

Hera: Evidence for Multiple Mineralization Events and Remobilization in a Sediment-Hosted Au-Pb-Zn-Ag Deposit, Central New South Wales, Australia [†]

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Abstract: The Hera Au-Ag-Pb-Zn deposit of central New South Wales, Australia with a total undepleted resource of 3.6 Mt @ 3.3 g/t Au, 25 g/t Ag, 2.6% Pb and 3.8% Zn occurs on the SE margin of the Cobar Basin. It is hosted by the shallow marine Mouramba Group and overlying turbiditic Amphitheatre Group. The siltstones comprise various mixtures of quartz, plagioclase, muscovite-phengite, biotite and clinochlore, along with accessory titanite and ilmenite. The deposit comprises a number of discrete lodes which are steeply west-dipping and strike NNW. Each lode has different abundances of the main ore minerals sphalerite, galena, chalcopyrite, pyrrhotite and electrum-gold. The North Pod and Far West lenses have the most diverse mineralogy in additionally containing arsenopyrite, native silver, gudmundite, Ag-tetrahedrite, acanthite, dyscrasite, native antimony, nisbite and breithauptite. Electrum (continuous spectrum from Ag-rich to Au-rich) is associated with sulfides in the main ore lenses while native gold occurs in the host rocks along cleavages/lineations and away from the main ore. The sulfur isotope data from across the deposit indicates a magmatic source. Most of the deposit has experienced greenschist facies metamorphism with pervasive green chlorite alteration, though the North Pod differs in being distinctly Ag- and Sb-rich and has reached at least amphibolite facies metamorphism with a garnet-wollastonite-vesuvianite-tremolite assemblage. Tremolite is relatively abundant throughout most of the deposit suggesting widespread low-T skarn alteration. Cross-cutting pegmatites comprise quartz, plagioclase (labradorite-andesine) and microcline. Hydrothermal remobilization is relatively extensive and best explains the unusual Ag-Sb-As assemblages of the North Pod and Far West lodes.

Keywords: sediment-hosted; remobilization; gold; Cobar Basin; Hera mine; skarn; pegmatites; sulfides; chemistry

1. Introduction

The Hera mine is located within the southern part of the Cobar Basin, ~5 km south of the historic copper mining town of Nymagee, central New South Wales, Australia (Figure 1). The deposit is mined using a decline to access the underground workings with mineralization starting at ~180 metres below the surface. Commercial production from the mine began in September of 2014 and the deposit has a total undepleted resource of 3.6 Mt @ 3.3 g/t Au, 25 g/t Ag, 2.6% Pb and 3.8% Zn.

The Cobar Basin is a complex Silurian to Devonian sedimentary and intrusive sequence that mainly hosts Cobar-type structurally controlled sediment-hosted copper-gold and lead-zinc deposits. Within the basin, cycles of deformation mainly involved regional crustal extension and compression causing basin inversion during the late Silurian to early Devonian (~440–400 Ma), leading to the formation of deep-water troughs and intracratonic basins [1]. Although Glen et al. [2] suggested that the initial deformation within the Cobar Basin occurred at 395–400 Ma, Sun et al. [3] instead proposed a later age of 385–389 Ma. Lawrie and Hinman [4] listed a number of criteria for Cobar-type deposits including zones of silicification along ore-body contacts, multiple orebodies within the one deposit, variable metal ratios within adjacent lodes, two episodes of mineralization, no obvious linkage to any igneous activity and vertical zonation of minerals within alteration zones.

