AN OVERVIEW OF SEDIMENTARY ROCK-HOSTED STRATIFORM COPPER DEPOSITS (SSCs)

Bill Williams
18 May 2016
What are SSCs?

Why are SSCs important?

How did SSCs form?

Where did SSCs form?

When did SSCs form?

What makes an SSC ore deposit?
SSCs are zoned Cu & Cu-Fe sulfides hosted by reduced siliciclastic or dolomitic sedimentary rocks; generally parallel to stratification.

- py
- sp-ga
- cp
- bn
- cc

oxidized

hm

reduced

Boseto

Tenke

Red Cliff

Copperwood
SSCs host >15% of the known world copper inventory and constitute ~15% of world mine copper production with substantial Ag &/or Co byproducts.

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Cu, Mt</th>
<th>Cu, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCD</td>
<td>535</td>
<td>2,022</td>
<td>0.49</td>
</tr>
<tr>
<td>SSC</td>
<td>143</td>
<td>489</td>
<td>1.48</td>
</tr>
<tr>
<td>IOCG</td>
<td>77</td>
<td>122</td>
<td>1.05</td>
</tr>
<tr>
<td>Skarn/CRD</td>
<td>116</td>
<td>107</td>
<td>0.81</td>
</tr>
<tr>
<td>Magmatic</td>
<td>58</td>
<td>78</td>
<td>0.57</td>
</tr>
<tr>
<td>Cu-rich VMS</td>
<td>556</td>
<td>124</td>
<td>1.47</td>
</tr>
</tbody>
</table>

~35% of known SSCs are >500,000t of contained copper at >1% Cu.
SSCs are tabular bodies formed where Cu in oxidized, near-neutral, chloride-rich fluids passed through reduced sediments or sedimentary rocks at <250ºC

**SOURCE**
- Copper
  - footwall redbeds
  - mafic volcanics
  - pre-existing mineralization (ACB)
- Sulfur
  - seawater sulfate reduction
  - gypsum, anhydrite (cement)

**HOST ROCKS**
- Permeable

**TRAP (REDOX FRONT)**
- Pyrite
- Organic material
- Residual hydrocarbons
**Sulfur Source**

Framboidal Pyrite from bacteriogenic seawater sulfate reduction

**Redox Front**

Pyrite + Organic Material

Redstone

Cp-Bo

Sulfide after gypsum

Cu-Fe sulfide replacement of sulfates

**White Pine North**

WP-524
Upper Transition Zone
0.47% Cu

WP-522
Upper Transition Zone
3.23% Cu

10mm
SSCs formed along the margins of fault-controlled rift basins where fluids moved upwards due to sediment loading, high heat flow, uplift, etc.
Kupferschiefer-type

Host Rocks - shales, siltstones, &/or dolomites deposited in paralic environments
(Sub)vertical fluid flow
ACB, White Pine(?)

Red Bed-type (incl. Revett)

Host Rocks - sandstones deposited in continental or paralic environments
(Sub)horizontal fluid flow
Corocoro, Spar Lake, Dzezkazgan

evaporites

pre-lithification

Hm
Cc
Bn + Cp
Py

black shale
red shale, SS, conglomerate

post-lithification

dark siltstone, shale

sandstone, cong

Hm
Cc
Bn + Cp
Py

Hitzman, 2014
SSCs started forming at the onset of atmospheric oxygenation during the early Proterozoic (~2.2Ga)

<table>
<thead>
<tr>
<th>Region</th>
<th>% SSC Cu</th>
<th>Eon</th>
<th>% SSC Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACB</td>
<td>44%</td>
<td>Ceno</td>
<td>1%</td>
</tr>
<tr>
<td>Kupfer</td>
<td>36%</td>
<td>Meso</td>
<td>1%</td>
</tr>
<tr>
<td>Asia</td>
<td>14%</td>
<td>Paleo</td>
<td>44%</td>
</tr>
<tr>
<td>NA</td>
<td>5%</td>
<td>Pt3</td>
<td>45%</td>
</tr>
<tr>
<td>SA</td>
<td>1%</td>
<td>Pt2</td>
<td>5%</td>
</tr>
<tr>
<td>Aus</td>
<td>1%</td>
<td>Pt1</td>
<td>5%</td>
</tr>
</tbody>
</table>

- 175Mt Cu @ 1.15% (Permian)
- 30Mt Cu @ 1.21% (Carboniferous)
- 25Mt Cu @ 2.05% (PaleoProterozoic)
- 3.5Mt Cu @ 0.70% (MesoProterozoic)
- 2.7Mt Cu @ 1.30% (PaleoProterozoic)
- 8Mt Cu @ 1.10% (PaleoProterozoic)
- 208Mt Cu @ 2.20% (NeoProterozoic)
- 16Mt Cu @ 1.30% (MesoProterozoic)
- 3Mt Cu @ 0.85% (MesoProterozoic)
- 6Mt Cu @ 2.50% (Cambrian?)

