INTRUSION-RELATED GOLD DEPOSITS

SE Europe Geoscience Foundation
Shortcourse

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OVERVIEW

• Part 1: Classification, nomenclature & deposit comparison

• Part 2: Examples: Tintina Gold Province

• Part 3: Other examples & exploration
INTRUSION RELATED GOLD DEposits CHARACTERISTICS

- Sillitoe (1991)
  - Gold-rich porphyry deposits
  - Epithermal & skarn in porphyry Cu environments
  - Gold related to alkalic magmatism
  - Mostly associated oxidized intrusions
- Intrusion related gold deposits in Sn-W terranes
  (Thompson et al., 1999)
NOMENCLATURE

- Porphyry Au (Hollister, 1992)
- Fort Knox-style Au (Bakke, 1995)
- Intrinsic Au (Newberry et al., 1995)
- Plutonic Au (McCoy et al., 1997)
- Intrusion-related Au (Thompson et al., 1999)
- Granitoid Au (Goldfarb et al., 1999)
- Thermal aureole gold systems (Wall, 2005)
CHARACTERISTICS

• Intrusion related Au deposits in Sn-W terranes
• Metals
  – Au, Bi, Te, W, Mo, As (Sb, Sn, Pb, Cu)
• Magmas
  – Intermediate to felsic (wide range SiO2)
  – I-type (crustal input, transitional S-type)
  – Ilm>Mag
  – W-Sn-Mo association

(Thompson et al., 1999)
CHARACTERISTICS

• Tectonic environment
  – Continental setting, inboard, commonly late
• Age
  – Phanerozoic (Precambrian – Archean?)
  – Intrusions = mineralization
• Ore
  – Au, Bi, Te, W, Mo, As (Sb, Sn, Pb, Cu)
  – Reduced (no Mag-Hem), low sulfide (Po-Py-Apy)
• Style
  – Sheeted, breccia, stockwork, flat-vein, disseminated

(Thompson et al., 1999)
LOCATION OF MAJOR GRANITE RELATED GOLD DEPOSITS

(Lang & Baker, 2001)
INTRUSION RELATED GOLD SYSTEMS IN Sn-W PROVINCES

(Baker et al., 2005a)
<table>
<thead>
<tr>
<th>Metallogenic Association</th>
<th>Region/Deposit</th>
<th>Granite type</th>
<th>SiO2 wt %</th>
<th>Granitoid Series</th>
<th>Alumina saturation</th>
<th>Accessory minerals (in addition to zircon &amp; apatite)</th>
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</thead>
<tbody>
<tr>
<td>Sn-W-Bi</td>
<td>Cornwall</td>
<td>S</td>
<td>71-74</td>
<td>Ilmenite</td>
<td>peraluminous</td>
<td>ilmenite, monazite, andalusite, topaz, fluorite</td>
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<td>I</td>
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<td>Tintina Gold Province</td>
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<td>Au-Bi-Mo</td>
<td>Tasman Fold Belt</td>
<td>I</td>
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<td>Both</td>
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<td>Cu-Au-Mo</td>
<td>SW Arizona</td>
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</table>

(Baker et al., 2005a)
MAGMAS & METALS

(Baker et al., 2005a)
MAGMAS & METALS

(Baker et al., 2005a)
GRANITE Au-Bi & Sn-W COMPARISON

Au-Bi+/-W Deposits

Kidston
Shotgun
Pogo

Fort Knox
Dublin Gulch

Timbarra

Jilau

Korri Kollo

Sn-W Deposits

Bolivia

Herberton

Cornwall

Panasqueira

Jiangxi

Thailand

E Yukon

Granites associated with Au-Bi+/-W:
- Rb/Sr 0.1 to 1.0
- Fe₂O₃/FeO 0.1 to 0.6
- Metaluminous to peraluminous I-type

Granites associated with W+/-Sn:
- Rb/Sr 0.1 to 10
- Fe₂O₃/FeO 0.1 to 2.0
- Peraluminous to locally metaluminous I-type and S-type

Granites associated with Sn+/-W:
- Rb/Sr 1 to 100
- Fe₂O₃/FeO 0.01 to 0.5
- Peraluminous I-type and S-type

