Mineral geochemistry for precious and base metal exploration

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COESSING 2018
University of Ghana
Who am I?/ Where I’ve lived?

- Matthew’s Ridge, Guyana (home)
- Georgetown, Guyana
- Gettysburg, PA
- Tampa, FL
- Ann Arbor, MI
- Houston, TX
How do we feel about mining?

• Why do we mine?
• What do we mine?
**Elements of a Smartphone**

**Screen**
- Indium tin oxide is a mixture of indium oxide and tin oxide, used in a transparent film in the screen that conducts electricity. This allows the screen to function as a touch screen.
- The glass used on the majority of smartphones is an aluminosilicate glass, composed of a mix of alumina ($\text{Al}_2\text{O}_3$) and silica ($\text{SiO}_2$). This glass also contains potassium ions, which help to strengthen it.
- A variety of Rare Earth Elements compounds are used in small quantities to produce the colours in the smartphone's screen. Some compounds are also used to reduce UV light penetration into the phone.

**Electronics**
- Copper is used for wiring in the phone, whilst copper, gold and silver are the major metals from which microelectrical components are fashioned. Tantalum is the major component of micro-capacitors.
- Nickel is used in the microphone as well as for other electrical connections. Alloys including the elements praseodymium, gadolinium and neodymium are used in the magnets in the speaker and microphone. Neodymium, terbium and dysprosium are used in the vibration unit.
- Pure silicon is used to manufacture the chip in the phone. It is oxidised to produce non-conducting regions, then other elements are added in order to allow the chip to conduct electricity.
- Tin & lead are used to solder electronics in the phone. Newer lead-free solders use a mix of tin, copper and silver.

**Battery**
- The majority of phones use lithium ion batteries, which are composed of lithium cobalt oxide as a positive electrode and graphite (carbon) as the negative electrode. Some batteries use other metals, such as manganese, in place of cobalt. The battery's casing is made of aluminium.

**Casing**
- Magnesium compounds are alloyed to make some phone cases, whilst many are made of plastics. Plastics will also include flame retardant compounds, some of which contain bromine, whilst nickel can be included to reduce electromagnetic interference.
Objectives

• To provide an introduction to economic geology and natural resources

• Introduction to using geochemistry for exploration

• To (hopefully) change the way you think about (geo)chemistry and natural resources
Geology 101

• Rocks are our friends.

• Atoms – elements – minerals – rocks
What is Economic Geology?

Economic geology
From Wikipedia, the free encyclopedia

"Economic Geology" redirects here. For the journal, see Economic Geology (journal).

Economic geology is concerned with earth materials that can be used for economic and/or industrial purposes. These materials include precious and base metals, nonmetallic minerals, construction-grade stone, petroleum minerals, coal, and water. Economic geology is a subdiscipline of the geosciences; according to Lindgren (1933) it is "the application of geology". Today, we might call it the scientific study of the Earth’s sources of mineral raw materials and the practical application of the acquired knowledge.[1] The term commonly refers to metallic mineral deposits and mineral resources. The techniques employed by other earth science disciplines (such as geochemistry, mineralogy, geophysics, petrology and structural geology) might all be used to understand, describe, and exploit an ore deposit.

Economic geology is studied and practiced by geologists. Economic geology may be of interest to other professions such as engineers, environmental scientists, and conservationists because of the far-reaching impact that extractive industries have on society, the economy, and the environment.

Contents
1 Purpose of studies
2 Mineral resources
3 Ore geology
4 Coal and petroleum geology
5 See also
6 References
When you look at stars in a clear night sky, what differences can you see?
Periodic Groups and Natural Systems

<table>
<thead>
<tr>
<th>Periodic Table</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic number</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transition Elements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lanthanides (REE)</td>
<td>57</td>
<td>Ce</td>
<td>Pr</td>
<td>Nd</td>
<td>Sm</td>
<td>Eu</td>
<td>Gd</td>
<td>Lu</td>
</tr>
<tr>
<td>Actinides</td>
<td>89</td>
<td>Ac</td>
<td>Th</td>
<td>Pa</td>
<td>U</td>
<td>Np</td>
<td>Pu</td>
<td></td>
</tr>
</tbody>
</table>

