



**Research Programme
- Short Calls, Final Report -**

Signature of Lead Applicant:

Date: June 28th, 2019

This report covers the period November 1st 2017 to October 31st 2018

1. (a) Project information:

Final project report (*max 2500 words, excluding figures and headings*):

- (i) Progress of objectives and scientific/engineering targets beyond the state of the art & methods used

This study aimed to characterize the form and distribution of gold elucidating the siting of precious metals in the Avoca deposit and Kilmacoo Au occurrence to assess the extent of syn-tectonic enrichment during the Caledonian Orogeny. The project applied a *state of the art* micro-analytical approach to a historically significant yet under-explored deposit. The application of this expertise to the study of metal zonation and sulphide paragenesis within the Avoca orebodies and Kilmacoo Au occurrence has refined the mineral deposit model for gold mineralization across the Avoca District. The project also contributes important mineral chemical data on sulphide phases hosting Au, greatly benefiting exploration and support of any future metallurgical work on the orebodies at Avoca and Kilmacoo, as well as possible remediation of historical tailings and spoils, which pose significant environmental risk to the region.

The project was developed to address outstanding questions surrounding the genesis of volcanogenic massive sulphides at the Avoca Cu-Zn deposit and possible genetic links to the adjacent Kilmacoo Au occurrence. These questions have relevance to local geology and mineral resources, but also to broader questions of fluid evolution in response to Caledonian geodynamics and correlation with equivalent Peri-Gondwanan systems in the Appalachians of eastern Canada. The main research questions central to this research were as follows:

- 1)** Do mineralized sequences at the Avoca Cu-Zn deposit and Kilmacoo Au occurrence exhibit any classic metal zonation with respect to their footwall - hanging wall contacts and the host volcanic stratigraphy?

Exhalative sulphide lenses do not appear to exhibit metal zonation consistent with hydrothermal recrystallization of massive sulphides, which typically enriches Cu, Bi and Co towards the base of massive sulphide lenses with a concomitant increase in Ag, Sb, Au, and Sn towards the hanging wall. For many Appalachian VMS deposits, syngenetic Au is typically concentrated in discrete pyritic sulphide lenses towards the distal flanks (hanging wall) large well-developed hydrothermal systems. Given the low apparent thickness of massive sulphides at



Avoca, it is possible that the exhalative sulphide lenses were not thick enough to insulate underlying sulfide assemblages and temperatures were depressed near the paleo-seafloor. Nevertheless, sphalerite does exhibit chalcopyrite disease with numerous inclusions of chalcopyrite indicating metasomatism by cupriferous fluids. The apparent lack of Au in massive sulphides of the Avoca deposit would also indicate less evolved exhalative sulphides at the paleo-seafloor, as VMS deposits with a well-developed hydrothermal architecture, typically exhibit significant zonation of Au and distinct hanging wall facies with increased Au concentrations, typically on the fringes of the VMS system.

2) What is the mineralogical distribution of Au in sulphides, both among different sulphide phases and within individual pyrite grains that show multiple generations of growth?

Visible Au phases were not identified in Cu-rich stockwork sulphides or exhalative Zn-Pb massive sulphides at Avoca. This is not unusual in VMS systems, where Au is commonly found in arsenian pyrite and arsenopyrite as nanoparticles or a lattice bound refractory phase. Avoca has no historical Au grade associated with its 260 years of episodic production; it is unknown whether Au was recovered as a smelter credit. Examination of sulphide phases at Avoca reveal that pyrite hosts low levels of Au in early primary (syngenetic) forms, with arsenopyrite, chalcopyrite and sphalerite exhibiting negligible levels. Late euhedral metamorphic rims and porphyroblasts of pyrite exhibit lower levels of Au than the primary morphologies, suggesting that Au has not been remobilized by metamorphic fluids and that metamorphic pyrite growth did not coincide with any auriferous fluids. The effects of syn-metamorphic (upper-greenschist) deformation at the large Brunswick No.12 VMS deposit in the Bathurst Mining Camp resulted in only minor remobilization of precious metals, suggesting that the overall Au tenor is largely related to primary hydrothermal processes. Alternatively, data on pyrite and arsenopyrite from the Caribou and Murray Brook deposits in the Bathurst Mining Camp, has shown that late enhancement of gold due to orogenesis can indeed occur in unique structural settings.

3) What is a feasible genetic model for Au mineralization in the Avoca District and how does the timing relate to the known Duncannon volcanic stratigraphy and wider geodynamics of the Caledonian Orogeny?

