Alteration facies of IOA, IOCG and affiliated deposits: Understanding the similarities Recognising the diversity in these ore systems

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Acknowledgments 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.

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Recommended citation

Acronyms and abbreviations

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

Minerals
Ab-albite, Act-actinolite, Amp-amphibole, Ank-ankerite, Ap-apatite,
Apy-arsenopyrite, Bi-bismuthinite, Bn-bornite, Bt-barite, Bt-biotite, Cb-carbonate,
Cal-calcite, Ccp-chalcopyrite, Cct-chalcocite, Chl-chlorite, Cpx-clinopyroxene,
Ep-epidote, Fl-fluorite, Gn-galena, Grt-garnet, Hbl-hornblende, Hem-hematite,
Ilm-ilmenite Kfs-K-feldspar, Mag-magnetite, Mol-molybdenite, Pl-plagioclase,
Py-pyrite, Qz-quartz, Rt-rutile, Scp-scapolite, Sd-siderite, Ser-white mica (sericite),
Sp-sphalerite, Sul-sulphides, Ttn-titanite, Tur-tourmaline, Urn-uraninite (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.

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The Great Bear magmatic zone, Canada, as a case example

Similarities: evolution of mineral systems through a regular sequence of alteration facies

Differences: each alteration facies leads to distinct deposit types and critical, base and precious metal, U and Th associations

Alteration facies: fluid and metal pathways to ores; help prognosticate fault zones & understand rock physical properties, etc.

Disruption: fluid and magma ingress, tectonic and volcanic activities

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
IOA systems of the Great Bear magmatic zone

Epithermal caps + Hem-Qz±Ba vein, replacement and breccia:
Echo Bay Gossan, Port Radium, NICO, East Hottah, Hem Fe zone, etc.

IOCG: Hem to Mag IOCG Cu-Au-Ag Sue Dianne deposit, Brooke prospect
Mag-IOCG zones in and above Au-Co-Bi NICO deposit, Fab prospect

IOCG variants and affiliated deposits
Au-Co-Bi IOCG variant, NICO deposit
Albitite-hosted U (Mo-Cu), Southern Breccia
Pb-Zn skarn, Southern Great Bear, Grouard

IOA (Iron Oxide-Apatite): Fe ±V-LREE, Camsell River, Port Radium-Echo Bay, etc.

Mag Hill: Ab to IOA to Hem to epithermal cap

Diorite (deeper)

Longitudinal expression of system

Paleosurface epithermal cap (Cu-Ag-Pb-Zn)
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) well preserved (albitite replacing 1.87 Ga andesite)

Undeformed, unmetamorphosed, 1.868 Ma dykes cutting 1873-1868 Ma mineral systems

Hildebrand et al. 1987, 2010; Mumin et al. 2007, 2010; Corriveau et al. 2010a, b, 2016, 2018; Davis et al. 2011; Montreuil et al. 2016a, b, c
Selective to texture-destructive alteration
Can be difficult to fully appreciate epigenetic origin of alteration minerals

See Figure 14 in Corriveau et al. 2010b, Geological Association of Canada, Short Course Notes 20
Extensive iron oxide and alkali-calcic alteration

Wide diversity of
- alteration assemblages and mineral contents
- grain sizes, textures, intensity of alteration
- density of veins and types of breccia

Regular to cyclical or telescoped sequences of crystallisation

Mapping: complex and non-intuitive without appropriate tools

Mumin et al. 2007, 2010; Corriveau et al. 2010b, 2016, 2018b; Montreuil et al. 2015, 2016b, c; see also Corriveau et al. 2018a for IOAA systems metamorphosed to granulite
Mineral assemblages grouped into alteration facies

The sum of the iron oxide alkali-calcic facies accounts for the development of the entire mineral systems (other alteration facies needed for epithermal caps)
Albitite replaces any host rocks
Patchy to pervasive albitisation

First generations of albite (white Ab1) regularly cut by pink Ab2
‘Pink’ hue distinct for albite (pink), K-feldspar (reddish-brown), hematite (brown)
Incipient brecciation of albittite