**Goldschmidt’s Classification**
- Siderophile
- Chalcophile
- Lithophile
- Atmosphere
- Biophile

Figure 5.1: Periodic Table with superimposed Goldschmidt Classification.

from McQueen (2009)
Copper (Cu)

- Porphyry copper deposits
- Stratiform Cu deposits
- Iron oxide copper gold deposits

Chile, Peru, DRC, Zambia, USA
Iron (Fe): magnetite ($\text{Fe}_3\text{O}_4$) & hematite ($\text{Fe}_2\text{O}_3$)

- Manufacture of steel
- Banded iron formations
- Iron oxide copper gold deposits
- Iron oxide apatite deposits
- China, Australia, Brasil
Gold (Au)

- Jewelry
- Finances
- Electronics
- Dentistry and medicine

- Orogenic gold deposits
- Porphyry deposits
- Placer deposits

- China, South Africa, Ghana, Russia, USA, Canada, Australia
Aluminium (Al) \([\text{Al}_2\text{O}_3]\)

- Bauxite
- Australia, China, Brasil
Phosphorus (P) – $\text{Ca}_5(\text{PO}_4)_3(\text{F,Cl,OH})$

- Agriculture: Fertilizers and supplements for animals
- Construction
- Pharmaceuticals
- Water treatment

- Phosphorite
- Apatite

- USA, China, Morocco
<table>
<thead>
<tr>
<th>Element</th>
<th>Oxidation state</th>
<th>Deposit type (volcano)</th>
<th>Grade&lt;sup&gt;a&lt;/sup&gt; (median)</th>
<th>Crustal abundance&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Clarke value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td></td>
<td></td>
<td>0.54%</td>
<td>27 ppm</td>
<td>200</td>
</tr>
</tbody>
</table>

<sup>a</sup> All percentages are in weight percent.  
<sup>b</sup> Continental crust; see Chapter 3.01.  
<sup>c</sup> Highly variable.  
<sup>d</sup> In concentrate.

The Clarke value is the ratio of the concentration of an element in an ore, relative to its average crustal concentration.

Simon, 2015
## Economic Geology: From Background to Ore

<table>
<thead>
<tr>
<th>Element</th>
<th>Oxidation state</th>
<th>Deposit type</th>
<th>Grade(^a) (median)</th>
<th>Crustal abundance(^b)</th>
<th>Clarke value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td></td>
<td>Porphyry</td>
<td>0.54%</td>
<td>27 ppm</td>
<td>200</td>
</tr>
<tr>
<td>Na</td>
<td></td>
<td>Halite</td>
<td>40%</td>
<td>2.3%</td>
<td>17</td>
</tr>
<tr>
<td>Zn</td>
<td></td>
<td>Sedimentary exhalative</td>
<td>5.6%</td>
<td>72 ppm</td>
<td>780</td>
</tr>
<tr>
<td>As</td>
<td></td>
<td>Sulfide deposits(^c)</td>
<td>~0.1%</td>
<td>2.5 ppm</td>
<td>~400</td>
</tr>
<tr>
<td>Rb</td>
<td></td>
<td>Lepidolite(^d)</td>
<td>Up to 3%</td>
<td>49 ppm</td>
<td>~610</td>
</tr>
<tr>
<td>Mo</td>
<td></td>
<td>Climax</td>
<td>0.19%</td>
<td>0.8 ppm</td>
<td>~7,400</td>
</tr>
<tr>
<td>W</td>
<td></td>
<td>Skarn</td>
<td>0.66% WO(_3)</td>
<td>1 ppm</td>
<td>6,600</td>
</tr>
<tr>
<td>Pb</td>
<td></td>
<td>Sedimentary exhalative</td>
<td>2.8%</td>
<td>11 ppm</td>
<td>2,500</td>
</tr>
<tr>
<td>V</td>
<td></td>
<td>Layered mafic intrusions</td>
<td>~0.6%</td>
<td>138 ppm</td>
<td>~43</td>
</tr>
<tr>
<td>Au</td>
<td></td>
<td>Veins/Homestake</td>
<td>~10 ppm</td>
<td>1.3 ppb</td>
<td>~7,700</td>
</tr>
<tr>
<td>Ag</td>
<td></td>
<td>Creed vein</td>
<td>125 ppm</td>
<td>56 ppb</td>
<td>2,200</td>
</tr>
<tr>
<td>Ni</td>
<td></td>
<td>Komatiite</td>
<td>1.5%</td>
<td>59 ppm</td>
<td>250</td>
</tr>
</tbody>
</table>

