Alteration facies in ‘IOCG terranes’: a global view on mineral systems with IOCG and affiliated deposit types

L. Corriveau and E.G. Potter, Geological Survey of Canada
J.F. Montreuil, Red Pine Exploration
O. Blein, BRGM; K. Ehrig, BHP-Olympic Dam; A. Fabris and A.J. Reid, GSSA

Discovery Day, 2019
Acknowledgment and recommended citation

This presentation for the Geological Survey of South Australia Discovery Day 2019 meeting will be updated further, expanded and submitted for formal publication within the Scientific Presentation Series of the Geological survey of Canada and will be available for free download through GEOSCAN (http://geoscan.nrcan.gc.ca/).

The slides summarise research on the geology of iron-oxide and alkali-calcic alteration mineral systems and their IOCG and affiliated deposits undertaken at the Geological Survey of Canada by the Targeted Geoscience Initiative and the Geomapping for Energy and Minerals programs in collaboration with Canadian territorial and provincial surveys, the Geological Survey of South Australia, academia and private sector.

The authors acknowledge Dr. Chris Lawley for his review of this presentation. We also acknowledge the late Dr. Sunil Gandhi and Dr. Patrick Williams who served as key IOCG mentors to the first two authors. We follow in their footsteps. Additional acknowledgments can be found at slide 33.

Recommended citation

Acronyms and abbreviations

IOCG-iron oxide copper-gold deposits; IOA-iron oxide±apatite deposits
IOAA-iron oxide alkali-calcic alteration systems; Grp-group
HT-high temperature; LT-low(er) temperature
REE-rare-earth elements and Y; BIF-banded iron formation (sedimentary)
MLYRMB-Middle-Lower Yangtze River metallogenic belt
BIF-banded iron formation

Minerals
Ab-albite, Act-actinote, Amp-amphibole, Ank-ankerite, Ap-apatite,
Apy-arsenopyrite, Bn-bornite, Brt-barite, Bt-biotite, Cb-carbonate, Cal-calcite,
Ccp-chalcopyrite, Cct-chalcocite, Chl-chlorite, Cpx-clinopyroxene, Ep-epidote,
Fl-fluorite, Grt-garnet, Hbl-hornblende, Hem-hematite, Kfs-K-feldspar,
Mag-magnetite, Pl-plagioclase, Py-pyrite, Rt-rutile, Scp-scapolite, Sd-siderite,
Ser-white mica (sericite), Sp-sphalerite, Sul-sulphides, Ttn-titanite
(Whitney and Evans 2010)

N.B. Previously published figures included in this presentation are veiled by a figure caption referring to their source publication. This editorial choice is prompted by the importance of linking the abundant and more detailed illustration of the mineral systems provided in this presentation with our published description and discussion of the systems.
The Great Bear magmatic zone, Canada, as a case example

IOCG’s in large mineral systems that evolve to distinct deposit types through a regular sequence of alteration facies

Disruption = fluid and magma ingress, tectonic activity, volcanism

Spectrum of base, precious and critical metals, U, Th, etc.

Alteration facies: metal pathways to ore

Mappable criteria for mineral potential assessment

Hildebrand et al. (1987, 2010); Mumin et al. (2007, 2010, 2014); Corriveau et al. (2010a, b, 2016); Jackson et al. (2013); Mumin (2015); Montreuil et al. (2016a, b, c); Ootes et al. (2017)
Well exposed and preserved mineral systems from bottom to top

Hosts well preserved where least altered (1.88 Ga metasedimentary rocks)

Iron oxide and alkali-calcic alteration (IOAA) preserved (albitite replacing 1.87 Ga andesite)

Undeformed, unmetamorphosed, 1868 Ma dykes cutting 1873-1868 Ma mineral systems

Hildebrand et al. (1987, 2010); Mumin et al. (2007, 2010); Corriveau et al. (2010a, b, 2016, 2018b); Davis et al. (2011); Montreuil et al. (2016a, b, c)
Albitite replaces any host rocks

Hildebrand (1986); Reardon (1992); Corriveau et al. (2010b, 2014); Montreuil et al. (2015); Mumin (2015); Potter et al. (2019)
Albitite breccia

Ab haloes along fractures

Fractures
Kinks
Breccia

Ab → Porosity

Bt breakdown

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Corriveau et al. (2011); Montreuil et al. (2015); Potter et al. (2019)
High temperature (HT) Na-Ca-Fe alteration