Stratabound Ab1
Haloes along fractures

Ab1
Ab2

1 cm

Stratabound Ab1
Kinks
Set of parallel fractures

© Her Majesty the Queen in Right of Canada as represented by the Minister of Natural Resources, Corriveau et al. 2011; Montreuil et al. 2015; Potter et al. 2019

Ab → High porosity

Bt breakdown
Porosity increases during albitisation

Porosity is critical to brecciation, fluid flow and subsequent alteration, and mineralisation of albitite

Porous albitite

Crystallisation of hydrothermal zircon and rutile due to relative enrichment of Zr, Nb, Ta, Sn in albitite

Pores filled with uraninite, brannerite, davidite, coffinite

Albitisation leaches metals
Albitite subsequently mineralised in U, Cu, Au, etc.

See Potter et al. (2019)

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Albitite breccia: Preferential ground preparation for subsequent alteration

See Montreuil et al. 2015

Tourmaline

Ab1

Kfs

Stratabound Ab of clasts

Skarn infill

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Natural Resources Canada

Corriveau et al. 2010b; Montreuil et al. 2015, 2016b; Kelly et al. 2020
HT Na-Ca-Fe alteration

- Ab-Amp
- Ab-Amp-Mag
- Ab-Amp-Ap
- Ab-Amp-Mag-Ap

Stratabound-selective
Pervasive
Vein+halo

Lichen

Ab
Amp
Mag

Ap
Amp

1 cm
Kfs

Ab
Amp

2 cm

Ab
Amp
Mag
Ab-Amp-Mag-Ap replacement of andesite

See

Corriveau et al. 2010a, b
Porphyritic andesite pervasively replaced by a pegmatitic Ab-Amp-Ap-Mag alteration facies

See Corriveau et al. 2010a, b
Skarn

- Cpx-Grt
- Cpx ± Scp
- Grt

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

Albitite + albitite breccia

Knox 1998; Neale et al. 1997; Corriveau et al. 2016, 2018b; Montreuil et al. 2016b
Stratabound HT Ca-Fe alteration

Ab → Kfs

Resembles BIF

Amp

Mag along shear

10 cm

Corriveau et al. 2010b, 2016; Montreuil et al. 2016b
Veins, shears, folds, breccia, replacement

Mag
Ab
Amp

Mag
Ab
Amp

Mag

Vein+ stratabound halo

Mag

Ductile: folding at HT Ca-Fe

Mag

IOA breccia

Mag

Amp

Amp

Ab

Mag

10 cm

5 mm

Mumin et al. 2010, 2014; Corriveau et al. 2016, 2018b; Montreuil et al. 2016a, b; Potter et al. 2019
In situ replacement of albitised andesite matrix by magnetite
(plagioclase phenocrysts of andesite are albitised)

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Corriveau et al. 2010b, 2016; Mumin et al. 2007, 2010;

See Corriveau et al. (2010b)
Selective magnetite alteration of albitite clasts in albitite breccia

Host rock is a metasiltstone moderately to completely albitized and brecciated. Breccia matrix and clasts are replaced by magnetite.
Mag-altered andesite breccia, El Laco, Chili
IOA breccia

See Corriveau et al. (2016) Economic Geology, v. 111

Fluidised IOA breccia

Albitite breccia

Photo courtesy of DEMCo
HT Ca-K-Fe facies
Au-Co-Bi±Cu IOCG variants

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

+ sulphides: Co-Apy, Co-Py, Py, Po
+ metals: Au, Co, Bi, W

Metasiltstone replaced by Amp-Mag assemblages (HT Ca-Fe), then by HT Ca-K-Fe alteration and Apy-bearing mineralisation. And then back to HT Ca-Fe facies with Mag vein.