\(^a\) All percentages are in weight percent. \(^b\) Continental crust; see Chapter 3.01. \(^c\) Highly variable. \(^d\) In concentrate.

The Clarke value is the ratio of the concentration of an element in an ore, relative to its average crustal concentration.

Simon, 2015
## Origin of Mineral Deposits - Differentiation

### Composition of Earth

<table>
<thead>
<tr>
<th>Major Elements</th>
<th>Crust</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>46.6</td>
<td>36.0</td>
</tr>
<tr>
<td>Si</td>
<td>27.7</td>
<td>15.0</td>
</tr>
<tr>
<td>Al</td>
<td>8.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Fe</td>
<td>5.0</td>
<td>35.0</td>
</tr>
<tr>
<td>Ca</td>
<td>3.6</td>
<td>1.1</td>
</tr>
<tr>
<td>Na</td>
<td>2.8</td>
<td>0.6</td>
</tr>
<tr>
<td>K</td>
<td>2.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Mg</td>
<td>2.1</td>
<td>13.0</td>
</tr>
<tr>
<td>Ti</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td>H</td>
<td>0.1</td>
<td>------</td>
</tr>
</tbody>
</table>

### Trace Elements

<table>
<thead>
<tr>
<th>Trace Elements</th>
<th>Crust</th>
<th>Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>0.009</td>
<td>0.022</td>
</tr>
</tbody>
</table>

as ppm (parts per million)

<table>
<thead>
<tr>
<th>Element</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn</td>
<td>2</td>
</tr>
<tr>
<td>Cu</td>
<td>28</td>
</tr>
<tr>
<td>Ni</td>
<td>58</td>
</tr>
<tr>
<td>Nb</td>
<td>20</td>
</tr>
</tbody>
</table>

Note how elements concentrate in different reservoirs.

Simon, 2015
ORIGIN OF MINERAL DEPOSITS - DIFFERENTIATION
Composition of Mantle, Ocean Crust and Continental Crust

<table>
<thead>
<tr>
<th></th>
<th>Mantle-ULTRAMAFIC</th>
<th>Ocean crust-MAFIC</th>
<th>Continental Crust-FELSIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>19.8%</td>
<td>23.5%</td>
<td>34.7%</td>
</tr>
<tr>
<td>Al</td>
<td>1.2%</td>
<td>8.3%</td>
<td>7.2%</td>
</tr>
<tr>
<td>Mg</td>
<td>23.2%</td>
<td>4.6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Fe</td>
<td>9.6%</td>
<td>8.6%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Cu</td>
<td>15 ppm</td>
<td>94 ppm</td>
<td>55</td>
</tr>
<tr>
<td>Pb</td>
<td>0.5 ppm</td>
<td>7 ppm</td>
<td>15</td>
</tr>
<tr>
<td>Sn</td>
<td>0.5 ppm</td>
<td>1.5 ppm</td>
<td>3</td>
</tr>
<tr>
<td>Ni</td>
<td>2000 ppm</td>
<td>145 ppm</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Simon, 2015
**ORIGIN OF MINERAL DEPOSITS**

Geologic processes that form mineral deposits (by forming ore minerals) along with deposits and elements that form by each process.

