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The Ore and Gangue Mineralogy of the Newly-Discovered Federation Massive Sulfide Deposit, Central New South Wales, Australia

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Abstract: The newly-discovered Federation deposit with a resource estimate of 2.6Mt @ 7.7% Pb, 13.5% Zn, 0.8g/t Au and 9g/t Ag lies 10 km south of the Hera deposit within the Cobar Basin of the Lachlan Orogen. Located just north of the Erimeran Granite contact and between the Lower Amphitheatre Group and underlying shallow marine Mouramba Group Roset Sandstone, the host siltstones and sandstones have been brecciated, intensely silicified and chloritized close to mineralization. Orientated in an overall east-northeast strike and with a steep south-southeast dip, the siltstones mainly comprise quartz, clinochlore, biotite and muscovite. Federation also has highly fragmented zones with breccia and vein-fill of calcite. Main ore mineralization includes sphalerite and galena with lesser chalcopyrite, pyrrhotite, pyrite, gold and very rare meneghinite. Mineralization occurs within silicified veins and breccias of Zn-Pb sulfides which generally grade to moderate veining of sulfides with Pb and Cu dominant sulfides as well as minor veining of base metals associated with visible gold. Mineralization throughout the deposit is fairly simple with a low diversity of minerals. Iron concentration varies throughout the deposit, decreasing towards the center. Observations of massive sphalerite with gradations of red to honey-comb yellow indicate the transition from high Fe (7-10%) to low Fe (2-5%) within the coarse sulfide assemblages over a very short distance. Within the main mineralized corridor, fibrous amphibole inclusions within galena/sphalerite assemblages are observed at 251m as well as epidote associated with sulfides at 573m. Other ore associated gangue minerals include ilmenite, siderite, scheelite, magnetite, apatite and rutile.

Keywords: Federation deposit; Cobar Basin; mineralization; gold; base metal sulfides; mineralogy.

1. Introduction

The Federation deposit is located 10km south of the active Hera mine near the town of Nymagee, in central New South Wales, Australia (Figure 1). Past exploration by various companies failed to return significant mineralization results in the area. In mid-2019 a pole-dipole induced polarization (IP) geophysical survey was conducted by Aurelia Metals, returning a significant chargeability anomaly at the deposit [1]. Current drilling indicates a mineralized zone extending to a depth of over 600m and over a strike-length of 460m. An initial mineral resource estimate of 2.6Mt @ 7.7% Pb, 13.5% Zn, 0.8g/t Au and 9g/t Ag was reported in June 2019 [2]. Mineralization varies through the deposit with a steeply-dipping high-grade mineralized corridor in the northeastern section (Figure 2a) expanding out to several other steeply-dipping vein breccia and massive sulfide lenses along a broad corridor with a northeast-southwest strike (Figure 2b).

The Cobar Basin comprises Silurian to Devonian sequences that vary in intensity of deformation and metamorphism stages (Figure 1) and is host to numerous mines and deposits, mainly Cobar-type structurally-controlled sediment-hosted copper-gold and lead-zinc deposits. During the late Silurian to early Devonian (440-400 Mya) deformation cycles in the Lachlan Orogen mainly involving crustal extension and compression led to the formation of four deep -water troughs and intracratonic basins within the Cobar Basin [3]. As the Cobar Basin is considered to be one of the most economically significant regions in NSW [4], understanding the ore and gangue mineralogy of the Federation deposit will provide a further understanding of geological interpretations and resource estimates as well as extending the operation of the nearby processing plant at Hera by feeding the ore from Federation.

Many mines and deposits within the Cobar Basin have gone through several phases of exploration history leading to an increase in overall knowledge of the basin and a classification of Cobar-type deposits as epigenetic high sulfide gold-base metal type deposits [5]. Most of these deposits adhere to the criteria of a 'Cobar-type' deposit [6] including; multiple ore lenses within the deposit, significant variation in metal ratios between nearby lodes, alignment of orebodies to regional cleavage, mineralization during basin inversion in the Early Devonian (440-400 Mya), lower greenschist metamorphism and the presence of common gangue minerals including quartz, chlorite, carbonates and albite. While the Federation deposit currently adheres to the criteria of a typical Cobar-type deposit, its unusually low copper and high gold content are shared with the nearby Hera mine, though it lacks the high temperature skarn stage of the latter [7].