Goad et al. 2000a, b; Corriveau et al. 2010b, 2016, 2018b; Mumin et al. 2010; Acosta-Góngora et al. 2015a, b, 2018b; Montreuil et al. 2016b
Identifying cryptic or confusing K and K-Fe alteration in the field

Gamma-ray spectrometers (U-Th-K) are a useful tool

Mag + Biotite
$K_2O = 4 \text{ wt } \%$
$U = 4 \text{ ppm}$

See Corriveau et al. 2010b, Geological Association of Canada, Short course notes 20

K-feldspar
$K_2O = 7 \text{ wt } \%$
$U = 7 \text{ ppm}$
HT Ca-Fe-K + associated brecciation

Amp-Mag = Ccp precipitation

Kfs, Ep

See Corriveau et al. 2010b, Geological Association of Canada, Short course notes 20

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Magnetite-group IOCG
Chalcopyrite

Kfs halo to Mag breccia

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

Mag-Ccp in matrix
Kfs replaces fragments

See Figure 10 in Mumin et al. 2010, Geological Association of Canada, Short course notes 20

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K-feldspar-rich K-Fe = brecciation + chalcopyrite precipitation

Ccp veins + breccia infills form as soon as Kfs-rich HT K-Fe alteration forms

In thin sections, Ccp veins cut K-Fe assemblage but mapping shows Ccp precipitation is intimately associated with the development of the HT through LT K-Fe facies
K-Fe (K-feldspar) alteration
Port Radium–Echo Bay district

Lichen

K$_2$O = 6 wt %
Fe$_2$O$_3$ = 11 wt %
Ce = 9249 ppm
U = 12 ppm

Mag to Hem transition

K$_2$O = 6.4 wt %
Fe$_2$O$_3$ = 5 wt %
U = 4 - 8 ppm

Lichen

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Canada
K-felsite breccia

See Corriveau et al. 2010b

Stained sample

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K-skarn at the HT to LT K-Fe alteration

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

K skarn

Cpx-Kfs ± Ep
Grt-Kfs
Cpx-Grt-Kfs

Sul: sphalerite, galena, chalcopryrite
Great Bear
Mag to Hem-IOCG

Kfs-Hem
Ser-Hem
Ser-Kfs-Hem

LT K-Fe to Fe-Si-Ba-CO₂

Hem-Qz
Hem-Cb-Qz
Hem-Qz-Ba

Sue Dianne

1 cm

Stained

Kfs
Hem

Fe Zone

PL → Qz
Hem

Lichen

273

5 cm

Corriveau et al. 2010b, 2016; Mumin et al. 2010

Fe Zone

5 cm

Hem
Hem-IOCG, Olympic Dam

LT K-Fe

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

U$_3$O$_8$ (ppm)

Cu

0-100
100-200
200-500
500-1000
1000-10$^4$

1km

Hem-Ser

Olympic Dam, collection of P. Williamsa

Source BHP-Olympic Dam

Ehrig et al. 2012, 2017a, b; Corriveau et al. 2016, 2018b, in preparation
Great Bear LT K-Fe replacement, breccia, mineralisation

Pervasively hematised andesitic volcanic breccia

Hem + Ser
\[ K_2O = 4 \text{ wt}\% \]

K2 showing, Port Radium-Echo Bay district
(A.H. Mumin)

K-feldspar-hematite altered andesite fragments + Chlorite, hematite, quartz, tourmaline, sulpharsenide matrix

Mumin et al. 2007
Pervasive replacement of andesite by hematite (Fe zone, Port Radium-Echo Bay)
Layering: metasomatic pseudomorphing of flow foliation or metasomatic layering?
Hematite breccia, East Hottah, Great Bear
LT Ca-Fe-Mg

Chl±Hem
Chl-Cb±Hem
Chl-Tlc
Tlc

LT Ca-Mg
Ep
Ep-Hem
Ep-Hem-Qz
Ep-Qz-Cb
Ep-Hem-Qz-Cb

Chl-Py-Ccp

Chl = Ccp (Terra)

Urн

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Canada
Apical epithermal system and gossans