Stratabound-selective
Pervasive
Vein+halo

Corriveau et al. (2010a, b, 2016); Mumin et al. (2010)
Replaces carbonate, can precipitate Fe, Pb, Zn
Cuts and replaces albitite
No causative intrusion (heat = fluid plume)

HT Ca-Fe Facies
• Systematically replaces skarn
• Must be mapped separately from skarn!
• Leads to iron oxide±apatite deposits ± HREE
HT Ca-Fe alteration: can preserve host textures extremely well

Resembles BIF

Corriveau et al. (2010b, 2016, 2018b); Montreuil et al. (2016a, b)
Veins, shears, folds, breccia, replacement, ore

Ductile: folding at HT Ca-Fe

Vein+ stratabound halo

Mumin et al. (2010, 2014); Corriveau et al. (2016, 2018b); Montreuil et al. (2016a, b)
Selective magnetite alteration of albitite clasts in albitite breccia
Au-Co-Bi IOCG variants

HT Ca-K-Fe

Amp-Bt-Mag-Kfs
Amp-Kfs-Mag
Amp-Bt-Mag
Amp-Bt

Sul: Co-Apy, Co-Py, Py, Po
Metals: Au, Co, Bi, W

Magnetite-group

IOCG

HT K-Fe

Kfs-Bt-Mag
Kfs-Mag
Bt-Mag
Bt

Chalcopyrite

Goad et al. (2000a, b); Corriere et al. (2010b, 2016, 2018b); Mumin et al. (2010); Acosta-Góngora et al. (2015a, b, 2018); Montreuil et al. (2016b)

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K-skarn at HT to Low Temperature (LT) K-Fe alteration

In carbonate alteration at Mag to Hem transition following fluid-induced temperature rise or in carbonate hosts

Sul: sphalerite, galena, chalcopyrite

Photo courtesy of Monax Mining

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Hem-IOCG

Kfs-Hem
Ser-Hem
Ser-Kfs-Hem
± Brt, Fl, Qz, Cb

Cu

\( \text{U}_3\text{O}_8 \) (ppm)

0-100
100-200
200-500
500-1000
1000-10^6

Source BHP-Olympic Dam

CORRIEVAU et al. 2019

Ehrig et al. (2012, 2017a, b); Corriveau et al. (2016, 2018b)
**Albitite-hosted U/Au-Co**

<table>
<thead>
<tr>
<th>LT Ca-Fe-Mg</th>
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<tbody>
<tr>
<td>Chl-Hem</td>
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<tr>
<td>Chl-Cb-Hem</td>
</tr>
<tr>
<td>Chl-Hem ± Kfs±Cb±Ser</td>
</tr>
<tr>
<td>Cb-Mag/Hem</td>
</tr>
<tr>
<td>Cb, Ep</td>
</tr>
</tbody>
</table>

**Epithermal cap, phyllic gossan, vein-type mineralisation**

- **Cu, Ag, Pb, Zn**
- **Gossan Island**
- **Port Radium-Echo Bay district**

Photo courtesy of A. H. Mumin

**Molybdenite vein (NICO)**

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Simplified analogy: A chain reaction!

Trigger: ascent of large volumes of hypersaline fluids

Driver: High disequilibrium between fluids and host rocks self-sustaining + propagating

Mineral stability → precipitates from fluids

Mineral instability → dissolved → elements move to fluids

Each facies = diagnostic assemblages + composition ranges

Molar proportions from whole-rock geochemical analysis

Igneous + sedimentary rocks

IOAA metasomatites:
1-3 dominant cations
Strong coupling/decoupling of cations and metals

3-4 dominant cations (except rhyolite)
Prograde path, ore mineralogy and metal associations

Alteration facies

Lower T
Younger
Shallower

<250°C
LT Si, K, Al, Ba, CO₂

250-350°C
LT K-Fe-H⁺ – Ca-Fe-Mg-CO₂
K-felsite breccia
K-skarn breccia (in Cb)

Ascending
compositionally
evolving
fluid plume

350-450°C
HT K-Fe

400-800°C
HT Ca-K-Fe
HT Ca-Fe
HT Na-Ca-Fe
Skarn (in Cb)

Higher temperature (HT)
Older, Deeper
Hypersaline

400-600°C
Na-Ca
Na

Mineralisation

Sul, U-, Th-, REE-, Mo-, Re-minerals
Metals from host system
Cu-Sul (Ccp, Bn, Cct), REE-, U-minerals,
Cu-Ag-Au-LREE-U-Bi-W-Mo
Barren (host for veins)
Zn-Pb-Cu-Sul, Au, Cu-Pb-Zn-Ag-U