<table>
<thead>
<tr>
<th>Surface Processes</th>
<th>Physical Sedimentation</th>
<th>Chemical Sedimentation</th>
<th>Organic Sedimentation</th>
<th>Subsurface Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flowing water</td>
<td>Placer deposits - gold, platinum, diamond, (stream or beach) ilmenite, rutile, zircon, sand, gravel</td>
<td>Dune deposits - sand</td>
<td>Involving Water Groundwater and related deposits - uranium, sulfur Basinal brines - Mississippi Valley-type, sedex Seawater - volcanogenic massive sulfide, sedex Magmatic Water - porphyry copper-molybdenum, skarn Metamorphic water - gold, copper</td>
</tr>
<tr>
<td></td>
<td>Wind</td>
<td>Precipitation from or in seawater Evaporite deposits - halite, sylvite, borax, trona Chemical deposits - iron, volcanogenic massive</td>
<td>Organic activity or accumulation Hydrocarbon deposits - oil, natural gas, coal Other deposits - sulfur, phosphate</td>
<td>Involving Magmas Crystal segregation - chromium, vanadium Immiscible magma separation - nickel, copper, cobalt, platinum-group elements</td>
</tr>
</tbody>
</table>

Simon, 2015
Exploration
Exploration 101

• Decide on a commodity/ metal(s) of interest
  ▪ What deposit type?
  ▪ How does it form?

• What data will be most useful for finding the deposit?
  ▪ Geochemistry?
  ▪ Geophysics?

• Are there data available that lead you to a specific geographic area?
  ▪ Where (country, region) do you want to be?
Geochemistry

• What elements will be most useful for finding the deposit?

• What samples can you collect?
  • Soil (stream/ lake sediments)
  • Rocks
  • Minerals
  • Stream water
  • Plant material
Geochem Targeting Tool Box

- Deposit models predict mineralogy, zonation and alteration
- Pathfinder elements or alteration zones can provide a larger target than the mineralization
- Element associations also depend on magma fractionation, weathering profile, sample type and analytical method

Bloom, 2018
<table>
<thead>
<tr>
<th>Style Of Deposit</th>
<th>Element Association*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni (Cu, PGM) Sulphides</td>
<td>Ni-Cu-PGM-(Cr-Se-Bi-Co-Au)</td>
</tr>
<tr>
<td>Porphyry CuAu, CuMo, Mo</td>
<td>Cu-Au-Mo-(Zn-Pb-Ag-Sb-Ag)</td>
</tr>
<tr>
<td>Epithermal AuAg</td>
<td>Au-Ag-As-(Cu-Pb-Zn-Sb-Hg-W)</td>
</tr>
<tr>
<td>Skarns</td>
<td>Cu-Au-Zn-Pb-W-Mo-Sn-Bi-As-Sb</td>
</tr>
<tr>
<td>Proterozoic Fe-CuAu</td>
<td>Cu-Au-U-Co-(REE-Ba-F-Sn-W-Mo-Bi-As)</td>
</tr>
<tr>
<td>VHMS</td>
<td>Cu-Pb-Zn-Ag-Au-(As-Sb-Sn-Bi-Mo-Ba-W)</td>
</tr>
<tr>
<td>SHMS</td>
<td>Cu-Pb-Zn-Ag-(As-Sb-Mo-Mn-Bi-Au)</td>
</tr>
<tr>
<td>MVT</td>
<td>Pb-Zn-(Cd-Ag-Ba-F-Cu-Ni)</td>
</tr>
<tr>
<td>Red Bed Cu</td>
<td>Cu-Ag-Co-(Pb-Zn-U-Se-Mo)</td>
</tr>
<tr>
<td>Sedimentary UV(Cu)</td>
<td>U-V-Au-Mo-Se-(Ni-As-Co-Cu-Pb-Zn)</td>
</tr>
<tr>
<td>Mesothermal Au</td>
<td>Au-As-(Sb-W-Cu-Pb-Zn-Hg)</td>
</tr>
</tbody>
</table>

*In the weathering environment, some of these elements will be present in resistate minerals e.g. cassiterite and chromite.