Mumin et al. 2010, Geological Association of Canada, Short course notes 20

Fe zone: massive hematite replacement body

Sericite replacement

Phyllic-potassic gossan

Cu, Ag, Pb, Zn

133 m @ 8.7 g/t Ag
3 m @ 197 g/t Ag

Photo courtesy of A.H. Mumin
Five element veins
Qz-Cb-Hem-Arsenides-Sulphides
(Cu-Co-Ni-Bi-Ag ± U, Au)
Molybdenite veins or replacement

Mumin et al. 2010; Corriveau et al. 2014; Acosta-Góngora et al. 2015a,b, 2018b
LT remobilisation – quartz veining

Giant quartz-hematite+sulphide vein stockworks
Hematite-chlorite-Kfs-Qz veinlets

See Montreuil et al. 2015

U = > 10000 ppm
Bi = 1490 ppm
Co = 124 ppm

Ab2+ K-Fe4

Uox

Hem2

Secondary U minerals in hematite-rich quartz stockworks

1 cm

Uranium-bearing earthy hematite veins (Hem2)

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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

[Diagram showing molar proportions from whole-rock analysis]

**Molar proportions from whole-rock analysis**

**Igneous + sedimentary rocks**

**IOAA metasomatites:**

1-3 dominant cations

Strong coupling/decoupling of cations and metals

**3-4 dominant cations (except rhyolite)**

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Corriveau et al. 2016, 2018b, in preparation; Blein et al. in preparation

**LT Si, K, Al, Ba, CO₂**

**LT Ca-Fe-Mg-H⁺-CO₂**

**LT K-Fe^{3+}**

**K**

**HT K-Fe-Mg-Ca (K-skarn)**

**HT K-Fe^{2+}**

**HT Ca-K-Fe**

**HT Ca-Fe**

**HT Ca-Fe-Mg (skarn)**

**HT Na-Ca-Fe**

**Na-Ca**

**Na**

**Ca**

**Fe**

**K**

**Mg**

T < 800°C
The rise of an hypersaline fluid through coupled dissolution-reprecipitation processes and structural-hydrothermal damage
Prograde path

Metal recharge (+++Ca, Fe, K, Mg, REE, Cu, Au, Ag, ...)

Other elements dissolved into outflow fluid
Al, Si, Zr, Ti conserved
Na precipitates

Albitite = Siltstone + Fluid 0

Ascent of hot, highly saline fluids (e.g. from hot magma chambers)

Outflow fluids induce the next metasomatic reaction and associated alteration facies

Prograde (forward) metasomatic path as fluid plume ascends = systematic sequence of alteration facies from
- Oldest to youngest facies,
- Depth to surface or laterally away from heat source(s)
- Higher to lower temperatures (i.e. temperatures largely decline during prograde metasomatism)

Captured fluids retrogress host metasomatites at microscopic scale = thin sections are not an optimal scale to define the prograde path = field observation provides an excellent scale to characterise systems

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Corrièveau et al. 2016, in preparation
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)
- 350-450°C
  - HT K-Fe
- 400-800°C
  - HT Ca-K-Fe
  - HT Ca-Fe
- Higher temperature (HT), Older, Deeper, Hypersaline: 400-600°C
  - HT Na-Ca-Fe
  - Skarn (in Cb)
  - 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**

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Corrièvre et al. 2010, 2016, 2018b, in preparation; Montreuil et al. 2016b
To each facies, its own deposit type

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

HT K-Fe
HT Ca-K-Fe

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

High temperature (HT)
Older, Deeper
Hypersaline

400-800°C
HT Na-Ca
Na (albitite corridor)

400-600°C

Deposit types

Epithermal, polymetallic veins
Central Andes, Great Bear, Olympic Dam, Merlin (Mo-Re)

Hematite-group IOCG
Olympic Dam, Prominent Hill, Carrapateena, Oak Dam

Polymetallic K-skarn (+Mag-to-Hem Grp IOCG)
Hillside, Punt Hill, Mile, Candelaria, Mt Elliott