Cu-Sul (Ccp), Cu-Ag-Au-Co-Bi
/ Fe-REE-Y-U-Th
Co-Sul (Apy, Py), Au-Co-Bi-Ni (F)
REE Ap, Mag (in systems with K)
Mag, Fe-V-Th-W (P-Cl-F)
Barren
Fe, Zn-Pb-Sul, decarbonation

Ground preparation (porosity, damage zones), metal source, ± decarbonation

Cations

\( \text{Na}, \text{Ca}, \text{Fe}, \text{K}, \text{Mg} \)
**To each facies, its own deposit type**

<table>
<thead>
<tr>
<th>Alteration facies</th>
<th>Deposit types</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower T Younger Shallower</td>
<td>Epithermal, polymetallic veins</td>
</tr>
<tr>
<td></td>
<td>Central Andes, Great Bear, Olympic Dam, Merlin (Mo-Re)</td>
</tr>
<tr>
<td>250-350°C</td>
<td>Hematite-group IOCG</td>
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<tr>
<td></td>
<td>Olympic Dam, Prominent Hill, Carrapateena, Oak Dam</td>
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<tr>
<td>350-450°C</td>
<td>Polymetallic K-skarn (+Mag-to-Hem Grp IOCG)</td>
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<tr>
<td></td>
<td>Hillside, Punt Hill, Mile, Candelaria, Mt Elliott</td>
</tr>
<tr>
<td>400-800°C</td>
<td>Magnetite-group IOCG</td>
</tr>
<tr>
<td></td>
<td>Ernest Henry, Sue Dianne, Salobo, Candelaria, Dahongshan</td>
</tr>
<tr>
<td>400-600°C</td>
<td>Co-Au-Bi IOCG variant</td>
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<td>NICO, Idaho Cobalt belt, Guelb Moghrain</td>
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<tr>
<td>400-600°C</td>
<td>IOA + REE Pea Ridge, Josette, Bayan Obo</td>
</tr>
<tr>
<td>Higher temperature (HT) Older, Deeper</td>
<td>NA + Ca Fe</td>
</tr>
<tr>
<td>Hypersaline</td>
<td>Skarn (in Cb)</td>
</tr>
<tr>
<td></td>
<td>Na-Ca</td>
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<tr>
<td></td>
<td>Fe skarn</td>
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<td></td>
<td>Middle-Lower Yangtze River Metallogenic Belt (MLYRMB)</td>
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<td></td>
<td>Preferential host for albiteite-hosted U, ± IOCG</td>
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<td></td>
<td>+ indicator of potential IOAA mineral systems: Cloncurry - Mt Isa, Great Bear</td>
</tr>
<tr>
<td></td>
<td>Fe skarn</td>
</tr>
<tr>
<td></td>
<td>Bambles, Gawler, Central Andes, El Laco, Kiruna</td>
</tr>
</tbody>
</table>

**Corriveau et al. 2019**

*Modified from Corriveau et al. (2010b, 2016, 2018b); Slack et al. (2013); Fabris et al. (2018a, b); BHP (2018, 2019); References listed in Corriveau et al. (2018b)*
IOA at HT Ca-Fe = High heat ingress

REE ore = orogenesis or magmas

Phyllic (K) / vein, breccia
Rapid cooling = Hem, Cb (Sd, Ank, Cal)
Oxidation = Mag to Hem

HT K-Fe

HT Ca-Fe  400-800°C
HT Na-Ca-Fe
Skarn (in Cb)
Na-Ca
Na

REE ore
Josette veins
Pea Ridge breccia

Late stage fluids remobilise REE into ore

LT fluids

Magnetite-group IOCG
Josette, Boss Bixby, K2 Norrex

IOA + HREE
Terra, Pea Ridge, Josette

IOA
Mag Hill, MLYRMB
Fe skarn
MLYRMB

High T gradient
Diorite

HT fluids
Magmatism

Clark et al. (2005, 2010); Magrina et al. (2005); Corriveau et al. (2010b, 2016, 2018b); Rusk et al. (2010); Bowdidge et al. (2014); Somarin and Mumin (2014); Perreault and Lafrance (2015); Aleinikoff et al. (2016); Day et al. (2016); Focus Graphite (2018)
Au-Co-Bi IOCG variants: HT Ca-K-Fe in sedimentary hosts

NICO, Idaho Cobalt belt, Guelb Moghrine

- LT Si, Ba, CO$_2$
- LT K-Fe-H$^+$-Ca-Mg-CO$_2$

K-felsite

- HT K-Fe Kfs-Mag
  - 350-450°C

- HT Ca-K-Fe
  - 400-800°C

- HT Ca-Fe
  - 400-800°C

- HT Na-Ca-Fe
  - Skarn in carbonate host
  - Na (±Na-Ca)