Granite types

- Diorite
- Granodiorite
- Granite
- Highly Fractionated Granite

Deposit styles

- Pegmatite
- Disseminated Greisen
- Breccia
- Skam
- Sheeted
- Flat
- Stockwork
- Veins
COMPARISON WITH OTHER ORE SYSTEMS

- Epithermal/epizonal gold
- Porphyry Cu-Au (PCD’s)
- Skarn & sed-hosted Au (Carlin-like)
- Mesothermal/orogenic gold
COMPARISON WITH OROGENIC GOLD

• Differences
  – Metals: Au-As-Sb-(W-Bi-Te)
  – Magma: Lacks spatial/temporal relationship
  – Structure: Regional scale faults
  – Ore: Py abundant
  – Alteration: Varies: host rock/metamorphic grade

• Similarities
  – Metals: Intrusion-hosted may have W-Bi-Te
  – Magma: Lacks spatial/temporal relationship
  – Structure: Deeper IRG have regional stress influence
  – Ore: Low-mod sulfide, reduced Po-Asp
  – Alteration: Albite, carbonate, quartz
  – Fluids: Low salinity, H$_2$O-CO$_2$-(CH$_4$)
EPITHERMAL/EPIZONAL GOLD

• Shallow-level IRG
  • Donlin Creek, Brewery Creek, Korri Kollo

• Similarities: depth; As-Sb-Hg association

• Differences:
  • General geological & tectonic environment
  • LS – lack textures & wide structurally-controlled veins
  • HS – lack acidic fluids & related-alteration features; low Cu
  • Shallow IRG - High CO₂ content to fluids

• Epizonal orogenic gold
  • Less well defined
  • Shallow IRG – spatial & temporal association with intrusions
SKARN & SED-HOSTED GOLD

• Parallels with reduced Au skarns (Meinert, 2000)
  – Part of total hydrothermal system
  – Calcareous host rocks
  – Associated with ilmenite series diorite to granodiorite
  – Reduced sulfide mineralogy; Au-Bi common

• Non-carbonate sequences may have links to Carlin systems (Poulson et al, 1997)
COMPARISON WITH PCD’s

- Metals: Cu-Au-Fe-Pb-Zn-Ag-Mo
- Magmas: Oxidized I-type, higher Fe content
- Style: Multiple intrusions, stockwork & breccia
- Ore: High sulfide content, oxidized
- Alteration: Extensive, variety of types
- Fluids: High salinity, aqueous; carbonic rare
REDUCED PCD’s (Rowins, 2000)

• Most examples NOT Cu deposits
• Some overlap with shallow porphyry-hosted environment (e.g. Shotgun but again no Cu)
• Also distinct from alkalic Au & Cu-Au systems
• More parallels with W-Sn-Mo systems
# THERMAL AUREOLE GOLD SYSTEMS

![Diagram of a geological map](image)

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Location</th>
<th>Age</th>
<th>Host Rocks</th>
<th>Gold Resource and Comments</th>
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<tbody>
<tr>
<td>Fort Knox</td>
<td>Alaska</td>
<td>Cretaceous</td>
<td>granitoids</td>
<td>&gt;5.6Moz; platon margin hosted</td>
</tr>
<tr>
<td>Pogo</td>
<td>Alaska</td>
<td>Cretaceous</td>
<td>gneisses</td>
<td>5.7Moz @ 17.8g/t; platon proximal</td>
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<td>Muruntau</td>
<td>Uzbekistan</td>
<td>Permian</td>
<td>metasediments</td>
<td>&gt;100Moz @ 2-3g/t; medium temperature mineralisation</td>
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<tr>
<td>Kumtor</td>
<td>Kyrgyzstan</td>
<td>Permian</td>
<td>metasediments</td>
<td>9.3Moz @ 3.6g/t; platon distal</td>
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<td>Vasilkovskoye</td>
<td>Kazakhstan</td>
<td>Early Palaeozoic</td>
<td>granitoids</td>
<td>13.3Moz @ 3g/t; platon margin hosted</td>
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<tr>
<td>Telfer</td>
<td>Australia</td>
<td>Late Proterozoic</td>
<td>mainly metasediments</td>
<td>&gt;31Moz; platon proximal</td>
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<td>Tanami</td>
<td>Australia</td>
<td>Early Proterozoic</td>
<td>metasediments</td>
<td>&gt;13Moz; medium-high gold grades platon proximal to distal</td>
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<td>Obuasi</td>
<td>Ghana</td>
<td>Early Proterozoic</td>
<td>metasediments</td>
<td>&gt;49Moz production + resources; platon distal</td>
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<tr>
<td>Morila</td>
<td>Mali</td>
<td>Early Proterozoic</td>
<td>metasediments</td>
<td>&gt;7.0Moz; platon proximal</td>
</tr>
<tr>
<td>Wallaby</td>
<td>Australia</td>
<td>Late Archaean</td>
<td>metasediments</td>
<td>7Moz; platon distal</td>
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<tr>
<td>Campbell-Red Lake</td>
<td>Canada</td>
<td>Late Archaean</td>
<td>mafics-ultramafics</td>
<td>&gt;25Moz @ &gt;15g/t; platon proximal</td>
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</tbody>
</table>