Magnetite-group IOCG
Ernest Henry, Sue Dianne, Salobo, Candelaria, Dahongshan

Co-Au-Bi IOCG variant
NICO, Idaho Cobalt belt, Guelb Moghrine

IOA + REE
Pea Ridge, Josette, Bayan Obo

IOA
Kiruna, El Laco, Central Andes, MLYRMB, Caim Hill, Oak Dam, Great Bear (Mag Hill, Port Radium, K2 at depth)

Fe skarn
Middle-Lower Yangtze River Metallogenic Belt (MLYRMB)

Preferential host for albitite-hosted U, ± IOCG
+ indicator of potential IOAA mineral systems: Cloncurry - Mt Isa, Great Bear, Bamble, Gawler, Central Andes, El Laco, Kiruna

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

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Canada
Brittle to ductile behaviour during syn-metasomatic deformation

- **<250°C**
  - LT Si, K, CO₂, etc. Vein, Breccia

- **250-350°C**
  - LT Ca-Fe-Mg
  - LT K-Fe
  - K-felsite
  - K-skarn (in Cb)

- **350-450°C**
  - HT K-Fe
    - Breccia (Kfs-Mag)
    - Foliation to breccia (Bt-Mag)
  - HT Ca-K-Fe
    - Rare breccia; Foliation, C & S fabric

- **400-800°C**
  - HT Ca-Fe
    - Rare breccia and fluidisation; Foliation, C & S fabric; Folds
  - HT Na-Ca-Fe
    - Skarn (in Cb)
      - Rare breccia, undeformed
      - Brecciation of albite along faults
      - Rare recrystallisation to hypidiomorphic granular

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Corriveau et al. 2016, in preparation
Chemical footprints: AIOCG diagram of Montreuil et al. (2013)

AIOCG alteration index 2 (AIOCG2)

\[ K(K+Na+0.5Ca) \text{mol} \]

AIOCG1 and 2 calculated from whole-rock geochemical analysis

\[ \text{Ca,Fe} + \text{Si,Mg} - \]

\[ K + \text{Na} - \]

\[ \text{Na} + K - \]

\[ \text{Na, Si} + \text{Ca, Fe, K} - \]

\[ 2\text{Ca}+5\text{Fe}+2\text{Mn})/2\text{Ca}+5\text{Fe}+2\text{Mn}+\text{Mg}+\text{Si})\text{mol} \]
Signatures of least-altered host rocks (Great Bear example)

Least-altered field based on samples combining a lack of field evidence for alteration and a low Ishikawa alteration index.
Chemical footprints

Prograde path of alteration facies based on high intensity alteration of IOAA systems of the Great Bear magmatic zone

Modified from Figure 4 in Corrièveau et al. 2017

Prograde alteration of felsic and intermediate hosts near Olympic Dam

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Blein and Corrièveau 2017; Corrièveau et al. 2017, 2018a, b, in preparation
IOA at HT Ca-Fe = High heat ingress

REE ore = orogenesis or magmas

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

See Corriveau et al. (2016)

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Corriveau et al. 2010, 2016, 2018b; Bowdidge et al. 2014; Aleinikoff et al. 2016; Day et al. 2016; Focus Graphite 2018
Tectonic impact on fluidisation of metasomatic IOA crystal mush

Phyllic
LT Fe-H⁺-CO₂

Epithermal

Ascent of IOA fluidised breccia
Terra

Inspired by Knipping et al. (2019)

Telescopied path + compression?

HT Ca-Fe
HT Na-Ca-Fe
Skarn in carbonates
Na (±Na-Ca)

IOA

Albitite

Na albitite

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See Corriveau et al. (2016)
Iron oxide±apatite (IOA) deposits