Region: ACB 44% Ceno 1% Kupfer 36% Meso 1% Asia 14% Paleo 44% NA 5% Pt3 45% SA 1% Pt2 5% Aus 1% Pt1 5%
SSC - Rodinia Rifting

~880Ma

Global Ice Age, i.e., “Snowball Earth”, resulted in isolated reducing basins where SSCs developed

De Waele, et al., 2008
SSC - Central African Copper Belt

Kamoa
966Mt @ 2.50% Cu

Zone 5
100Mt @ 1.95% Cu

Dolomite- & Siltstone-hosted; Bn-Cp ores (w/ Co)

Shale-hosted Bn-Cc ores (w/ Ag)
Global Ice Age, i.e., “Snowball Earth”, resulted in isolated reducing Basins where SSCs developed.
SSC - Pangea Rifting

Hitzman, et al., 2010

Laurentia

Land

Panthalassic Ocean

continental sediments
continental margin shelf

Ural foldbelt

periodic ingress of marine water to basin

continental platform

carbonate platform

Zechstein Basin

periodic ingress of marine water to basin

German, Polish Kupferschiefer districts

continental margin shelf

Tethys ocean floor

Sahara Platform

1000 km

Land
A Recipe for (Super)Giant SSC Deposits

Hitzman, 2014

- Intracontinental rift basins with occasional marine incursions
- Host rocks overlain by evaporites
  - Brines increase sulfur budget
- Long-lived, evolving basin
  - Closed system
  - Fluids passed through various stratigraphic levels (esp. ACB)
  - Large alteration footprint
- Superposed events
**SSC - African Copper Belt (Cu-Co)**

- **DRC Kamoia area**
  - Mwashya (shallow marine, sandy facies)
  - Kamoia

- **DRC Mines Series Basin**
  - Nguba
  - Kakontwe Lms.
  - Grand Conglomerat

- **Zambian Copperbelt**
  - Lomishi
  - Kansanshi
  - Frontier
  - Sentinel
  - Upper Roan
  - Lower Roan
  - Konkola
  - Lumwana

- **Central Zambian Basin**
  - Mwashya gabbros (750 Ma)
  - Hook igneous suite (600 Ma)

**Jequitai diamictite?**
SSC - Alteration

Albite + Fe-Dolomite (Kansanshi)

Potassic Alteration
Sodic Alteration
Copper Deposit

Ksp-Dolomite (Nkana)
SSC - Kupferschiefer (Cu-Ag) - Rote Faule

Native Cu

Calumet Cgl, Michigan

Hm

fluid flow

fluid flow

fluid flow

fluid flow

200 km

Gesen Permian Basin

Aderstedt-Bernburg

S. Brandenburg

Lubin

Kaleje

FSM

FSB

Sulmierzyce

Holy Cross Mtns

Variscan Basement
SSC - Alteration (Western Syncline)

![Graph showing mineral alteration]

- **Ab + Kspr**: Ab + Kspr (Ab = Albite, Kspr = K-feldspar)
- **Illite + Smectite**
- **Kaolinite + Chlorite**
- **(Na+K)/Al (molar)**
- **(2Ca+Na+K)/Al (molar)**

Legend:
- **Blue**: Unmineralized
- **Red Diamond**: Mineralized

Mineralization path:
- **Pre-mineral (Illite + Smectite)**
- **Mineralization to Ab + Kspr + Illite + Smectite**

SIMEXMIN 2016

Metallorum LLC
**Room-and-Pillar (>2.2m thick) = US$45/t ore**

- Mining = US$20/t ore
- Processing = US$10/t ore
- G&A = US$ 5/t ore
- Con Sales = US$10/t ore

*varies due to forex, energy & labor costs, etc.*
**SSC - Economic Considerations**

**ZONE 5, Botswana**

Sublevel Stoping (>2.2m wide) = US$60/t ore*

- Mining = US$35/t ore
- Processing = US$10/t ore
- G&A = US$5/t ore
- Con Sales = US$10/t ore

*varies due to forex, energy & labor costs, etc.
### CuEq Head Grade

<table>
<thead>
<tr>
<th>Cu Price</th>
<th>1.00%</th>
<th>1.20%</th>
<th>1.40%</th>
<th>1.60%</th>
<th>1.80%</th>
<th>2.00%</th>
<th>2.20%</th>
<th>2.40%</th>
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</thead>
<tbody>
<tr>
<td>$2.00</td>
<td>$2.00</td>
<td>$34</td>
<td>$40</td>
<td>$47</td>
<td>$54</td>
<td>$61</td>
<td>$67</td>
<td>$74</td>
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<tr>
<td>$2.50</td>
<td>$2.50</td>
<td>$42</td>
<td>$51</td>
<td>$59</td>
<td>$67</td>
<td>$76</td>
<td>$84</td>
<td>$93</td>
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<tr>
<td>$3.00</td>
<td>$3.00</td>
<td>$51</td>
<td>$61</td>
<td>$71</td>
<td>$81</td>
<td>$91</td>
<td>$101</td>
<td>$111</td>
</tr>
</tbody>
</table>

*In situ* value of mineralization - assumes 15% dilution/ore loss, 90% recovery

![Graph showing net in situ value vs. Cu grade and price](image)
SUMMARY

• SSCs are formed by the passing of Cu in oxidized fluids through reduced lithologies
  • Early diagenetic and later

• Rift-controlled basins under anoxic conditions
  • Especially Neoproterozoic and Permian

• (Super)giant deposits formed in closed systems
  • Overlying evaporites contain fluid flow (& add S)
  • Superposed events common

• Target >2.2 meter thickness with >1% CuEq
SSC Potential in Brazil

- Jequitai diamictite (~746 ma)
- Older sequences?
- No platform facies for Cu
- Pb-Zn deposits