Bloom, 2018
**Primary Geochemistry**

Element distribution in rocks associated with deposit formation

**Secondary Geochemistry**

Element distribution in the geochemical cycle (water, vegetation, soils, streams, glacial sediments)

Dispersion mechanically or by chemical mobility
Zones of geochemical enrichment in target and/or pathfinder elements

Leybourne, 2018
Analytical methods

Choice of analytes to focus on for data analysis and interpretation – depends on the style of mineralization and the relative mobility by mechanical or hydromorphic dispersion

<table>
<thead>
<tr>
<th>Type of deposit</th>
<th>Major components</th>
<th>Minor components</th>
<th>Labile components</th>
<th>Relatively immobile components</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMS</td>
<td>Fe, S, Cu, Zn, Pb</td>
<td>Cd, Hg, Au, As, Sb, Ba</td>
<td>Fe, S, Zn, Cu, As, Cd,</td>
<td>Pb, Bi, In, Au, Ag, Ba</td>
</tr>
<tr>
<td>Porphyry Cu ± Mo</td>
<td>Cu, Mo, S</td>
<td>Fe, Ag, Au, Se, Re, As</td>
<td>Cu, Mo, S, Fe, Se, As,</td>
<td>Ag, Au</td>
</tr>
<tr>
<td>SEDEX</td>
<td>Fe, S, Cu, Zn, Pb</td>
<td>Ag, Au, Ba, Cd</td>
<td>Fe, S, Zn, Cu, Cd</td>
<td>Pb, Ba, Au, Ag</td>
</tr>
<tr>
<td>Gold (vein)</td>
<td>Au, Ag</td>
<td>As, Sb, Se, Te, S, Hg</td>
<td>S, Se, As, Hg, Te, Sb</td>
<td>Au, Ag</td>
</tr>
<tr>
<td>Ni-Ci-PGE</td>
<td>Ni, Cu, PGE</td>
<td>Cr, Co, S</td>
<td>Cu, S, PGE</td>
<td>Co, Ni, Cr</td>
</tr>
<tr>
<td>Kimberlite (diamond)</td>
<td>Sr, Nb, Ba, Cr, Ni</td>
<td>LILE, HFSE, REE</td>
<td>Sr, LILE</td>
<td>Ba, HFSE, Nb, Ba</td>
</tr>
<tr>
<td>Unconformity uranium</td>
<td>U</td>
<td>Se, Mo, V, Cu, Pb</td>
<td>U, Se, Cu, Mo</td>
<td>U, Pb, V</td>
</tr>
</tbody>
</table>

Leybourne, 2018
Gold!!!!!
Gold deposits

- Greenstone hosted/ orogenic deposits
- Reduced intrusion related gold deposits
- Porphyry, epithermal and skarn deposits
- Iron oxide copper gold deposits
- Gold rich volcanogenic massive sulphide deposits
- Placer gold deposits
Gold Indicator Minerals

- Recovered from stream sediments since Roman times
- Most well known and widely used indicator mineral
- Others indicator minerals include sulphides, arsenides, tellurides, scheelite, tourmaline, rutile, barite, secondary minerals (jarosite, limonite, goethite, pyrolosite)
- Gold grains easily recovered from 10 μm to 2 mm size fraction of sediments
- Most gold grains recovered from till, 10 to 75 μm
- Gold within sulphides or in solid solution with sulphides will be detected with automated mineralogy methods and matrix till geochemistry
Gold Grain Morphology

• DiLabio (1990) classification scheme describes conditions and surface textures of gold grains related to glacial transport distance

• Pristine gold grains:
  - Primary shapes and surface textures
  - Appear not to have been damaged in transport
  - Angular wires, rods and delicate leaves that once filled in fractures, occurred as crystals with grain molds, and as inclusions in sulphides

• Modified gold grains:
  - Some primary surface textures
  - Edges and protrusions have been damaged during transport
  - Commonly striated
  - Irregular edges and protrusions are crumpled, folded and curled
  - Grain molds and primary surface textures preserved on protected faces of grains