The Federation deposit lies on the eastern boundary of the Cobar Basin, between the Mouramba Groups Roset Sandstone and overlying Lower Amphitheatre Group and just north of the Erimeran Granite surface boundary [2]. Lying immediately west of the NNW-trending Rookery Fault (Figure 1), Federation consists of a structurally-controlled, sediment-hosted deposit containing silicified and brecciated sandstones and siltstones arranged into ENE-NE trending lodes (Figure 2b).

Due to its recent discovery, little is known about the geology of the deposit especially regarding its host sequence, ore and gangue mineralogy and the gold distribution, grain size, chemistry and association with other minerals. This study presents details on the mineralogy of the hostrocks, ore mineralization and gangue, along with petrographic analysis of the hostrock and mineralized samples through the collection and analysis of recently collected drill core samples. It has utilized petrographic analysis, X-ray diffraction (XRD) analysis, pXRF/pXRD analysis, sulfur isotope analysis and scanning electron microscope (SEM)/Electron Probe MicroAnalyser (EPMA) analysis.

2. Materials and Methods

The main diamond drill core samples and intervals investigated were FDD078 (530-625m), FRCD050 (330-368m), FRCD062 (311-360m), FRCD066 (308-317m), and FRCD068 (243-292m). Samples were selected to provide a range of the ore and gangue mineralization along with the unmineralized host assemblage in an attempt to provide a representation of the deposit as a whole. The locations and resources for these drill holes are shown in Figure 2a. Mineral species were identified and confirmed through petrographic analysis (transmitted and reflected light microscopy), XRD analysis, SEM analysis and EPMA analysis. These analyses were all undertaken within the UNSW Mark Wainwright Analytical Centre, while sulfur isotope analyses were completed at the Central Science Laboratory, University of Tasmania.

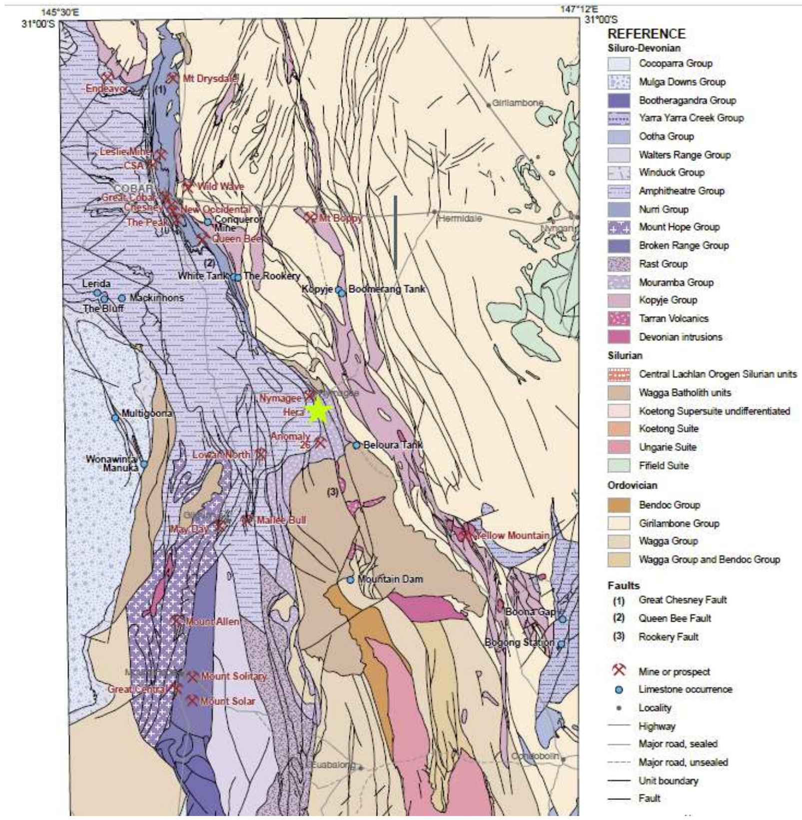


Figure 1 Regional geological map of the Cobar Basin with location of the Federation deposit and Hera mine indicated by green star (modified from [7])