- Kiirunavaara (682 Mt, 47% Fe)
- El Laco (734 Mt, 49% Fe), High Andes
- Pea Ridge (161 Mt, ~54% Fe; 0.2Mt, 12% REE), SE Missouri, US
- Marcona (~1940 Mt, 55% Fe) (+ Cu), Central Andes
- Oak Dam E (~560 Mt, 41–56% Fe) + IOCG (Cu, U, Au), Olympic Cu-Au
- Josette (6.9 Mt at 2.7% \(\text{REE}_2\text{O}_3\) (ms. + ind.) + 1.3 Mt at 3.6% \(\text{REE}_2\text{O}_3\) (inf.) Grenville
- Bayan Obo, China: IOA(?) (1500 Mt @ 35% Fe; 57 Mt @ 6% \(\text{REE}_2\text{O}_3\) + 2 Mt @ 0.13% \(\text{Nb}_2\text{O}_5\))

Genesis

Ore deposit models invoke:
- Metasomatism, magmatic-hydrothermal alteration, highly saline fluids
- Iron oxide magmas (immiscible from silicate magmas)
- Iron oxide salt melt
- Fluidisation of hydrothermal magnetite
- Flotation of igneous magnetite
Au-Co-Bi IOCG variants: HT Ca-K-Fe in sedimentary hosts

NICO example (also Idaho Cobalt belt, Guelb Moghrein)

LT Si, Ba, CO₂
LT K-Fe-H⁺-Ca-Mg-CO₂  
K-felsite

Hem-Kfs-Chl-Cal-Ccp Cu-mineralisation at NICO

HT K-Fe Kfs-Mag  
350-450°C

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

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

HT Ca-K-Fe

NICO: cycles of
Amp-Mag-Bt-Kfs-Apy
Amp-Bt-Mag±Kfs
Amp-Mag

HT Ca-Fe

400-800°C

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

Ascending (and evolving) fluid plume

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Goad et al. 2000a, b; Corriveau et al. 2016, in preparation;
Slack et al. 2013; Acosta-Góngora et al. 2015a, b, 2018b;
Kirschbaum and Hitzman 2016; Montreuil et al. 2016b
Cobalt in Apy at NICO

- East Zone
- NICO stockpile
- Discovery Zone
- near #25 Zone
- #25 Zone
- #1 Zone
- #2 Zone
- #3 Zone

Veins

Ore in HT Ca-K-Fe

See McMartin et al. 2011

300 µm

Act
Bismuthinite

Metals in metasomatites

Co (ppm)

0 5 10 50 500 30k

W (ppm)

0 2 4 25 500 15k

Corriveau et al. in preparation
Critical metals in metasomatitites, GBMZ

Representative samples of alteration zones reach 330 ppm Ag, 10587 ppm Ba, 31 ppm Be, 14475 ppm Bi, 123 ppm Cd, 27635 Co, 1966 ppm Cr, 64 ppm Cs, 71089 ppm Cu, 54 ppm Ga, 1.9 ppm Ge, 67 ppm Hf, 11 ppm In, 147 ppm Li, 3857 ppm Ni, 4980 ppm Mo, 589 ppm Nb, 33241 ppm Pb, 1070 ppm Rb, 305 ppm Sb, 378 ppm Sc, 30 ppm Se, 222 ppm Sn, 2574 ppm Sr, 162 ppm Ta, 26 ppm Te, 880 ppm Th, 2 ppm Tl, 7770 ppm U, 1837 ppm V, 13400 ppm W, 32400 ppm Zn. Rare earth elements reach 7447 ppm La, 10222 ppm Ce, 955 ppm Pr, 2845 ppm Nd, 318 ppm Sm, 32 ppm Eu, 218 ppm Gd, 41 ppm Tb, 254 ppm Dy, 51 ppm Ho, 144 ppm Er, 21 ppm Tm, 128 ppm Yb, 19 ppm Lu, 1655 ppm Y.