• Reshaped gold grains:
  - Primary surface textures destroyed
  - Original grain shape no longer discernible
  - Flattened to rounded resulting from folding of leaves, wires, rods
  - Surfaces may be pitted from impact marks from other grains
  - Surfaces are not leached of silver in most cases in glaciated terrain

McClenaghan, 2018
Gold geochemistry

Lode and Placer Gold Composition in the Klondike District, Yukon Territory, Canada: Implications for the Nature and Genesis of Klondike Placer and Lode Gold Deposits

J. B. Knight,†

Micro Science, RR #1, Site 29, Comp 10, Smithers, British Columbia, Canada V0J 2N0

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AND S. R. Morison

Gartner Lee Ltd., Unit 212, 212 Main St., Whitehorse, Yukon Territory, Canada Y1A 2A9

Application of microchemical characterization of placer gold grains to exploration for epithermal gold mineralization in regions of poor exposure

R.J. Chapman a,*, J.K. Mortensen b
Gold in Ghana....
Visible gold associated with pyrite from orogenic gold deposits of the Birimian shield in Ghana

Gold Ore from the Tarkwa basin
Figure 5-7. Location of Obuasi gold mine along the Axim-Konongo shear zone along the northwestern margin of the Ashanti greenstone belt. Other significant mines are also shown (Metal News, 2008).
Ashanti belt main structure

Mined out pit on the Ashanti main structure
Using geochem for exploration in Ghana
CHANNEL SAMPLING

Channel Sampling Line-14 samples picked at 1-2m intervals

4m @ 1.93g/t

AsankoGold, 2018
Structure and Mineralization Characteristics

- **Structure**
  - Conforms with the general regional strike NNE – SSW structure, with folds plunging to NE
  - Multiplicity of deformational episode

- **Mineralisation**
  - Complex arrangement of deformed rocks
  - Mineralisation is hosted in deformation zones and proximal to contacts
    - Styles of mineralization
      - Disseminated Arsenopyrite domains (Refractory)
      - Contact-related Vein Quartz
      - Granitoid/Stockworks (primary non-refractory)
      - Supergene oxide and transition ore
    - Types of mineralization
      - Quartz vein type (quartz with free Gold, in association with lesser amount of various metal sulphides containing iron, zinc, lead and copper), non-refractory
      - Sulphide ore (inclusion of gold in the crystal structure of arsenopyrite minerals. Higher gold grades tend to be associated with finer grain arsenopyrite crystals. Sulphide ore is generally refractory

AngloGoldAshanti, 2018
Two types of Mineralization

Sulphide Mineralisation with ASP

Quartz with Spec of Gold

Vary from 1-40m wide and 1-1,000g/t Au.

Associated Attributes:
Strong shearing, potentially faulted, fractured and friable domains

AngloGoldAshanti, 2018
Deposition mechanism:

Chirano gold system comprises two types of shear hosted:

1. Chirano: *Porphyry intrusion-mafic volcanic-hosted deposit*
2. Bibiani: *Sediment-hosted deposit*

- Different mineralogy and chemistry
- Fluid mixing (evidence pyrite deposition of graphite selvages in black breccia - Akwaaba)

**Chirano:**
- Hematite-magnetite-pyrite
- Intense albite-ferroan dolomite alteration
- W-Mo-Bi pathfinder signature
- Phengitic sercite and Mg-rich chlorite
- Arsenic depletion
- Gold is strongly related to pyrite

**Bibiani:**
- Style graphitic shear
- Pyrite-arsenopyrite-graphite
- Intense sercite (paragonite)
- As-Sb pathfinder signature

Kinross, 2018
• Prestea Underground is hosted within Birimian Phyllites

• Gold mineralization is associated with the prolific fault zone referred to as the Ashanti Trend

• West Reef mineralization is hosted in a fault structure parallel to the Main Reef located ~250m in the hanging wall