*Table 1: Some examples of TAG deposits* (Wall, 2005)
OVERVIEW

• Part 1: Classification, nomenclature & deposit comparison

• Part 2: Examples: Tintina Gold Province

• Part 3: Other examples & exploration
<table>
<thead>
<tr>
<th>Deposit</th>
<th>Size (Mt)</th>
<th>Grade (g/t)</th>
<th>Country rocks</th>
<th>Intrusion composition</th>
<th>Deposit type</th>
<th>Age (Ma)</th>
<th>Metal suite</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fort Knox, Alaska</strong></td>
<td>158</td>
<td>0.8</td>
<td>Mica-quartz schist</td>
<td>Porphyritic granite</td>
<td>Sheeted veins</td>
<td>92</td>
<td>Bi, Te, Mo, As, Sb, W</td>
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<tr>
<td><strong>Pogo, Alaska</strong></td>
<td>10</td>
<td>~15</td>
<td>Gneiss</td>
<td>Granite, aplite</td>
<td>Flat lenses</td>
<td>107-92?</td>
<td>Bi, Te, As, Ag, Cu, Pb</td>
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<tr>
<td><strong>Ryan Lode, Alaska</strong></td>
<td>4.1</td>
<td>3.1</td>
<td>Quartz-mica schist</td>
<td>Granodiorite</td>
<td>Veins, breccia</td>
<td>90</td>
<td>As, Sb</td>
</tr>
<tr>
<td><strong>True North, Alaska</strong></td>
<td>16.5</td>
<td>2.5</td>
<td>Schist &amp; eclogite</td>
<td>Granite</td>
<td>Disseminated, breccia</td>
<td>90</td>
<td>As, Sb, (Hg)</td>
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<tr>
<td><strong>Dublin Gulch, Alaska</strong></td>
<td>50.3</td>
<td>2</td>
<td>Qtz-bt &amp; calcareous schist</td>
<td>Granodiorite</td>
<td>Sheeted veins</td>
<td>92</td>
<td>Bi, Te, Mo, As, Sb, W, Pb</td>
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<tr>
<td><strong>Brewery Creek, Yukon</strong></td>
<td>13.3</td>
<td>1.4</td>
<td>Calcareous schist</td>
<td>Monzonite, syenite</td>
<td>Disseminated, veinlets</td>
<td>91.4</td>
<td>As, Sb, (Hg)</td>
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<td><strong>Shotgun, Alaska</strong></td>
<td>~1M.oz.</td>
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<td>Quartz-biotite schist</td>
<td>Granite</td>
<td>Stockwork</td>
<td>70</td>
<td>Ag, Bi, Mo, Te, Cu</td>
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<td><strong>Donlin Creek, Alaska</strong></td>
<td>111</td>
<td></td>
<td>Greywacke &amp; shale</td>
<td>Rhyodacite</td>
<td>Veins, veinlets</td>
<td>70</td>
<td>Ag, As, Sb, Hg</td>
</tr>
</tbody>
</table>

*(Thompson et al., 1999)*
TINTINA GOLD BELT

- 500 kilometres
- Alaska
- Pogo
- Dublin Gulch
- Brewery Creek
- Yukon
- Tintina Gold Belt
- Tombstone Plutonic Suite
- Tungsten Plutonic Suite
- Major gold deposits
- Gold occurrences

Major gold deposits:
- Fort Knox, Ryan Lode & True North
- Donlin Creek
- Shotgun
- Denali Fault
- Kaltag Fault