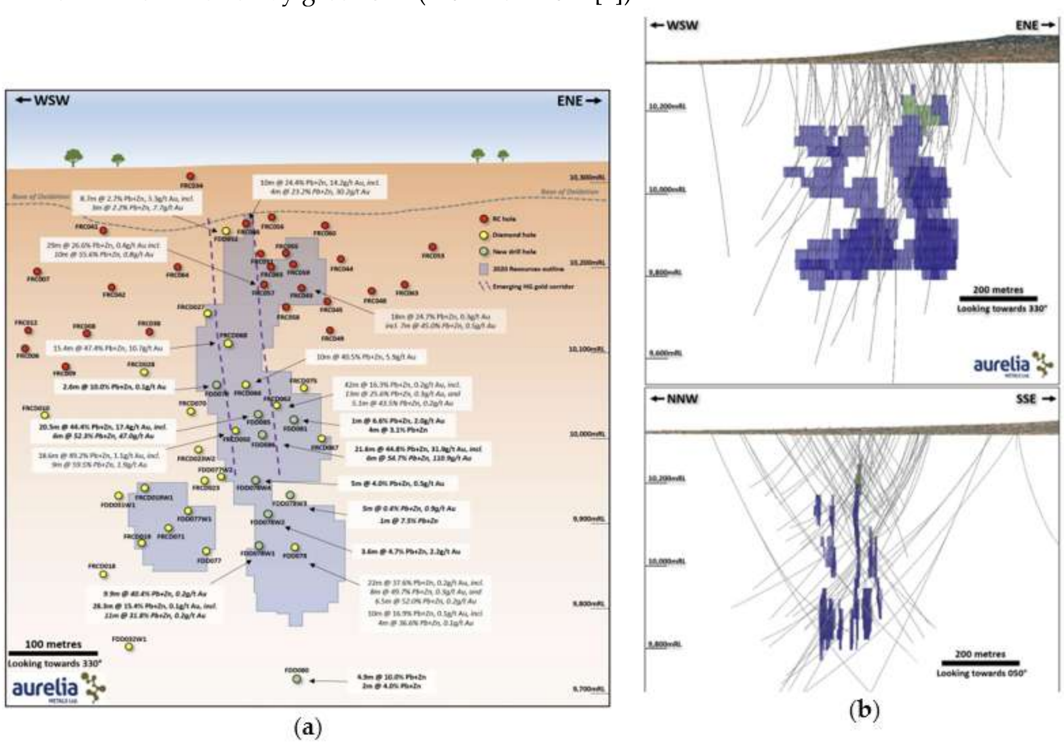


Figure 2 Cross and long sectional views of the Federation deposit: (a) long section of the high grade mineralized corridor in the north eastern section of the deposit with selected drill intercepts [8]; (b) over all long (top) and cross (bottom) sectional model of the Federation deposit [2].

A total of 131 samples were crushed and mounted into 20mm aluminium holders for lab XRD analysis using the PANalytical Empyrean II XRD machine operated at 45kV and 40mA, and analyzed from 3- 70° 2θ using the PIXcel^{1D} detector with a step size of 0.013° 2θ. Resultant XRD patterns were then studied using X-plot software to identify the contained mineralogy. 18 samples were chosen for polished mounts and were then investigated under reflected light using a Leica DM2500P polarizing microscope. EPMA analyses were made using the JEOL JXA-8500F Hyperprobe at 20 kV for the sulfides and 15 kV for the silicates, carbonates, oxides and phosphates. Sulfur stable isotopes were measured with flash combustion isotope ratio mass spectrometry using the Elementar varioPYRO cube coupled to the Isoprime100 mass spectrometer. Abundances were reported in delta (∂) values as the deviation from the conventional CDT (Canyon Diablo Troilite) standard in parts per mil (‰).

3. Results

3.1 Ore mineralization and distribution

The modelled lenses with significant mineralization currently extend to a depth of over 600m and a strike length of 460m [2]. Mineralization is epigenetic in nature and hosted in fine-grained sandstones and siltstones which have been silicified and brecciated. It is strongly structurally-controlled with several vein breccia and massive sulfide lenses steeply dipping in the center of a broad corridor of sulfide and quartz vein stockwork mineralization with a northeast-southwest strike (Figure 2b). Mineralization in the upper parts dominantly occurs as silica-sulfide infill within silicified veins and breccias of Zn-Pb sulfides (Figure 3a) and progresses downwards towards zinc-rich (55-65 wt%) massive sulfides and sulfide breccia base-metal mineralization associated with intense black chlorite alteration (Figure 3b) and visible gold. Iron concentration varies throughout the deposit, decreasing towards the centre of the deposit. Observations of massive sphalerite with gradations of red to honeycomb yellow over only a few centimeters indicates a rapid transition from high Fe (7-10 wt%) to low Fe (2-5 wt%) within the coarse sulfide assemblages (Figure 4a). Coarse gold grains were only observed as visible grains in the cores (Figure 4b) during this study from parts of the high-grade northeastern mineralized corridor in holes FDD078W2 (531m), FRCD050 (356-365m), FRCD066 (312m) and FRCD068 (248-252m) (Figure 2a).