The Hera deposit is located at the boundary between the shallow marine Mouramba Group and overlying Amphitheatre Group, characterized by sandstone and siltstone turbidites, all now steeply-dipping [5]. Although a number of granites occur within this region, they have been dated at 428–422 Ma [6,7] and predate the host sedimentary units of the Hera deposit with the Amphitheatre Group being dated at 419–407 Ma [8]. In addition, Waltenberg et al. [7] obtained consistent U-Pb ages of 383 Ma on euhedral titanite crystals from quartz veins on the 435 Level vent access and 460 Level of the Hera mine that cross-cut the sulfide orebodies at these locations and Downes and Phillips [9] obtained an almost identical preliminary age of 382 Ma for muscovite intergrown with sulfides from the Far West zone. Based on chlorite geothermometry and limited fluid inclusion data, Page [10] suggested that the Hera mineralization formed at temperatures of 270–365 °C while Fitzherbert et al. [11] noted an earlier higher temperature pre-deformation skarn-forming assemblage which suggested peak hydrothermal temperatures of 450 °C. The host siltstones and sandstones display a strong subvertical cleavage and have been metamorphosed to low-middle greenschist facies [12–14].

Previous studies on the Hera deposit largely focused on regional scale aspects during the development of the mine [10,12,13] and more recently on the skarn assemblages [5,11,15]. This paper presents the first detailed description of the Hera deposit in terms of the hostrock, ore and gangue mineralogy, detailed electron microprobe analysis (EMPA) of the main ore-forming phases, textural analysis of the ore-hostrock relationships and sulfur isotope analysis, and it provides evidence of substantial remobilization of the ore components, with comparison to typical ‘Cobar-style’ deposits and provides a complex multi-stage model for the evolution of the deposit.

2. Materials and Methods

This paper is largely based on the honors research projects of Burrows [16], Liepa [17] and Schellen [18] and as part of the PhD project of Lay [19]. Importantly, samples were collected over a 4-year period and from as many different parts of the mine (both vertically and horizontally) as possible. Mineral species were verified using a combination of X-ray diffraction (XRD), scanning electron microscopy (SEM) and electron microprobe analysis (EMPA). All of these were carried-out at the Mark Wainright Analytical Centre, UNSW, Sydney, NSW, while the sulfur isotopes were analyzed at the Central Science Laboratory, University of Tasmania.

The XRD analyses were performed using a PANalytical Empyrean II X-ray Diffraction System (MPD) with Co K-alpha radiation under operating conditions of 45 kV and

40 mA, with a 2θ scan angle ranging from 3 to 70° and a step-size of 0.013° 2θ . SEM analyses were conducted using a Hitachi S-3400N at 15–20 kV. EMPA analyses were made using a JEOL JXA-8500F Hyperprobe electron probe micro-analyzer (EPMA) with a probe current of 15–40 nA and accelerating voltage of 20 kV. A series of synthetic metals and natural mineral standards were used as calibration standards. Analysis of secondary standards yielded accuracy of $\pm 2\%$ relative for major and minor elements. Sulfur stable isotopes were measured using flash combustion isotope mass spectrometry (Elementar varioPYRO cube coupled to Isoprime 100 mass spectrometer). Abundances are reported in delta (δ) values as deviation from the conventional CDT (Canyon Diablo Troilite) standard in parts per mil (‰).

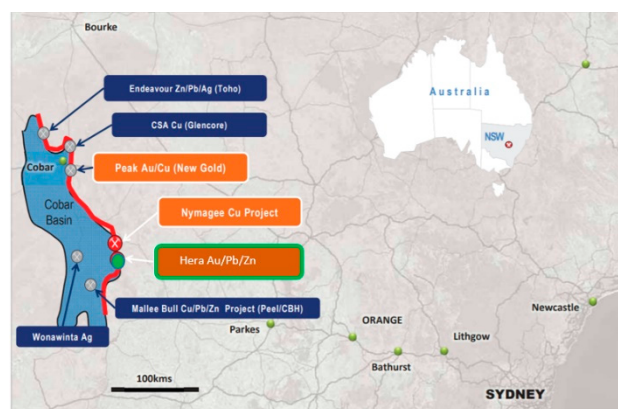


Figure 1. Location of the Hera mine and other major mines and prospects within the Cobar Basin, Australia (modified from Aurelia Metals Ltd., [20]).