Tintina Fault

Kula (85Ma)
Kula (56Ma)
Farallon (100Ma)

(Flanigan et al., 2000)
TECTONIC SETTING

• Central-eastern Alaska & Yukon
  • Orthogonal subduction Farallon plate 115-100 Ma
  • Continued subduction - dextral component 100-85 Ma
  • Coincident magmatism – younging cratonwards
  • Strong crustal component ($Nd_T$ –7.6 to –15; $^{87}\text{Sr}/^{86}\text{Sr}$ 0.709-0.702)
  • Kula plate oblique subduction, dextral strike-slip 85 Ma

• Western Alaska
  • Magmatic arc 77 to 58 Ma
  • Local N-S compression – plate reorganization ~ 70 Ma
  • Kuskokwim magmatism – shallow at continental margin

(Flanigan et al., 2000; Goldfarb et al., 2000)
TINTINA GOLD BELT

(Goldfarb et al., 2000)
Shallow-level examples

Porphyry-style examples

Type-examples

Pogo

GEOLOGICAL EXPLORATION MODEL
TINTINA GOLD BELT

- Fort Knox, Ryan Lode & True North
- Kaltag Fault
- Donlin Creek
- Shotgun Creek
- Farewell Fault
- Denali Fault
- Tintina Fault
- Dublin Gulch
- Pogo
- Brewery Creek
- Tintina Gold Belt
- Tombstone Plutonic Suite
- Tungsten Plutonic Suite
- Major gold deposits
- Gold occurrences

(Kula (85Ma) Kula (56Ma) Farallon (100Ma))

(Flanigan et al., 2000)
FORT KNOX (7.2 M.oz.)

- Exploration & mining
  - Placer gold 1902 in creeks down stream
  - Au-W veins & skarns 1913 peripheral to FK
  - Bismuthinite with Au 1980 proximal creeks
  - Visible Au in granite 1984
  - Advanced exploration 1987 to 1994
  - Construction 1995; bulk tonnage open pit
  - Production 1996; 169 Mt @ 0.93 g/t
  - 1 M.oz. 1999

(Bakke, 1994)
FORT KNOX

- Intrusion Characteristics
  Tombstone suite
  Granodiorite to granite
  Ilmenite series, I-type
  Late aplites & pegmatites
  Locally UST & brain rock textures

- Age
  U-Pb 92 Ma - Intrusion
  Ar-Ar ~88-86 Ma - Muscovite alt.
  Re-Os 92.5 Ma - Molybdenite

(Bakke, 1994; Hart et al., 2001)
FORT KNOX

150m

Med.Granite
Coarse Granite
Schist
Shear Zone

(Bakke, 1994)
FORT KNOX (looking W)

(Bakke, 2000)
FORT KNOX

• Vein Characteristics
  Pegmatites & sheeted veins (min’l)
  Overprinted quartz filled faults (min’l)
  Au-Bi-Te-As-Sb-W-Mo (inc. deeper)
  Sulfide <1% - Py, Po, Apy, Mo, Sch

• Ore Characteristics
  Bi, Bi₂S₃, Bi₂Te₃
  Free Au, ~111microns, >960 fineness
  Au:Bi 0.86
  (Bakke, 1994; McCoy et al., 1997)
FORT KNOX
FORT KNOX
FORT KNOX

• Alteration
  Early Albite > K-feldspar
  Quartz-Sericite-Carbonate
  Regional propylitic & pyrite halo

• Fluids
  Low salinity aqueous-carbonic
  250-500°C @ >1.5kbar, >5km
  Oxygen isotopes fluid 5 to 10 per mil
  Sulphur isotopes 0±5 per mil

(Bakke, 1994; McCoy et al., 1997)
DUBLIN GULCH
DUBLIN GULCH (~2 M.oz.)