Northeast of Cronebane, a silica-rich zone consisting of intensely sheared sulphidic tuffs and banded quartz is host to the Kilmacoo Au occurrence. Historical drilling in this region has intersected both the Au-hosted banded quartz and base metal sulphides of the Connary Zone, which appear to occur together; intersections include 7.8 m at 10.9% Zn and 5.22% Pb, with 8.3 m at 4.52 g/t Au. Intersections of the Kilmacoo mineralization in drill core can be complex, having the appearance of base-metal sulphides (Avoca) with anastomosing units of banded silica distributed throughout. In other holes, mineralization can be pyrite dominant with an association of chalcopyrite. Despite the sparsity of Au at Avoca, visible Au is abundant and readily identifiable at the nearby Kilmacoo Au prospect. The occurrence has been described historically; where visible Au is associated with silica-rich veins, the paragenesis of which was unknown. Reflected light microscopy and SEM through this study has identified discrete phases of native Au and electrum associated with chalcopyrite as fine-grained inclusions, veins and fracture fills. Given its position on the distal peripheries of the Avoca VMS system and the gold-rich nature of the Kilmacoo mineralization, these banded quartz units could represent silica



sinter deposits on the flanks of an epithermal system; these have been described for mineralized Ordovician sequences at Parys Mountain, Wales. Given the simple sulphide mineralogy, lack of high-sulphidation phases (i.e. Bornite and Adularia), and occurrence of black shale, it is unlikely that shallow epithermal systems were active around the Avoca VMS system. Furthermore, close examination of the banded silica units reveals that they distinctly cross-cut the regional Caledonian S_1 fabric, which imparts a Silurian penetrative cleavage on the host volcanic and sedimentary rocks of the Ordovician Ribband and Duncannon groups and which has structurally modified massive sulphides at Avoca. This cross-cutting relationship conclusively places the timing and origin of these Au-bearing banded quartz units as a later stage of Caledonian orogenesis and post-dating VMS mineralization at Avoca considerably.

The precise age of Au mineralization at Kilmacoo is unknown, but based on fabric relationships, auriferous mineralization in the region appears to post-date D_1 and concentrates along late (Silurian) cross-cutting shear zones. Limited outcrop around Kilmacoo prevents an interpretation of the structures hosting Au mineralization. Nevertheless, late north-south trending faults that cross-cut D_1 structural lineaments and offset stratigraphy by several kilometres could represent a reactivation of earlier shear structures hosting orogenic Au including mineralization at Kilmacoo. Addressing issues surrounding the extent of late-orogenic Au enhancement of massive sulphides at Avoca has significant implications for exploration strategies throughout southeast Ireland. Orogenic gold and stratiform VMS form two diverse mineralization styles that require different strategies for exploration. Although massive sulphides have been extensively modified by the effects of early D_1 shearing, Au appears to be controlled by late (Silurian) structures. Exploration in the region should consider these late shear structures as potential Au targets. Ordovician VMS in southeast Ireland may enhance Au deposition from auriferous orogenic fluids acting as a chemical trap promoting precipitation and enhancement of gold in massive sulphides. Iron Formation at Ballard to the northeast has been overprinted with late pyrite porphyroblastic growths and exhibits anomalous Au suggesting late enhancement; this would seem to support the process of a late auriferous fluids on a regional scale. Lastly, base-metal potential at Avoca remains high, with a strong likelihood of undiscovered Cu-Pb-Zn resources at depth.

A mineralogical assessment of sulphides at the Avoca deposit indicates that Au contents in primary epigenetic stockwork (Cu-resource) and syngenetic exhalative sulphides (Zn-Pb-resource) are low overall. Visible gold phases (electrum, native gold) were not identified in any of the sections examined. Laser ablation ICP-MS analyses of major sulphide minerals indicate that what limited gold exists in the Avoca deposit, overwhelmingly occurs as a refractory phase in pyrite (Avg., 0.29 ppm) and arsenopyrite (Avg., 0.33 ppm). Given the preponderance of pyrite in massive sulphides in the VMS mineralization, the mineralogical balance of Au is hosted by pyrite.

Massive sulphides at Avoca exhibit mineralogical zonation consistent with a vertically zoned hydrothermal architecture. The large Cu-resource comprising epigenetic stockwork sulphides and Cu-rich massive sulphides are stratigraphically overlain by banded Zn-Pb sulphides. An exhalative origin is ascribed to this Py-Sp-Gn facies due to its association with black shale and strong layered appearance representing pseudo-bedding (S_0) that has been modified by syn-metamorphic deformation (D_1). Given the established zonation sequence for VMS deposits in Peri-Gondwanan terranes, and the large Cu tonnage associated with Avoca, further undiscovered Zn-Pb resources at Avoca seems likely given the disproportionate distribution of Cu over Zn and Pb.

Although massive sulphides at Avoca have been extensively modified by the effects of ductile remobilization during early D_1 shearing, primary Au signatures are largely unaffected by



Caledonian metasomatism. The core of primary colloform pyrite masses (Py_1) contain higher Au contents than late euhedral rims (Py_2), which have grown and annealed in response to greenschist facies metamorphism. This suggests that prograde metamorphism was not a significant source of Au-bearing hydrothermal fluids in the region.