Magnetite-group IOCG in overlying volcanic rocks
Mag-Bt-Kfs-Ccp Cu-mineralisation at NICO

Repeated dyking + tectonics = renewed heat + HT resetting of fluid
plume conditions = HT Ca-Fe to HT Ca-K-Fe over and over again

NICO: a cycle of
- Amp-Mag-Bt-Kfs-Apy
- Amp-Bt-Mag±Kfs
- Amp-Mag

Ascending (and evolving) fluid plume

Goad et al. (2000a, b); Corriveau et al. (2010b, 2016); Enkin et al. (2012); Slack (2013); Acosta-Góngora et al. (2015a, b, 2018); Kirschbaum and Hitzman, 2016; Montreuil et al. (2016b); Fortune Minerals (2019)
Magnetite-group IOCG: Kfs clasts + magnetite infilled breccia

- **LT Si, K, Al, Ba**
- **LT Fe-Ca-CO₂**
- K-felsite breccia
- K-skarn breccia

**450-350°C**
- HT K-Fe Kfs-Mag
- HT K-Fe Bt-Mag
- HT Ca-K-Fe

Evolved directly from HT K-Fe to reduced LT Ca-Fe (Cal-Mag)

Repeated ingress of Kfs-Mag-Ccp
- Bt-Mag-Ccp
- Bt-Kfs-Mag-Ccp

**Cb-Mag-Ccp fluidised breccia**
- Local Hem alteration of Mag
- K-felsite halo along HT K-Fe breccia body

Magnetite-group IOCG in breccia
- Co-rich pyrite within ore zone

**HT Ca-Fe**
- HT Na-Ca-Fe
- Skarn in carbonate host
- Na (±Na-Ca)

Mag infill in albitite breccia, vein, replacement
- Local skarn
- Ground preparation, metal source + decarbonation of carbonate unit

Ascending (and evolving) fluid plume

Ernest Henry

Oliver et al. (2004, 2008, 2009); Mark et al. (2006); Corriveau et al. (2010, 2016, 2018b); Lily et al. (2017); Cave et al. (2018)
Magnetite to Hematite-Group, polymetallic K-skarn, Hematite-Group IOCG

LT Si, K, Al, Ba, CO₂
LT K-Fe-H⁺ – Ca-Fe-Mg-CO₂
K-felsite breccia
K-skarn breccia (in Cb)
HT K-Fe
HT Ca-K-Fe
HT Ca-Fe
HT Na-Ca-Fe
Skarn (in Cb)
Na-Ca
Na

Epithermal, polymetallic veins
Hematite-group IOCG (OD, Prominent Hill, Carrapatena, Oak Dam west)
Mag-Hem IOCG and skarn (Hillside)
Polymetallic K-skarn (Punt Hill)

Photo courtesy of Monax Mining

Conor et al. (2010); Corriveau et al. (2010, 2016, 2018b); Reid et al. (2011); Ehrig et al. (2012, 2017a, b); Ismail et al. (2014); Schlegel et al. (2015, 2018); BHP (2018, 2019); Fabris et al. (2018a, b)
Metasomatic reaction paths for albitite-hosted U / Au-Co-Cu

- **LT Si, K, Al, Ba, CO₂**
  - LT Ca-Fe-Mg-CO₂
  - LT K-Fe-H⁺
  - K-felsite breccia
  - K-skarn breccia (in Cb)

- **HT K-Fe**
  - HT Ca-K-Fe
  - HT Ca-Fe
  - HT Na-Ca-Fe
  - Skarn (in Cb)
  - Na-Ca

- **Na**

Differential uplift with telescoping of alteration facies and / or

Collapse of system through cooling or ingress of LT fluids and / or

Low T gradient due to lack of coeval magmatism within parts of the system

Modified from Corriveau et al. (2018b); see also Corriveau et al. (2011, 2014, 2016, 2018a); Wilde (2013); Montreuil et al. (2015, 2016b); Hayward et al. (2016); Acosta-Góngora et al. (2019); Potter et al. (2019)
Metasomatic reaction paths for vein-type mineralisation

- Fluid circulation during collapse of IOAA system
- Ingress of low temperature fluids
- Active tectonics
- Polymetallic veins with metals derived from IOAA systems