• Exploration
  – Placer Au mining established 1895 – 1898; scheelite reported
  – Rex-Peso Pb-Zn-Ag veins explored 1910
  – Cassiterite found – Tin Dome (<0.3 % Sn)
  – Au-W-Bi reported (Boyle, 1965)
  – Ray Gulch 5.4 Mt.@ 0.82 % WO$_3$
  – Gold in peripheral veins explored – 1986-1988
  – 1991 to 1996 gold soil anomaly around Eagle Zone drilled

(Maloof et al, 2001)
Biotite hornfels and calc-silicate skarn aureole
Granite and aplite
Granodiorite

Eagle Zone
Ray Gulch
Peso-Ag
Rex-Ag

Upper Schist
Central Quartzite
Lower Schist
Grit Unit

(Maloof et al, 2001)
DUBLIN GULCH

• Intrusion Characteristics
  Granodiorite to granite
  Ilmenite series, I-type
  Late aplites & pegmatites

• Vein & Ore Characteristics
  Predominantly sheeted veins (2 main stages)
  Au-Bi-Te-As-Sb-Pb-W-Mo (inc. deeper)
  Sulphide <3% - Py, Po, Apy, Sch, Gal, Au-Pb-Bi-Te-Sb
  Free Au & Au-Bi, ~155microns, ~1000 fineness
  Au:Bi – 0.89

(Maloof et al, 2001)
EAGLE ZONE

(Maloof et al, 2001)
<table>
<thead>
<tr>
<th></th>
<th>Stage I</th>
<th>Stagell</th>
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<tr>
<td>Gold</td>
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</table>

(Maloof et al, 2001)
EAGLE ZONE PARAGENESIS

- 1.8mm quartz
- carb
- scheelite
- carb/ser frac
- K-spar

(Maloof et al, 2001)
EAGLE ZONE PARAGENESIS

(Maloof et al, 2001)
## EAGLE ZONE GEOCHEMISTRY

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<tr>
<th></th>
<th>Au</th>
<th>Bi</th>
<th>As</th>
<th>Sb</th>
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<th>Mo</th>
<th>W</th>
<th>Zn</th>
<th>Pb</th>
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<td>0.79</td>
<td>0.85</td>
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<td>Sb</td>
<td>0.07</td>
<td>0.05</td>
<td>0.61</td>
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<td>As</td>
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</table>

(Maloof et al, 2001)
RAY GULCH

(W) LOOKING NORTH (E)

CALC-SILICATE SKARN (scheelite bearing)
APLITE DYKES
GRANODIORITE
BIOTITE-QUARTZ HORNFELS AND PHYLITES

60m

(Brown et al, 2001)
# Ray Gulch Paragenesis

## Stages

<table>
<thead>
<tr>
<th></th>
<th>Stage I</th>
<th>Stage II</th>
<th>Stage III</th>
<th>Stage IV</th>
<th>Stage V</th>
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<tr>
<td></td>
<td>(Alt'n)</td>
<td>(Alt'n)</td>
<td>(Vein)</td>
<td>(Vein)</td>
<td>(Vein)</td>
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</table>

- **Qtz**: Quartz
- **Wol**: Wolframite
- **Pyx**: Pyrite
- **Gnt**: Ganister
- **Sch**: Schist
- **Fsp**: Feldspar
- **Amp**: Amphibole
- **Cal**: Calcite
- **Chl**: Chlorite
- **Mol**: Molybdenite
- **Py**: Pyrite
- **Po**: Potassium Feldspar
- **Apy**: Apatite

**Granodiorite**

**Aplitic**

(Brown et al, 2001)
### EAGLE ZONE GEOCHEMISTRY

<table>
<thead>
<tr>
<th>Element</th>
<th>Maximum Concentration</th>
<th>Average (ppm)</th>
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<tbody>
<tr>
<td>Au</td>
<td>up to 40 g/t</td>
<td>0.83</td>
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<tr>
<td>Bi</td>
<td>up to 500 ppm</td>
<td>19</td>
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<tr>
<td>W</td>
<td>up to 2000 ppm</td>
<td>11</td>
</tr>
<tr>
<td>Mo</td>
<td>up to 700 ppm</td>
<td>6</td>
</tr>
<tr>
<td>As</td>
<td>up to &amp; &gt;10,000 ppm</td>
<td>195</td>
</tr>
<tr>
<td>Pb</td>
<td>up to &amp; &gt;10,000 ppm</td>
<td>59</td>
</tr>
<tr>
<td>Zn</td>
<td>up to &amp; &gt;10,000 ppm</td>
<td>108</td>
</tr>
<tr>
<td>Sb</td>
<td>up to 5,000 ppm</td>
<td>11</td>
</tr>
<tr>
<td>Cu</td>
<td>up to 355 ppm</td>
<td>34</td>
</tr>
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</table>

