Mineralogy and geochemistry of the Madison Gold skarn deposit, Silver Star, Montana

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*Now with International Silver, Butte
Madison Gold skarn deposit

Historic Broadway Mine, Silver Star

- 1880’s to 1950’s
- ~ 150k ounces gold @ 0.32 opt

Coronado acquires property

- 2005-2006: Drilling
- 2007: Begin underground development
- 2007-2012 production*:
  - 7570 oz gold
  - 2.68 M lbs copper

Jill Sotendahl (2012) M.S. Thesis
- Mineralogy and geochemistry

* Dan Everett, pers. comm. May, 2013
Location within Montana
Boulder Batholith
Smedes et al. 1973

Butte Granite (bqm)
74.5 Ma (Lund et al., 2002)

Rader Creek Granodiorite (rc)
80.4 Ma (Lund et al., 2002)
Silver Star
Au
Ag-Cu skarn
Highlands Au skarn
Beal Au skarn
Calvert W skarn
Ivanhoe W skarn
Diamond Hill Au skarn
Elkhorn Au skarn
Highlands Au skarn
Silver Star Au-Ag-Cu skarn
Ivanhoe W skarn
Local Geology

Simplified from O’Neill et al., 1996
Prograde skarn

Retrograde skarn

“Late oxidation event”

Ore Mineralization
Prograde skarn

- **Exoskarn**: hedenbergite, garnet-diopside
- **Endoskarn**: epidote, unaltered intrusion, Fe, Si
- **Ultramafic Intrusion**: Ca, Al, Mg
- **Marble**: unaltered limestone
- **Heat**: mass transfer
Prograde Skarn

\[ \text{CaCO}_3 + \text{Fe}^{2+} + 2\text{SiO}_2(\text{aq}) + \text{H}_2\text{O} \rightarrow \text{CaFeSi}_2\text{O}_6,\text{hedenbergite} + 2\text{H}^+ + \text{CO}_2 \]
Retrograde Exoskarn

\[ \text{CaCO}_3 + \text{Fe}^{2+} + \text{H}_2\text{S} + \text{H}_2\text{O} \rightarrow \text{FeS} + \text{Ca}^{2+} + 2\text{H}_2\text{O} + \text{CO}_2 \]
Retrograde Endoskarn

- **Exoskarn**
  - Hedenbergite
  - Garnet-diopside

- **Endoskarn**
  - Epidote

- Unaltered intrusion
  - Calcium mass transfer

- Heat (Fe, Si)
  - Mass transfer (Al, Mg)

- Unaltered limestone
### Paragenesis: gangue minerals

<table>
<thead>
<tr>
<th></th>
<th>Prograde Skarn</th>
<th>Retrograde Skarn</th>
<th>Oxidation &amp; Weathering</th>
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<tbody>
<tr>
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</table>

*includes tellurobismuthite (Bi$_2$Te$_3$), tsumoite (BiTe), hedleyite (Bi$_7$Te$_3$)
Prograde Mineralization

Reflected light microscopy

SEM-Backscatter Electron Image
Retrograde Mineralization

C: clays, pyrite (cpy), pyrite (py)

D: phlogopite (phl), pyrite (py)

E: phlogopite (phl), po, cpx, hisingerite

F: pyrite (py), scheelite, po, hisingerite

Scale: 0.5 mm
Retrograde Mineralization Cont...
Late oxidation and silicification

Au-bearing jasperoid cut by calcite veins

red hematite pods (after chalcocite?)
Jasper replacing massive sulfide

Doesn’t look supergene

Photo: Dan Everett
Breakdown of hedenbergite to nontronite

\[2\text{CaFeSi}_2\text{O}_6, \text{hedenbergite} + 2\text{CO}_2 + 2\text{H}_2\text{O} = \text{Fe}_2\text{Si}_4\text{O}_{10}(\text{OH})_2, \text{nontronite} + 2\text{CaCO}_3, \text{calcite} + \text{H}_2\]
Secondary enrichment of copper

native copper pods and vein

chalcopyrite replacing pyrite
20 lb Cu nugget.
Oxidation/Weathering Event

- Fe-jasperoid with calcite stockwork
- pyrite
- pyrite pod
- "fresh" hedenbergite skarn
- Nontronite(?) zone

Redox front (moving to right with time)

- oxidized, low-T hydrothermal fluid
- Cu
- Cu²⁺
- Chalcocite
- Native copper

10 cm
# Temperature of Formation for Calcites Collected in the Mine

<table>
<thead>
<tr>
<th>Location</th>
<th>Description</th>
<th>$\delta^{18}$O of calcite VSMOW, ‰</th>
<th>$\delta^{18}$O of water* VSMOW, ‰</th>
<th>$\Delta$ calcite - water</th>
<th>Temperature °C</th>
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<td>-18</td>
<td>30.0</td>
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<td>-18</td>
<td>30.9</td>
<td>17.7</td>
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</table>
Temperature of calcite veins vs. elevation in mine.

![Graph showing temperature vs. depth]

- Zone of heating indicated.
Pyrite and pyrrhotite oxidation is \textit{exothermic} process

Pyrite + O_2 + water $\rightarrow$ H_2SO_4 + \underline{heat}

Pyrrhotite + O_2 + water $\rightarrow$ H_2SO_4 + \underline{heat}
Hypogene Oxidation Model

Water Table

Circulation and heating of O₂-rich groundwater
Summary

• Skarn mineralization
  – Pyrrhotite, pyrite, chalcopyrite
  – Electrum, Bi- and Ag-tellurides

• Late oxidation
  – Jasper (goethite-quartz) + calcite veins
  – Chalcopyrite → chalcocite, native copper
  – Gold stays put
  – “Self-heating” hypothesis?

• Source of mineralization?
  – Rader Creek pluton doesn’t look sexy enough
  – Possible Cu-porphyry at depth??
Questions?

Big thank you to Dan Everett and Coronado Resources for supporting the project and for giving Jill a job at the mine!

...and Gary Wyss for help with SEM!
Primary references