(a) **(b)**

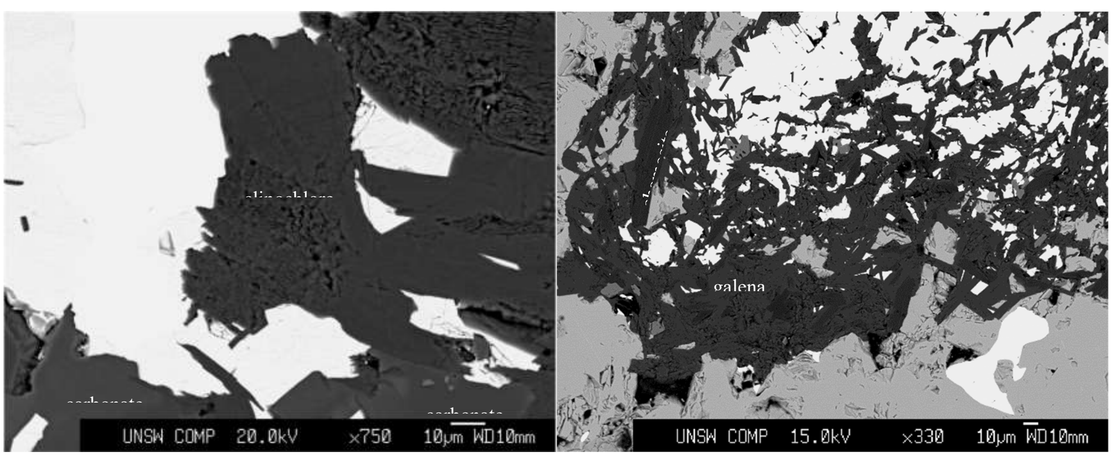
Figure 3 Selected mineralogical features within the Federation deposit: (a) heavily silicified zone with high iron sphalerite, galena and chalcopyrite from drill hole FRCD050 (362.85m); (b) massive sulfides with intense black chlorite from drill hole FRCD050 (348.5m)

(a) (b)

Figure 4 Selected mineralogical features within the Federation deposit: (a) visible gradation of red to honeycomb yellow sphalerite indicating transition from high (red) to low (yellow) iron composition from drill hole FRCD050 (363.8m); (b) visible coarse gold grains circled in red from drill hole FDD078W2 (531.3m)

3.2 Mineralogy of the host-rocks, ore and gangue

XRD analyses of the host rocks within Federation show that they mostly consist of quartz, chlorite, muscovite, phengite, biotite, calcite, fluorapatite, ilmenite, albite and rutile (Table 1). Further analyses through EMPA detected additional accessory minerals including magnetite, Mn-bearing ankerite, Ca-siderite, titanite and orthoclase. There are two phases of chlorite alteration with clinochlore being much more abundant. Its euhedral morphology and overprinting relationship indicate that this clinochlore is associated with a later stage of alteration (Figure 5a). An Al-bearing chamosite appears intergrown with the sulfides and is often overprinted by other minerals indicating an association with an earlier phase (Figure 5b). The presence of several calcite veins and its abundance through the host rock as found in the XRD analyses suggest a role in the fragmentation and brittleness of the host rocks, particularly in the deeper parts (530-630m) of drill hole FDD078.