- Renewed fluid circulation (magmatism, orogenesis, unconformity)
- LT fluids remobilisation of IOAA metals
- Polymetallic veins with metals derived from IOAA systems
- Five-element veins
- REE ore
- ‘Orogenic’ Au-Co-U in albitite

Ascending (and evolving) fluid plume

- LT Si, K, Al, Ba, CO₂
- LT Ca-Fe-Mg-CO₂
- LT K-Fe-H⁺
- K-felsite breccia
- K-skarn breccia (in Cb)
- HT K-Fe
- HT Ca-K-Fe
- HT Ca-Fe
- HT Na-Ca-Fe
- Skarn (in Cb)
- Na-Ca
- Na

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Corriveau et al. (2014, 2018a, b); McLaughlin et al. (2016); see also Oliver et al. (1999); Mumin et al. (2007, 2010)
Chemical footprints: Alteration index, box plot, Na-Ca-K-Fe-Mg barcodes

Modified from Figure 4 in Corriveau et al. (2017)

Prograde path: Great Bear+OD intense alteration

Corriveau et al. 2019

Montreuil et al. (2013); Corriveau et al. (2015, 2017, 2018a, b); Blein and Corriveau (2017)

Source of data: BHP-Olympic Dam

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Sue Dianne deposit Resources
8.4 Mt @ 0.80% Cu, 0.07 g/t Au, 3.2 g/t Ag

See Figure A5 in Montreuil et al. 2016b

Goad et al. (2000a, b); Hennessey and Puritch (2008); Corriveau et al. (2016, 2018); Mumin et al. (2010); Montreuil et al. (2016b)
Rock physical properties

Modified from Enkin et al. (2016)
Economic Geology, v. 111
**Ore system and potential deposit types**

**Lower T, younger, shallower**
- 250-350°C
  - LT Si, K, Al, Ba
  - LT Ca-Fe-Mg-H⁺-CO₂
  - LT K-Fe±Si-H⁺-CO₂
  - K-felsite bx
  - K-skarn bx in Cb or earlier Cb alteration

250-350°C
- HT K-Fe
- HT Ca-K-Fe
- HT Ca-Fe (→ K in system)

350-450°C
- HT Ca-Fe
- HT Na-Ca-Fe
- Skarn in Cb host

**Higher T, older, deeper (unless telescoped)**
- 400-800°C
  - HT Ca-Fe
  - HT Na-Ca-Fe
- 400-600°C
  - Na (± Na-Ca)
- 2-10 km

**Epithermal, veins**
- Metals from host system

**Hematite-group IOCG**
- Cu-Ag-Au-LREE-U-Bi-W-Mo
- Olympic Dam, Prominent Hill

**Polymetallic K-skarn**
- (+ Mag-to-Hem Grp IOCG)
- Cu-Pb-Zn-Ag-U Hillside, Punt Hill, Mile

**Magnetite-group IOCG**
- Cu-Ag-Au-Co-Bi / Fe-REE-Y-U-Th
- Ernest Henry, Manxman, Sue Dianne, Dahongshan

**Co-Au-Bi IOCG variant**
- Au-Co-Bi-Ni (K-F) NICO, Idaho Co belt

**IOA + REE**
- Pea Ridge, Josette, Bayan Obo
- IOA Fe-V-Th-W (P-Cl-F)
- Kiruna, El Laco, MLYRMB, Cairn Hill

**Fe skarn**
- MLYRMB

**Remobilization + Telescoping**
- + Mixing with fluid column
- + Tectonic and volcanic activity

**New LT fluids + metals**

**New HT fluids**
- Magmas, metals

**Pea Ridge, Josette (Kwyjibo), Bayan Obo**

**Valtalian, Central Mineral Belt**

**Five elements Port Radium**

**REE mineralisation in IOA**

**Ernest Henry, Manxman, Sue Dianne, Dahongshan**

**Dahongshan Cu-Ag-Au-Co-Bi / Fe-REE-Y-U-Th**

**Pea Ridge, Josette, Bayan Obo**

**Corriveau et al. (2016, 2018b)**
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DEMCo, Diamonds North, Aurora Geosciences

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Fieldtrip: Oliver et al. SGA 2009 (Cloncurry), Day et al. (Missouri), Chávez and Petersen SEG (Chili), Tornos SGA 2011 (El Laco), GSSA and Rex Minerals (South Australia), X.-F. Zhao (Kangdian, MLYRMB); additional photos: Monax Mining, Ernest Henry Mine, A.H. Mumin

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Available at GAC.ca

A new IOCG volume coming soon!

Editors:
Louise Corriveau and Hamid Mumin

Geological Association of Canada
Short Course Notes 20