from Tellus data as they become available. Geophysical magnetic data will help to delineate orebodies (e.g. suspect “iron formations”) at depth, airborne radiometric data will assist with regional mapping, soil geochemistry and heavy mineral concentrates from river sediments will spatially constrain the surface expression of mineralized zones. This proposed project resents an excellent opportunity to utilize the Tellus dataset for applied geoscience research**.**

5. Deliverables

Month 6: Literature review (as part of TCD Geology progression procedures).

Month 12: PhD Confirmation Report (as part of TCD Geology progression procedures). Annual progress report to industry partners.

Month 24: 1st publication submitted (Economic Geology); Oral presentation at IGRM and / or Irish Association Economic Geology Meeting.

Month 36: 2nd publication submitted (Journal of the Geological Society); Annual progress report to industry partners; Oral presentation at an international conference.

Month 48: PhD thesis submitted to TCD; 3rd publication submitted (Ore Geology Reviews); Final report delivered to industry partners; oral presentation at an international conference.

6. Evaluation

Despite the Avoca Belt being well known internationally, there is still much speculation regarding a viable genetic model for mineralisation. The area has not received the focussed attention of a modern and integrated approach and lacks the kind of detailed studies performed in the mid 1980's and late 1990's on analogous deposits in New Brunswick and Newfoundland. It should be noted that research on the Canadian sites generated new exploration licences, new discoveries (e.g. Camelback) and peaked an interest resulting in further research and scientific publications on both areas.

The objectives of this project will be met by presenting a viable and integrated geological model. Such a model will be based on a solid grounding of field geology, structural analysis, litho-geochemistry, provenance analysis, isotope work (Nd and Pb), U-Pb dating and micro-geochemical mapping. Each of the individual project tasks will converge towards the greater objective of generating a better understanding of Cu-Zn-Pb-Au mineralisation along the Avoca Belt in SE Ireland.

The project will likely make a difference by reducing uncertainties of the processes and timing of mineralisation. Massive sulphide bodies have been encountered at depth at different localities in SE Ireland, but the economic potential of these deposits and their genetic relationship to surface geology in the Avoca area is not known. Having a research team in place to add value to the Tellus data as they become available will likely promote additional mineral exploration activities in underexplored areas.

7. Industry Partnerships

IMC: The IMC Exploration Group plc was incorporated in Ireland in June 2011 with a view to identifying precious and base metal deposits in Ireland. It holds 15 mineral prospecting licences in Ireland (5 precious metal and 10 base metal licences). The IMC Co. Wicklow licences include the former Avoca Copper mine and the Kilmacoo prospect.

Koza Gold: IMC has concluded a Joint Venture agreement with Koza Limited, a subsidiary of Turkish-based company Koza Altin Isletmeleri A.S. Koza gold currently has several productions in Turkey including: Izmir (Bergama) Ovacik, Izmir (Dikili)-Cukuralan, Izmir- Coraklitepe, Gumushane-Mastra, Eskisehir-Kaymaz and Kayseri-Himmetdede. It was the first Turkish owned exploration company to realise gold production in Turkey.

Support from IMC and Koza Gold to include sample collection/preparation, access to materials (drillcore and data) and facilities, and a contribution to laboratory analyses (for litho-geochem).