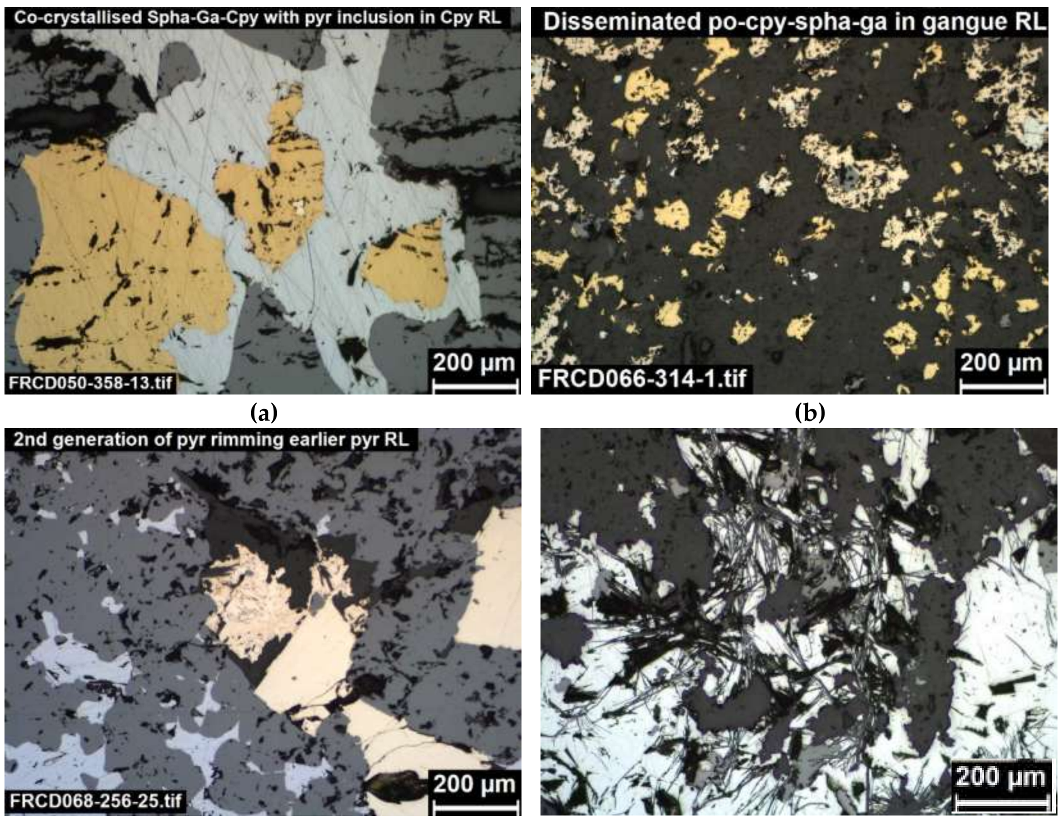


(a) (b)

Figure 5 SEM chlorite features within the Federation deposit: (a) Euhedral-subhedral clinochlore overprinting surrounding carbonates from drill hole FRCD062 (343m); (b) intergrown Al-bearing chamosite with sulfides from drill hole FRCD062 (322m).

The main ore mineralogy at Federation is fairly simple and similar to other deposits within the Cobar Basin [9] comprising sphalerite and galena intergrowths with chalcopyrite and minor pyrrhotite and pyrite (Figure 6a, b) and gold. This assemblage appears to have formed in two separate stages, with an earlier coarser phase exhibiting cuspate-lobate boundaries between the sphalerite, galena and chalcopyrite (Figure 6a) and a later fine-grained event associated with quartz gangue (Figure 6b).

The pyrrhotite and pyrite also appear to be associated with two separate mineralisation stages as indicated by: (1) euhedral pyrrhotite crystals sometimes being replaced by chalcopyrite or pyrite and euhedral pyrite inclusions in sulfides; and (2) massive pyrrhotite seen rimming other sulfides associated with the second main mineralization stage and a finer grained subhedral and brecciated pyrite usually overgrown over the earlier pyrite (Figure 6c). Other observed sulfides include arsenopyrite which is associated with pyrite and very rare meneghinite (a complex sulfosalt mineral found in hydrothermal veins and associated with other common sulfides). A single observation of fibrous amphibole inclusions within sulfides was also observed (Figure 6d) and identified to be a potassic ferro-eckermannite in drill hole FRCD068 at a downhole depth of 251m.



(c) (d)

Figure 6 Reflected light microscope observations of ore mineralogy features within the Federation deposit: (a) Intergrowth texture of sphalerite, galena and chalcopyrite with small pyrite inclusions from drill hole FRCD050 (358m); (b) Fine grained pyrrhotite, chalcopyrite, sphalerite and galena in gangue quartz from drill hole FRCD066 (314m); (c) Two generations of pyrite with brecciated pyrite (II) rimming earlier euhedral pyrite below from drill hole FRCD068 (256m); (d) Fibrous amphibole inclusions in galena and sphalerite from drill hole FRCD068 (251m)

The gold in Federation shows little correlation to other metals, mostly visible as discrete grains in parts of the high grade northeastern mineralised corridor in holes FDD078W2 (531m), FRCD050 (356-365m), FRCD066 (312m) and FRCD068 (248-252m) (Figure 2a). Using Spearmans correlation, the assay data for gold shows little correlation to the other metals within the deposit. Gold was not observed in any of the thin sections or polished mounts.