The Kilmacoo Au occurrence to the northeast consists of varied mineralization including auriferous pyrite veins with chalcopyrite, a banded silica unit with reported sulphides and visible Au and massive Zn-Pb sulphides (VMS) that appear to be overprinted by the former vein assemblages. The Zn-Pb sulphides intersected in drill holes appear to be an equivalent exhalative facies to massive sulphides outlined along strike at the Connary zone. The auriferous banded quartz unit is intercalated within the massive Zn-Pb sulphides and can appear to exhibit D_1 deformation effects. However, upon closer examination, the banded quartz units are seen to be cutting penetrative D_1 fabrics which postdate sulphide deposition and structurally modify their distribution. This indicates that Au has not been concentrated during the synthesis of VMS mineralization and distinctly places Au mineralization in the region as post- D_1 , related to late cross-cutting shear structures.

Addressing issues surrounding the extent of late-orogenic Au enhancement of syngenetic massive sulphides has far-reaching implications for exploration strategies along the entire Avoca Belt. Orogenic gold and stratiform VMS form two diverse mineralization styles that require different strategies for exploration in a metallogenic terrane. The disparate styles of mineralization between the Avoca Cu-Zn-Pb VMS deposit, that is characterized by refractory Au signatures and low overall concentrations, and the Kilmacoo Au occurrence with visible phases of native Au, electrum and significant grades, highlights the differing ore-forming processes, and timing of emplacement. There are significant implications for exploration in the understanding of Au genesis in southeast Ireland. Late sulphide-bearing shear structures post-dating D_1 penetrative cleavages are targets for structurally hosted Au mineralization.

Volcanogenic massive sulphides are still prospective for Au mineralization as a chemical and structural trap for late auriferous fluids. Furthermore, occurrences of iron formation across the Avoca belt exhibit the effects of metasomatism from metamorphic hydrothermal fluids resulting in partial replacement by chalcopyrite with anomalous Au. Future research should focus on the structural setting of mineralization across the region, the role of metamorphism in the timing of hydrothermal Cu-Zn-Pb versus Au events supported through targeted dating of phases.

(ii) Implementation (please include any issues with timelines, milestones, management etc. or deviations from the original implementation plan)

Due to academic timetabling, any potential student would not have been able to commence the project until March 2018. Nevertheless, the migration of the project to an existing PhD student as part of an associated volcanogenic massive sulphide comparison study did add to the delay in implementation. The student completed sampling and thin section preparation during the originally planned Phase 1 of the project. Bulk sampling of the ore zones from outcrop exposures was completed in a timely manner and samples submitted for thin section preparation. Final stages of drill hole logging and sampling was completed later in June 2018. Phase 2 Petrography suffered delays, due to a leave of absence by the Principle Investigator, Sean McClenaghan. An unexpected shutdown of the Laser Ablation ICP-MS analytical laboratory, further compounded management of the timeline for completion of the project. Due to further delays, the Principle Investigator completed the data interpretation and writing to facilitate delivery of a final report to the Geological Survey of Ireland.



(iii) **Outputs** (please provide a short description and complete the table below)

Results of this study were presented in poster form at the annual Geoscience Ireland Forum in October, 2018. An Industry report detailing results of the Short Call research was presented to the Board of Directors of IMC (Industry Partner) in January of 2019. A peer-reviewed extended abstract has been accepted (in press) for the SGA Symposium in Glasgow, Scotland for August 2019. Results of the research will be presented to an international audience of geoscientists, and will support a post-conference field trip to the Avoca region. Output from the project is ongoing with research continuing on regional iron formation samples (associated with Avoca), which supported an undergraduate Honours thesis at Trinity College Dublin. The Honours thesis was successfully completed and submitted to the School of Natural Sciences in March, 2019. A manuscript is currently being prepared for submission to a peer-reviewed journal in September, 2019.

Task No.	Deliverable description	Planned delivery (as per proposal)	Date of delivery
1	Report for Industry Partners (IMC)	Month 12 – November/2018	Month 14 - January/2019
2	Poster for GSI Geoscience 2018	Month 11 – October/2018	Month 11 - October/2018
3	MSc Thesis Submission	Month 12 – November/2018	Withdrawn
4	Submission of Report of Findings to GSI	Month 12 – November/2018	Month 16 – March/2019
5	Journal Publication	Month 12 – November/2018	In Preparation
6	Oral presentation at International Conference – SGA Glasgow	Month 12 – November/2018	Month 21 - August/2019

Publications to date: *Please use format below and provide a copy of the presentation*

McClenaghan, S.H.; Riegler, T.; Drakou, F. (2019) Resolving the paragenesis of gold at the Avoca VMS Deposit: Implications for exploration in Caledonian terranes of southeast Ireland. Society for Geology applied to Mineral Deposits, 15th Biennial Meeting, Extended Abstract, 4p.

4. Data/outputs submitted with final report (please list the documents, presentations, datasets etc. submitted with this report)

- Final Summary Report – PDF File
- Peer Reviewed extended Abstract – PDF File