# Appendix B

Normative Mineral Proportion Calculation Algorithm

The normative mineralogy calculation has been created to calculate inferred mineral proportions based on lithogeochemical data and mineral chemistry. Mineral proportions are calculated for the dominant sulfide and arsenide minerals identified within the Phase 1 Cigar Lake ore: sphalerite, gersdorffite, nickeline, rammelsbergite, chalcopyrite, bornite, chalcocite, pyrite and galena. Several geochemical stoichiometric techniques are utilized in the calculations. Molar element ratios are used to differentiate element control by differing mineral phases. Minerals with element-constrained ratios, exhibiting the sole control over an element (e.g., Zn in sphalerite) or tri‑element minerals with more than one element-ratio (e.g., Ni:As and Ni:S in gersdorffite) are calculated first in the linear algorithm. A subtractive method, of calculating the element consumption by element‑constrained minerals before calculating the concentration of non-element constrained minerals is used to help differentiate between mineral phases. An overview of the norm calculation algorithm is provided:

Step 1: Calculating Sphalerite using Zn

The concentration of sphalerite is calculated using the whole-rock Zn wt.%. Allotting the Zn to sphalerite was substantiated by XRD, SEM-MLA and petrographic interpretations that identified sphalerite as the only controlling mineral phase of Zn. The sphalerite concentration is calculated using the formula (Zn0.96Fe0.04)S determined from LA-ICP-MS analysis. The sphalerite molecular mass (MM) / Zn MM ratio was used to quantify the concentration:

 Zn wt.% \* ((MM Zn+ MM S)/ MM Zn) = % sphalerite (1)

Step 2: Calculating concentration of sulfarsenides and sulf-diarsenides

Based on XRD, SEM-MLA and petrographic interpretations the dominant control on Ni-Co-As throughout the deposit was determined to be: gersdorffite, cobaltite and nickeline (listed in descending order of abundances). Whole-rock geochemistry confirmed these analyses showing that the Ni M% + Co M%/ As M% ratio is dominated by 1:1 molar ratio of Ni:As. Idealized formulas for nickeline, gersdorffite and cobaltite were determined reasonable using EPMA and LA-ICP-MS. However, it is noted that solid solution substitutions exist between the mineral phases. For the norm calculation algorithm, the Co M% + Ni M%: As M% ratio was used to differentiate Ni-As elemental control by sulfarsenides from sulf-diarsenides. Samples with Co M% +Ni M%: As M% ratios greater than one were calculated as cobaltite and gersdorffite using Co wt.% and Ni wt.% respectively. Mineral proportion were calculated using the mineral MM/ element MM ratios as illustrated in Step 1 (equation 1). Overestimation of mineral proportions, and overconsumption of As is avoided by multiplying the initial Co wt.% and Ni wt.% with the As M%/ (Ni M% + Co M%) ratio to balance the equation.

Based on XRD, SEM-MLA and petrographic interpretations samples with Co M% + Ni M%: As M% ratio lower than one contained the sulf-diarsenide rammelsbergite (NiAs2). Ni-Co Skutterrudite ((Ni;Co)As3) was identified but only in minor concentrations and is therefore omitted from the calculated normative mineral suite.

The concentration of rammelsbergite is calculated using Ni:As ratio linear equations:

Sulf-diarsenides: (2)

= y=mx+b

 = Ni M% + Co M% = (1/2) As M% + b

Sulfarsenides:

=y= mx+b

 = Ni M% + Co M% = (1/1) As M% + b

The intersection point of the sulfarsenide-sulf-diarsenide Ni:As ratios is used to quantify the whole-rock element control from the minerals. First, the steeper slope (equation 1: sulfarsenides) was aligned on the axis origin (0, 0). The Y intercept is then calculated for the sample using the linear equation of the shallower slope (equation 1: sulf-diarsenides):

Solve Y intercept (b) for sulf-diarsenides: (3)

y=mx+b

 y=1/2x+b

 b=y-1/2x

 b= (NiM% + CoM%) – (1/2)(AsM%)

Using the sulf-diarsenide y-intercept, the intersection point between the sulfarsenides and sulf-diarsenides linear equations can be calculated algebraically providing the stoichiometric control on the whole-rock geochemistry:

Solving intersection point (X) of the linear equations (Where y=NiM%+CoM% and x = AsM%):

 (4) 1/1x+0(sulfarsenide) = 1/2x+b(sulf-diarsenide)

1x(sulfarsenide) -.5x(sulf-diarsenide) =b

.5x=b

X=2b

Therefore:

 x(intersection)=2(y-1/2x)

 = 2((NiM% + CoM%) – (1/2)AsM%)

Since sulfarsenides have a 1:1 NiM%+CoM%:AsM% ratio, the Ni M% + Co M% is equal to the As M% at the intersection point. All the As above the As M% intersection point is interpreted to be controlled by the sulf-diarsenide rammelsbergite, whereas all the As below the intersection point is distributed to the remaining Ni and Co to quantifying the concentration of gersdorffite and cobaltite respectively. Mineral proportion were calculated using the mineral MM/ element MM ratios as illustrated in Step 1 (equation 1).