3. Results

3.1. Ore Mineralization, Vein and Pegmatite Distribution

The deposit contains a number of distinct ore bodies (Figure 2) mined at a number of levels (currently from 285–640). The main ore lenses are Far West, Far West Lower, Hays North, Hays South, Main North, Main South and North Pod. The ore bodies generally occur as steeply west-dipping lenses striking NNW [14]. Mineralization is strongly structurally-controlled, occurring as sulfide veins and breccia zones. Although much of the ore lenses comprise sub-massive to massive sulfides, sulfide veins are also abundant, as are breccia ores comprising angular to sub-rounded clasts of hostrock siltstones in a matrix of generally sphalerite and galena (Figure 3a). These are examples of such ‘durchbewegung’ textures as described by Vokes [21] and Gilligan and Marshall [22]. Late-stage quartz veins contain coarse-grained and commonly euhedral crystals of chalcopyrite, pyrrhotite, cubanite, galena and sphalerite. In addition, cross-cutting pegmatites have so far been found on the 285SB, 285SC, 310SA and 615FWA drives (Figure 3b). Although these were previously thought to be albite-bearing quartz veins, their coarse grain size, hypidiomorphic granular texture and microcline, orthoclase, labradorite-andesine-albite and quartz mineralogy show these to be granitic pegmatites.

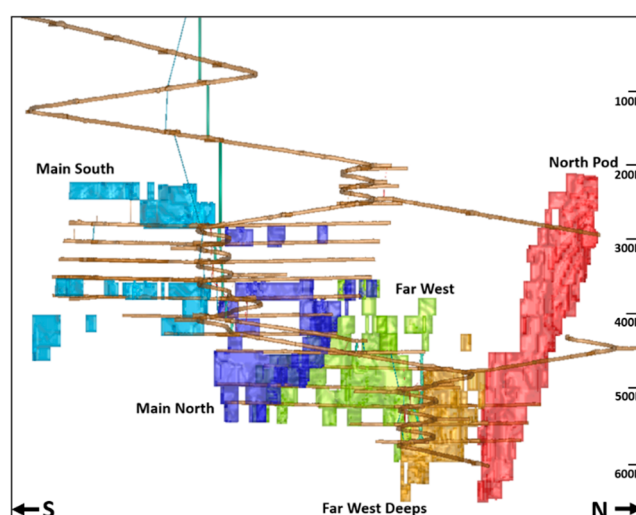


Figure 2. Ore lenses within the Hera deposit, excluding areas depleted by mining. Hays North and Hays South ore lenses are behind Main North and Main South and thus not visible.

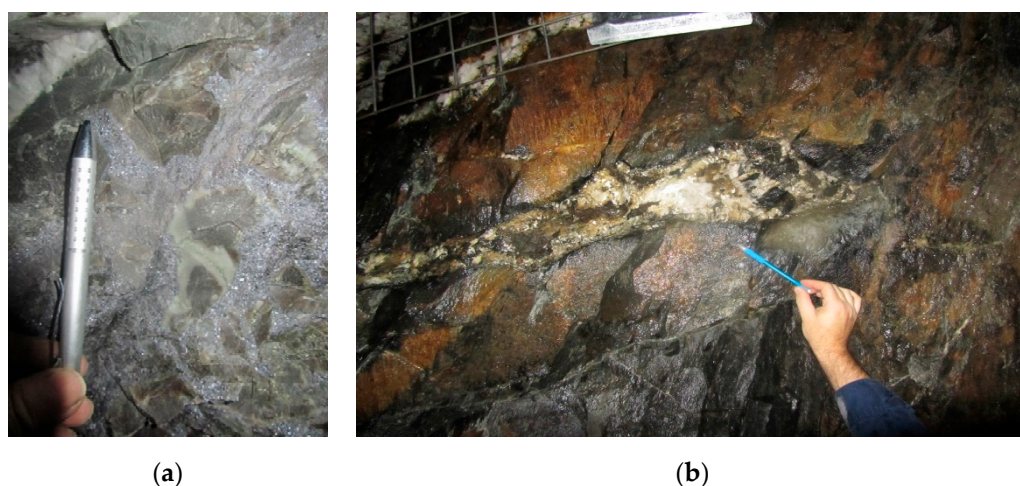


Figure 3. Underground exposures (a) rounded and partially bleached siltstone clasts in massive fine-grained galena. (b) cross-cutting granite pegmatite with siltstone clasts and chlorite selvage.