• Gold occurs as free gold along carbonaceous partings within the quartz veins or with pyrite and arsenopyrite
Au geochem for exploration?
Common Indicator
Mineral Suites

- Gold grains (Au)
- Native copper (Cu)
- Kimberlite indicator minerals
- Platinum Group minerals (PGM)
- Sulphide minerals
- Metamorphosed VMS (e.g. gahnite, staurolite)
- Magmatic Ni-Cu-PGE minerals
- Porphyry Cu-Mo-Au minerals
- Scheelite, wolframite (W)
- Cassiterite (Sn)
- Cinnabar (Hg)
- Fluorite, topaz (F)
- Uranium minerals
- Rare earth element (REE) minerals

- May be recovered from same heavy mineral concentrate
- Archived concentrates can be re-examined

McClenaghan 2018
## Trace Element Compositions Minerals

<table>
<thead>
<tr>
<th>Sulphides</th>
<th>Present in % Amounts</th>
<th>Present in Trace Amounts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyrite</td>
<td>Cu, Co, Ni, Zn, As, Pb</td>
<td>Pb, V, Sb, Se, Mn, Ag, Au, Bi, Mo Cd</td>
</tr>
<tr>
<td>Pyrrhotite</td>
<td>Ni</td>
<td>Co, Cu, Mn, V, Zn, Sn</td>
</tr>
<tr>
<td>Arsenopyrite</td>
<td>Co</td>
<td>Mn, Ni</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>Mn, Zn</td>
<td>Ni, Co, Sb, Ag, Se, As, Sn, V, Mo</td>
</tr>
<tr>
<td>Sphalerite</td>
<td>Fe, Mn, Cu, Cd, Sb, Sn, Ag, As</td>
<td>Co, Ni, Bi, In, Ga, Ti</td>
</tr>
<tr>
<td>Galena</td>
<td>Bi, Ag, Sb, Se, As</td>
<td>Cu, Mn, Sn, Zn, Cd</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Silicates</th>
<th>Present in Major Amounts</th>
<th>Present in Minor Amounts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagioclase</td>
<td>K, Sr, Ba, Rb, Ti, Mn</td>
<td>P, Ga, V, Zn, Ni</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>Na, Ca, Ba, Sr, Rb, Ti</td>
<td>P, Pb, Li, Ga, Mn, Al, Ti, Fe, Mg, Ca</td>
</tr>
<tr>
<td>Amphibole</td>
<td>Ti, F, K, Mn, Cl, Rb, Zn, Cr, V, Sr, Ni</td>
<td>Ba, P, Cu, Co, Ga, Pb</td>
</tr>
<tr>
<td>Pyroxene</td>
<td>Al, Ti, Na, Mn, K, Cr, V, Ni, Cl, Sr</td>
<td>P, Cu, Co, Zn, Li, Rb</td>
</tr>
<tr>
<td>Muscovite</td>
<td>Al, K, Fe, Ti, Mg, Ca, Na, Rb, Li</td>
<td>Mn</td>
</tr>
<tr>
<td>Biotite</td>
<td>Ti, F, Ca, Na, Ba, Mn, Rb, Cl, Zn, V, Cr, Li, Ni</td>
<td>Cu, Sr, Co, P, Pb, Ga</td>
</tr>
<tr>
<td>Olivine</td>
<td>Ni, Mn, Ca, Al, Cr, Ti, P, Co</td>
<td>Zn, V, Cu, Sc</td>
</tr>
</tbody>
</table>

*Data from Lelong et al (1976), Joyce (1984) and Vaughan and Craig (1978).*
Mineral geochem as a tool for exploration
Why Magnetite?

- Iron oxide ($\text{Fe}_3\text{O}_4$)
  - Can incorporate other elements into its structure.

Nadoll et al. 2014
Why magnetite geochemistry?