Step 3: Calculating concentration of arsenides

 Nickeline with the idealized chemical formula NiAs, could not be initially differentiated based solely on the NiM%+CoM%/AsM% ratio. Therefore, it is allocated if the sample becomes S-deficient after calculating the normative mineral proportion of sphalerite, preliminary-gersdorffite and cobaltite. Sulfur consumption is calculated by subtracting the allotted S (mineral wt.% \* S MM/ mineral MM) from the whole-rock S wt.%

Calculating S consumption: (5)

S wt.% remaining = S wt.%-(( S wt.% sphalerite) + (S wt.% gersdorffite) + (S wt.% cobaltite))

This assumes that the only non-sulfide control on Ni or As is nickeline. Based on XRD, SEM-MLA and petrographic interpretations this has been deemed reasonable. Only minor concentrations of arsenate minerals annabergite, erythrite and aerugite have been identified. The concentration of nickeline is calculated by balancing the S deficiency against the Ni content within nickeline.

Calculating nickeline concentration:

Nickeline wt.% =

ABS(S deficiency)\* (MM Ni + MM As + MM S)/ MM S) \*(MM Ni/ (MM Ni + MM As + MM S) \*

(MM Ni + MMAs)/ MM Ni)

 The concentration of gersdorffite is recalculated for S-deficient samples after accounting for the allotment of Ni to nickeline. Mineral proportion were calculated using the mineral MM/ element MM ratios as illustrated in Step 1 (equation 1). The norm calculation derived nickeline concentration provides a conservative estimate for nickeline since it is based on the S-deficiency prior to the allotment of S to Cu-bearing sulfides, pyrite and galena.

Step 4: Calculating concentration of Cu Sulfides

Based on XRD, SEM-MLA and petrographic interpretations the dominant control on Cu throughout the deposit was determined to be: chalcopyrite (CuFeS2), bornite (Cu5FeS4) and chalcocite (Cu2S) (listed in descending order of abundances). The Cu-bearing mineral phase is derived using the Cu M%/ S remaining M% after accounting for the S consumption by Zn and the Ni-As phases. If the sample contains a Cu M%/ S remaining M% ratio of greater than two the mineralogical control on Cu is interpreted to be from chalcocite (Cu2S). If the sample contains a Cu M%/ S remaining M% ratio of less than two but greater than 5/4 the mineralogical control on Cu is interpreted to be from chalcocite and bornite. If the sample contains a Cu M%/ S remaining M% ratio of less than 5/4 but greater than 1/2 the mineralogical control on Cu is interpreted to be from bornite and chalcopyrite. If the sample contains a Cu M%/ S remaining M% ratio of less than 1/2 the mineralogical control on Cu is interpreted to be from solely chalcopyrite.

Relative proportions of the Cu-bearing minerals were quantified using the linear algebraic method described for in Step 3 equations 2-4. Mineral proportion were again calculated using the mineral MM/ allotted element MM ratios as illustrated in Step 1 (equation 1). Since the Cu-bearing phase is being calculated prior to the allotment of S to pyrite, pyrrhotite, and galena, there is the potential to overestimate chalcopyrite at the expense of bornite and chalcocite. This compromise is deemed the most reasonable since chalcopyrite is the most abundant Cu-bearing mineral.

Step 5: Calculating concentration of Galena

Quantifying the concentration of galena (PbS) results in a lower level of confidence due to the high and often variable Pb contents within U-bearing and gangue mineral phases. The concentration of common Pb within the deposit typically accounts for less than 0.5% of the overall concentration of Pb. Within the deposit, the vast majority of Pb is radiogenic occurring as 206Pb, 207Pb resulting from the decay of U. To account for the concentration of Pb within the U-bearing and gangue mineral phases the bulk-rock geochemical U/Pb ratio is used to identify Pb-oversaturation indicative of the Pb-bearing sulfide galena.

Step 6: Calculating Concentration of Pyrite

 Pyrite has to be calculated at the end of the norm calculation algorithm since it contains only Fe (II) and S. Pyrite cannot be differentiated based on the Fe (II) concentration since Fe-chlorite is abundant throughout the deposit. Pyrite is calculated based on the concentration of remaining S after the metals have been allotted to sulfides. Therefore, the pyrite concentration derived from the norm calculation contains more error relative to early minerals calculated with the norm calculation.

Step 7: Calculating remaining element proportion

 The remaining element concentration are calculated for As, Ni, Co, S, Cu after the elements have been balanced and the predicted minerals generated. Remaining element concentrations can be used to evaluate missing mineral phases, incorrect mineral identification and element clay absorption. Remaining element concentrations are calculated by adding all the consumed element concentration allotted to the predicted mineral. For example, the remaining Co is calculated:

Co wt.% - (Cobaltite % \* Co MM / (Co MM +As MM +S MM))