3.2. Mineralogy of the Hostrocks, Ore And gangue, Gold-Electrum Composition and Sulfur Isotopes

Previously, the hostrocks were thought to be largely comprised of quartz, muscovite, biotite and chlorite. However, Liepa [17] showed that they additionally contain substantial plagioclase (up to 22 wt%; labradorite-andesine) and phengite-muscovite along with rare alkali feldspar (microcline) and abundant accessory titanite and ilmenite (commonly Mn-rich).

The first sulfides to have formed are widespread throughout the deposit as an early generation of dominantly pyrrhotite (I) with minor chalcopyrite (I) which occurs as stretched elongate aggregates along foliation planes. The main ore stage is characterized by an assemblage of sphalerite and galena (Figure 4a) with minor pyrrhotite (II), chalcopyrite (II) and rare pyrite. This style of mineralization is similar to other deposits within the Cobar Basin [4]. Skarn associated mineralization is mostly restricted to the Far West and North Pod lenses and consists of the assemblage sphalerite, galena, pyrrhotite, minor chalcopyrite, arsenopyrite, gudmundite (Figure 4b), native silver, native antimony, tetrahedrite, Ag-rich tetrahedrite, freibergite, acanthite, breithauptite, electrum and dyscrasite. This type of mineralization has not been observed elsewhere in the Cobar Basin. Unlike

other deposits of the Cobar Basin, pyrite is relatively rare and most of the sphalerite lacks any chalcopyrite exsolution lamellae. All of the ore lenses have undergone extensive chloritization with the main chlorite species being clinocllore. Phyllic alteration occurs throughout the deposit, mostly as ‘phengite’, an intermediate phase between illite and muscovite. Carbonate alteration is most abundant in the lower parts of the Main North, Main South and North Pod lenses, is dominantly calcite and commonly occurs intergrown with the sulfides. Talc is relatively common and has been found in the 515 Main lode, 535XC, 560 FWD and North Pod.

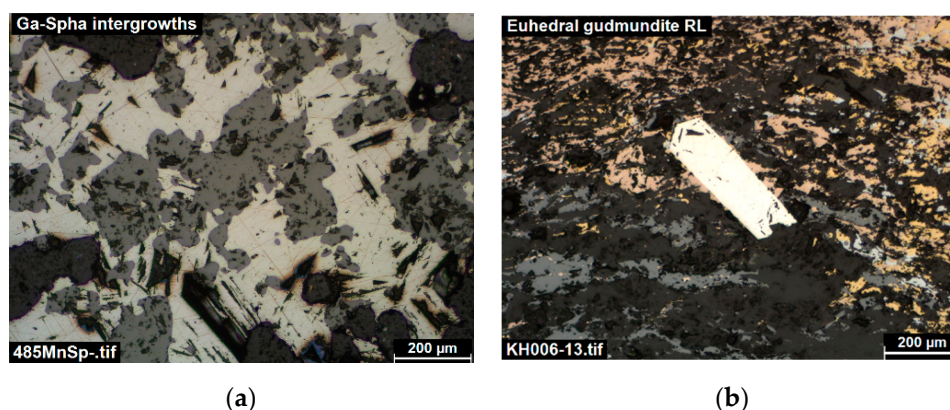


Figure 4. Sulfide minerals from the Hera deposit (a) sphalerite-galena intergrowths from 485 Main North (b) euhedral gudmundite from 615 level, North Pod.