Other selected elemental correlations were made with the company assay data using Sopearmans correlation coefficients (n=1400). Pb and Zn are well correlated with a coefficient of 0.82, as indicated by the dominant sphalerite and galena intergrowth in Federation. Cu and Zn also contain moderate correlation with a factor of 0.43, also indicated by moderate observations of chalcopyrite, sphalerite and galena intergrowths (Figure 6a). The Cu and Fe have a low correlation with each other of 0.31 while Fe and Zn have almost zero correlation.

Alteration within the deposit is mainly in the form of chloritisation with the primary chlorite mineral being clinochlore and secondary chamosite. Phyllic alteration is also present throughout, mostly as the phase phengite. Carbonate alteration is mostly present as calcite throughout the deposit with accesory Mn-bearing ankerite being present in some of the mineralised lenses. A full list of minerals identified in this study can be found in Table 1.

Table 1. List of ore and gangue minerals identified during this study

Sulfide Minerals	Relative Abundance	Gangue Minerals	Relative Abundance	Gangue Minerals	Relative Abundance
Sphalerite	Major	Quartz	Major	Siderite	Trace
Galena	Major	Clinochlore	Major	Magnetite	Trace
Chalcopyrite	Major	Chamosite	Major	Ankerite	Trace
Pyrrhotite	Major	Muscovite	Major	Scheelite	Trace
Pyrite	Minor	Calcite	Major	Epidote	Trace
Arsenopyrite	Minor	Fluorapatite	Minor	Talc	Trace
Gold	Minor	Rutile	Minor	Gypsum	Trace
Meneghinite	Trace	Ilmenite	Minor	Orthoclase	Trace
		Biotite	Minor	Albite	Trace
		Titanite	Trace	Ferro-eckermannite	Trace

3.3 Isotope analyses

Six samples of sphalerite from varying locations in the deposit were sent for sulfur isotope analysis giving a limited range of $\delta^{34}S$ values from 2.31 to 3.45. One sample was analyzed from FRCD062 at downhole depth 357m with a value of 3.45, two from FRCD066 at downhole depths of 310-312m with values of 2.62 and 2.31 and three from FRCD068 at downhole depths of 251, 254 and 256m with similar values of 2.59, 2.57 and 2.59.

4. Discussion and conclusion

Presently, there have been no published studies on the Federation deposit, and thus, the results from this study will hopefully contribute to the understanding of geological controls on alteration and mineralisation in similar deposits. The isotope sulfur data collected during this study contained a range of sulfur isotope values from 2.31 to 3.45 $\delta^{34}S$. According to Downes and Poulson [10], this narrow range of values suggest that the supply of sulfur came from reservoirs primarily containing magmatic sulfur.

Though the nearby Hera mine was originally classified as being a Cobar-type deposit, it contains a number of features which contrast to this type of deposit such as the presence of high-temperature skarn gangue mineral assemblages [7, 11, 12, 13] and unusually low copper and high gold content. While Federation lies 10 km south of Hera and shares a similar high gold content, low $\delta^{34}S$ values with several of Heras lodes and some similar mineral assemblages, including common sphalerite-galena intergrowths and widespread chlorite alteration, the overall mineralogy is less variable. On average, sulfur isotopes are lower at Federation suggesting a closer proximity to the theorised intrusion responsible for the high temperature skarn gangue mineral assemblage at Hera. Federation also contains far more pyrite than at Hera. Skarn alteration within Federation characterized by potassic ferro-eckermannite is highly localised in occurrence in drill hole FRCD068 at a downhole depth of 251m. To date, Federation primarily contains low-temperature alteration assemblages, whereas Hera additionally contains high-temperature skarn alteration assemblages.

The results add to our overall knowledge on structurally-controlled sediment-hosted Au-Pb-Zn-Cu deposits worldwide as well as placing important constraints on the existing genetic models for these deposits. More research will have to be done to determine the associations and further instances of skarn alteration within Federation as well as determining any association between the gold and other metals.

Author Contributions: K.S. collected the samples, analyzed and interpreted some of the data used for this project and wrote the manuscript. I.T.G. supervised the project, provided technical input and petrographic analyses and assisted with SEM/EPMA analyses. A.McK. co-supervised the project, provided technical input, arranged access to the deposit as well as funding for the project. K.P. coordinated all SEM and EPMA analyses. C.D. carried out the sulfur isotope analyses.

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Conflicts of Interest: The authors declare no conflict of interest.

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