**DETRITAL MAGNETITE AS A PROVENANCE INDICATOR**

JEFFRY D. GRIGSBY  
Department of Geology  
University of Cincinnati  
Cincinnati, Ohio 45221

Miner Deposita (2011) 46:319–335  
DOI 10.1007/s00126-011-0334-y

**ARTICLE**

**Discriminant diagrams for iron oxide trace element fingerprinting of mineral deposit types**

Céline Dupuis • Georges Beaudoin

Ore Geology Reviews 61 (2014) 1–32

Review  
The chemistry of hydrothermal magnetite: A review  
Patrick Nadoll a,*, Thomas Angerer b, Jeffrey L. Mauk c, David French d, John Walshe a
Variations in magnetite chemistry

Dupuis and Beaudoin, 2011
Variations in magnetite chemistry

Dupuis and Beaudoin, 2011
Guyana Magnetite project

• Collect magnetite grains
• Analyze magnetite grains
• Use magnetite discriminant plots to determine ore deposit potential
Mineral geochemistry for understanding how ore deposits form
Los Colorados apatite chemistry?

\[ \text{Ca}_5(\text{PO}_4)_3(\text{F}, \text{Cl}, \text{OH}) \left[ \text{A}_5(\text{XO}_4)_3(\text{Z}) \right] \]

- **A** = Ca\(^{2+}\), Sr\(^{2+}\), Pb\(^{2+}\), Ba\(^{2+}\), Mg\(^{2+}\), Fe\(^{2+}\), REE\(^{3+}\), Eu\(^{2+}\), Cd\(^{2+}\), Na\(^{+}\), Al\(^{3+}\), Y\(^{3+}\), K\(^{+}\), Mn\(^{2+}\), Cu\(^{2+}\)
- **X** = P\(^{5+}\), Si\(^{4+}\), S\(^{4/6+}\), As\(^{5+}\), V\(^{5+}\), C\(^{4+}\)
- **Z** = F\(^{-}\), Cl\(^{-}\), S\(^{2-/1-}\), OH\(^{-}\)

- Major (F, Cl, OH) and trace element chemistry can provide insights into fluid history.
La Cruz et al. in prep
Similarities with magnetite and apatite chem

Knipping et al., 2015 a,b
Aqueous geochem for exploration
Water chemistry

Major ions in water – typically not useful for direct exploration, but can help identify changes in water sources, water-rock reactions.

Here > 600 surface water samples – a subset has anomalously elevated $\text{SO}_4$ – and elevated Au

Leybourne 2018
Biogeochemistry as a tool for exploration

Base Metals Southern British Columbia

Dunn 2018
Metal Uptake and Transport in Trees

Transport in vascular system

Incorporation into Tissues

Metal uptake facilitated by mycorrhizae

Transpiration

Sap leakage through wounds

Water Table

Metals released by degradation and bacterial action

Gold in outer bark
Douglas-fir Treetop Sampling
Separation of Needles from Twigs

Dunn 2018
THALLIUM
Douglas-fir top needles (ash)

Dunn 2018

South Tsuius Anomaly
Bark Sampling

Dunn 2018
THALLIUM – Dry Western Hemlock Bark
South of Tsuius Ck

Contoured percentiles

3D Surface Image

Dunn 2018
Continuous rock trench – 3 trenches

Dunn 2018
Summary of metal enrichments

- **Zinc** - best continuous section = 3m @ 8.98%
- **Rhenium** (580 ppb)
- **Molybdenum** (max 1339 ppm)
- **Anomalous Cu, Pb, Bi, Ni, V, (Sn, W)**

Dunn 2018
A Diamond Mine Udachnaya Pipe, an open-pit diamond mine in Russia, is more than 600 meters (1,970 ft) deep.
Arakaka trend, northwestern Guyana
Medium scale mining in northwestern Guyana
Medium scale mining in northwestern Guyana
Summary

• Ore deposits and mining are important for society to exist.
• If we don’t grow it, we must mine it. (We also mine to be able to grow things.)
• Can we figure out better ways to mine and regulate mining in order to mitigate harmful effects?
• The resources we need come from different types of deposits that exist globally.
• Geochemistry is a useful tool for finding these deposits.