Corriveau et al. 2015; unpublished data

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Stratabound Mag-group IOCG: Biotite>Kfs

Alteration

LT Si, K, Al, Ba
LT Ca-Fe-Mg-CO₂ Late stage carbonate veins
LT K-Fe-H⁺ Locally hematite and sericite overprint

K-felsite breccia

K-skarn breccia in carbonates or earlier transient carbonate alteration

HT K-Fe

Amp-Bt-Mag evolves to Bt-Mag-Ccp
Minor Kfs

HT Ca-K-Fe

Stratabound replacement
Local Amp-Grt-Bt through syn-metasomatic deformation

HT Ca-Fe

HT Na-Ca-Fe
Skarn in carbonate host

Na (±Na-Ca)

In sedimentary rocks breccia are very rare
Nori in Great Bear

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Ootes et al. 2010; Zhao et al. 2017
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

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

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Oliver et al. 2009; Corriveau et al. 2010b, 2016, 2018b; Lilly et al. 2017
Magnetite to 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)

Epithermal, polymetallic veins

Hematite-group IOCG (OD, Prominent Hill)

Mag-Hem IOCG (Hillside)
Polymetallic K-skarn (Punt Hill)

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. 2010, 2016, 2018b;
Ehrig et al. 2012, 2017a b; Fabris et al. 2018a, b
HT to LT K-Fe alteration and mineralisation sampled during regional mapping
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

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

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

Fluid circulation during collapse of IOAA system
- Ingress of low temperature fluids
- Active tectonics

Polymetallic veins with metals derived from IOAA systems

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

Renewed fluid circulation (magmatism, orogenesis, unconformity)
- LT fluids remobilisation of IOAA metals

- Au, Cu, Ag from HT to LT K-Fe

Polymetallic veins with metals derived from IOAA systems

- LT fluids

Five-element veins
- REE ore
- ‘Orogenic’ Au-Co-U in albitite

Co, Au, Bi from HT Ca-K-Fe

IOA
- Albitite

Polymetallic veins
Central Mineral Belt (Labrador, Canada)

Mild to moderate Na
Host residual
Ca-K-Fe-Mg

Intense Na
Albitite

LT Ca-Fe-Mg and K-Fe overprints on albitite

Host’s Na content + albitization

Tectonic telescoping of albitite
Tectonically aided ingress of external low temperature fluids

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Acosta-Góngora et al. 2018a, 2019; Blein et al. in preparation; Corriveau et al. in preparation
NICO Au-Co-Bi-Cu

Drilling stops at a depth of 250 m
Magnetotelluric-derived conductor at 500 m

Goad et al. 2000a, b; Craven et al. 2013; Corriveau et al. 2016, this work; Hayward et al. 2013, 2016; Montreuil et al. 2016b; Fortune Minerals 2019
Rock physical properties

Intense IOAA metasomatism produces large petrophysical property variations (density, magnetic susceptibility, conductivity/resistivity; Enkin et al., 2016) that lead to high amplitude geophysical anomalies in magnetic, gravity and magnetotelluric surveys.

High porosity in albitite = extremely low magnetic susceptibility and density

Enkin et al. 2016
Economic Geology, v. 111
Ore system and potential deposit types

Lower T, younger, shallower
<250°C, ≤1 km
- LT Si, K, Al, Ba
- LT Ca-Fe-Mg-H+\text{CO}_2
- LT K-Fe±Si-H+\text{CO}_2
- K-felsite bx
  - K-skarn bx inCb or earlier Cb alteration

250-350°C
- HT K-Fe

350-450°C
- HT Ca-K-Fe
- HT Ca-Fe (→ K in system)

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

400-600°C
- Na (± Na-Ca)

2-10 km
- Higher T, older, deeper (unless telescoped)

New LT fluids + metals
- Epithermal, veins
  - Metals from host system
- Hematite-group IOCG
  - Cu-Ag-Au-LREE-U-Bi-W-Mo
  - Olympic Dam, Prominent Hill
- Polymetallic K-skarns
  - 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
- 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-CI-F)
  - Kiruna, El Laco, MLYRMB, Caim Hill
- Fe skarn
  - MLYRMB

Remobilization + Telescoping
- + Mixing with fluid column
- + Tectonic and volcanic activity
- Albite-hosted U, Au-Co-Cu
- Vanadinite, Central Mineral Belt
- Pea Ridge, Kwiibo, Bayan Obo

New HT fluids
- Magma, metals

Corriiveau et al. 2016, 2018b, in preparation; Montreuil et al. 2016b, c
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