Sulfur isotope analysis of mineral separates (mostly sphalerite) shows a consistent and very limited range of $\delta^{34}\text{S}$ values from 3.27 to 4.60. We specifically analyzed sphalerite from various levels of the North Pod orebody and these show very little vertical variation from 3.55–4.51 (615 level) to 4.55 (585 level) and 3.36 (535 level). The lowest value (3.27) is for 310SA while the highest value is for 560FWS. In addition, we analyzed 7 samples (either pyrite or mixed sulfide) from the sub-economic Kershaws lode as this is highly unusual for Hera in being pyrite-rich. These returned a similar but broader range of $\delta^{34}\text{S}$ values from 2.38 to 4.58.

3.3. Skarn Assemblages and Distribution

Fitzherbert et al. [11] were the first to describe skarn assemblages from the Hera deposit but did not give any locations for the samples analyzed nor their relative distribution. They described a vein assemblage of garnet-actinolite/tremolite-quartz $\pm$ chalcopyrite-galena-sphalerite grading with fine-grained garnet, tremolite and zoisite penetrating into the enclosing wallrocks for 0.1 meter. They also mentioned the occurrence of a garnet-tremolite-vesuvianite assemblage and wollastonite and suggested peak metamorphic conditions of amphibolite or pyroxene hornfels facies of at least 450 °C. Although they suggested that biotite alteration was pre-deformation and later overprinted by chlorite-sericite, we have found an additional later generation of subhedral biotite, commonly intergrown with other phyllosilicates including chlorite.

To date, we have found amphiboles throughout the deposit intimately associated with the ore minerals (Figure 5a) with actinolite being found on 285SC, 485MN, 640MN, 485FWS, 560FWS, 560FWD, 535NP, 585NP, 615NP and 640NP and tremolite being found on 555SP, 485MN, 640MN, 485FWS, 560FWS, 560FWD, 510NP, 585NP, 615NP, 640NP and in Hays. Other amphiboles were found as late-stage phases within quartz veins (edenite and winchite from 555SP, fluoro-edenite from 535NP, 585NP and 615NP). Such amphiboles are characteristic of a skarn mineralizing event [23,24] and these appear to increase in abundance with depth. In general, actinolite is later in paragenesis suggesting that the skarn-forming fluid moved to more Mg-poor and Fe-rich compositions. Other clearly skarn-forming minerals found widely distributed throughout the deposit include

diopside (555SP, 485MN, 615FWA, 640NP), garnet (485MN, 640MN, 560FWS, 360NP, 585NP, 615NP, 640NP and Hays), members of the epidote group (clinozoisite from 285SB and 560FWS; zoisite from 560FWS, 535NP, 585NP and Hays), while vesuvianite was only found at 615NP. There are two distinct generations of garnet, garnet I is coarser-grained, commonly euhedral in shape and in places has been partially to completely replaced by quartz (Figure 5b). Garnet II is finer-grained and commonly compositionally zoned. Although both generations of garnets lie along the grossular-spessartine join, garnet I is closer to spessartine while garnet II is closer to grossular. Thus, the early skarn-forming fluid was more Mn-rich and evolved to more Ca-rich compositions over time.

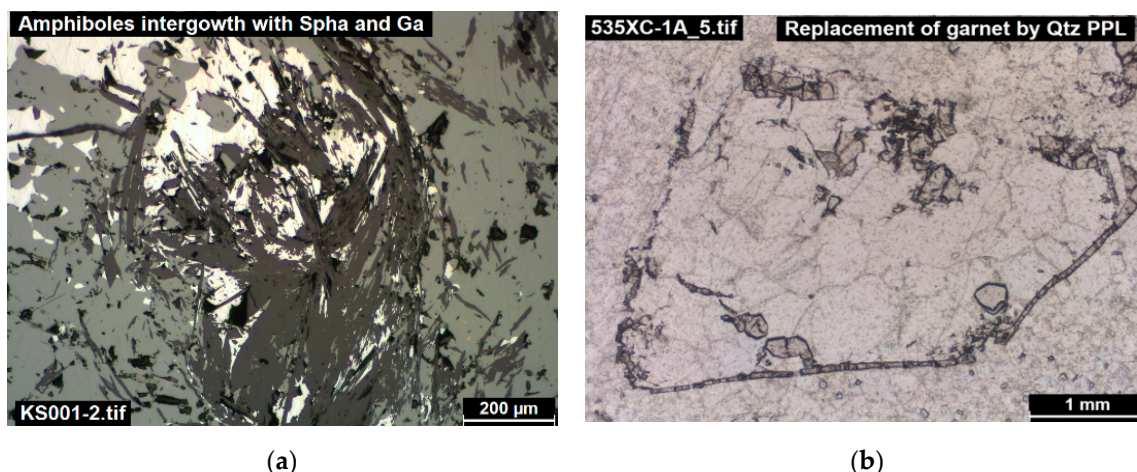


Figure 5. Skarn assemblages (a) fibrous tremolite intergrown with sulfides, RL image (b) first generation garnet almost completely replaced by quartz, PPL.

3.4. Major Element Analysis of the Ore Phases

The major element chemistry of arsenopyrite from the North Pod shows little variability (35.17–36.50 wt% Fe, 41.72–44.00 wt% As and 20.66–22.87 wt% S). Gudmundite from the Far West and North Pod lenses shows a similar chemistry but with more variability than arsenopyrite (24.87–27.61 wt% Fe, 50.41–59.23 wt% Sb and 14.58–17.36 wt% S). Sphalerite throughout the deposit is generally Fe-poor, with an overall composition of 53.80–62.83 wt% Zn, 3.47–10.77 wt% Fe and 31.48–34.28 wt% S. Importantly, sphalerite from the North Pod is the most Fe-rich (>7.68 wt% Fe), indicating a higher temperature of crystallization and/or lower sulfur fugacity [25]. Galena exhibits a wide variation in its Pb to S contents spanning 75.76–89.16 wt% Pb and 11.94–14.94 wt% S, though there is no systematic variation. Chalcopyrite is close to its stoichiometric end-member with a calculated empirical formula of $\text{Cu}_{0.99}\text{Fe}_{0.99}\text{S}_2$. Most tetrahedrite from the Main South and Far West lodes contains <4.74 wt% Ag, with a mean calculated empirical formula of $\text{Ag}_{0.43}\text{Cu}_{9.39}\text{Zn}_{0.68}\text{Fe}_{1.48}\text{Sb}_{3.89}\text{As}_{0.07}\text{S}_{13.03}$. In contrast, tetrahedrite from the North Pod shows a wide variation in composition of 0.04–9.65 wt% Ag, 31.54–38.82 wt% Cu, 0.93–2.60 wt% Zn, 5.30–6.27 wt% Fe, 23.65–25.40 wt% Sb, 0.01–0.40 wt% As and 23.65–25.40 wt% S and both Ag-rich tetrahedrite (with 11.11–22.27 wt% Ag) and freibergite (25.05–28.30 wt% Ag) were also found.

3.5. Chemistry of Gold-Electrum

Gold has a very low correlation with the other metals (the highest being with Ag, correlation coefficient of only 0.23) and has a wide spectrum of compositions from almost pure gold in the Main Lode within the host rock and well away from known ore bodies (0.89–0.92 Au atoms p.f.u) through 0.63–0.47 Au atoms p.f.u to Ag-rich electrum with 0.37–0.18 Au atoms p.f.u. (Figure 6a) in the ore bodies. The rare nickel antimonides nisbite and breithauptite were sometimes found partially rimming electrum from the central southern Far West and North Pod lenses (Figure 6b).

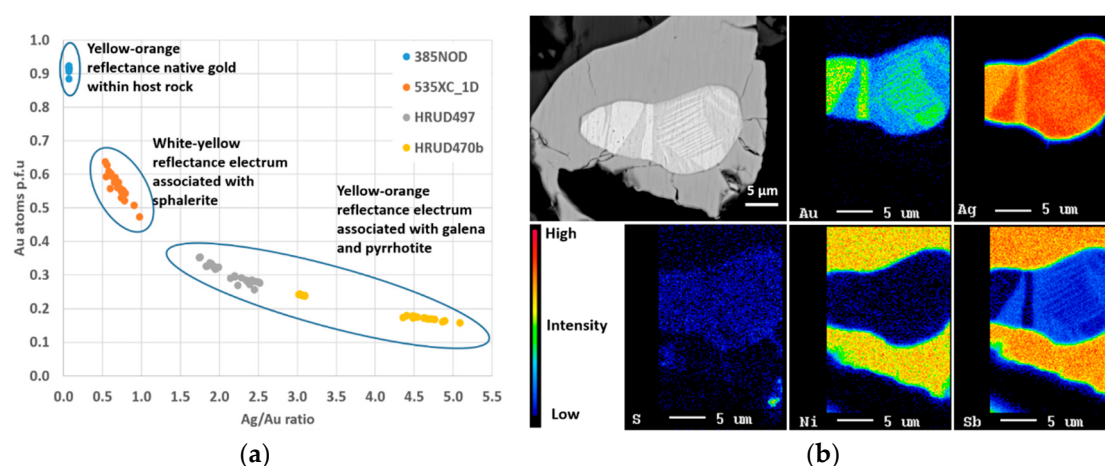


Figure 6. (a) Plot showing the variability in composition of gold-electrum from the Hera deposit (b) WDS elemental map of electrum rimmed by breithauptite from the North Pod.

4. Discussion and Conclusions

Remobilization involves physical and/or chemical translocation and disassociation of sulfides and wallrock from their original sites of formation [26]. Textural evidence of remobilization includes recrystallization of sulfides, elongation lineations, foliations, folding of sulfide layers, mixed breccia sulfide-silicate ores and boudinage [22], most of which are present at Hera, particularly within the North Pod [19].

The wide range for both gold-electrum occurrences and continuous spectrum for their chemistry strongly suggests multiple periods of gold mineralization, with early native gold possibly pre-dating the basin inversion and related to an earlier phase of orogenesis. The elevation in Ag content in electrum and enrichment in Ag, Sb and As towards the North Pod lenses strongly suggests that this was a conduit for focused hotter fluids which remobilized these and other metals. The occurrence of the rare phases breithauptite and nisbite rimming electrum and of later dyscrasite replacing the breithauptite provides additional evidence for hydrothermal remobilization [27].

The sulfur isotope values of 2.38–4.58 span the lower part of the range of 2.9–7.4 (61 analyses) for the overall Hera deposit [13,28] and provide additional data from lodes previously lacking sulfur isotopes. Furthermore, Downes and Poulson [28] suggested that these low values suggest a magmatic source for the sulfur while Fitzherbert et al. [29] went a step further and suggested a felsic igneous source. Thus, these values and the occurrence of cross-cutting granitic pegmatites strongly suggest the presence of a deeper igneous intrusion that supplied the heat source, fluids and some metals.

The Hera deposit has been categorized as being of the Cobar-type [13] as it has many features of this deposit type including location within the eastern margin of the Cobar Basin, being epigenetic and strongly structurally-controlled and having polymetallic ores. However, it has a number of distinct differences, especially widespread almost deposit-wide low-T skarn alteration (tremolite-actinolite) intimately associated with the sulfides and higher T skarn alteration assemblages (mostly spessartine-grossular) not only within the North Pod but also the Main and Far West lodes. In addition, the chemistry of sphalerite shows some similarities to that of skarn deposits [30], though the low iron and indium concentrations suggest that it formed lower than the peak metamorphic temperature of >450 °C [11], probably during retrogression.

Author Contributions: I.T.G. wrote the manuscript, provided technical input and supervised the project. A.M. co-supervised the project, provided technical input, arranged access to the deposit and funding. K.S., A.L., E.L. and L.B. collected the samples, undertook some of the analyses and interpreted the data. K.P. coordinated the SEM and EPMA analyses. H.Q. ran and helped interpret the XRD data while D.F. helped with data interpretation and C.D. ran the sulfur isotope analyses. All authors have read and agreed to the published version of the manuscript.

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