(Maloof et al, 2001)
### RAY GULCH GEOCHEMISTRY

<table>
<thead>
<tr>
<th></th>
<th>W</th>
<th>Mo</th>
<th>Sn</th>
<th>Au (ppb)</th>
<th>Bi</th>
<th>Sb</th>
<th>As</th>
<th>Zn</th>
<th>Ag</th>
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<tr>
<td><strong>Wol-Qtz Skarn</strong></td>
<td>&lt;334</td>
<td>&lt;6</td>
<td>bd</td>
<td>bd</td>
<td>&lt;1</td>
<td>&lt;0.5</td>
<td>1-5</td>
<td>bd</td>
<td>bd</td>
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<tr>
<td>(n=2)</td>
<td></td>
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<td></td>
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<tr>
<td><strong>Pyx Skarn</strong></td>
<td>200 to 50000</td>
<td>&lt;180</td>
<td>bd</td>
<td>bd (10, 38, 13)</td>
<td>&lt;1</td>
<td>&lt;5</td>
<td>&lt;5</td>
<td>&lt;300</td>
<td>bd</td>
</tr>
<tr>
<td>(n=9)</td>
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<tr>
<td><strong>Vein</strong></td>
<td>0 to &gt;100000</td>
<td>&lt;90</td>
<td>bd</td>
<td>bd (148)</td>
<td>&lt;1</td>
<td>&lt;5</td>
<td>&lt;14</td>
<td>&lt;150</td>
<td>bd</td>
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<td>(n=14)</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>

(Brown et al, 2001)
RAY GULCH VS EAGLE ZONE

• RG skarn replacement > vein (~10 vol. %)
• EZ sheeted veins
• EZ Stage II key – Au-Bi event
• Stage missing in RG skarn
• Stage III-V RG = Stage I EZ – Qtz-Fsp-Sch

(Brown et al, 2001)
OUTLINE OF EXAMPLES IN SHORTCOURSE

1. Type-examples

2. Porphyry-style examples

3. Shallow-level examples

4. Pogo
SHOTGUN (~1 M.oz.)

(Rombach & Newberry, 2001)
SHOTGUN

• Geology & Mineralization
  – Granite porphyry (70 Ma)
  – Stockwork & breccia; local UST/brain rock
  – Early albite, later sericite-carbonate
  – Apy-Py-Po-Loel-Cpy-Mo-Bn-Sch
  – Au-Bi-Te (Au:Bi 0.76)

(Rombach & Newberry, 2001)
SHOTGUN

- Fluids
  - Reduced ore assemblages (δS −5.5 to −5.0)
  - Fluid inclusions: vapour & brine; 300-600°C
  - Vapour: H₂O>CO₂>CH₄, low salinity
  - Brine: 40-60 wt.% NaCl equiv.
  - Pressure/depth: ~0.5 kbar/ ~2 km
  - O, H, S isotopes & fluids = magmatic

(Rombach & Newberry, 2001)
## Shotgun Paragenesis

<table>
<thead>
<tr>
<th>Sulfide assemblage(s)</th>
<th>Early</th>
<th>Late</th>
</tr>
</thead>
<tbody>
<tr>
<td>asp + lo + po + cpy* ± cb ± bn*</td>
<td>asp + po + cpy, cpy + bn*</td>
<td>py + asp + cpy ± spl</td>
</tr>
<tr>
<td>Alteration assemblage (plus quartz vein)</td>
<td>albite ± tourm (biotite, K-spar)</td>
<td>albite ± sericite ± (rutile ± tour ± chlorite)</td>
</tr>
<tr>
<td>Gold assemblage</td>
<td>Au° + Bi-Te, Au₂Bi</td>
<td>Au-Ag° + Bi₂S₃ ±, Bi-Te sulfide</td>
</tr>
<tr>
<td>Vein styles</td>
<td>Veinlet, disseminated</td>
<td>Vein, veinlet, breccia</td>
</tr>
<tr>
<td>Gold occurrence</td>
<td>Inclusions in arsenopyrite</td>
<td>Isolated grains</td>
</tr>
<tr>
<td>Approximate temperature range</td>
<td>&gt;500°C</td>
<td>500 to 400°C</td>
</tr>
</tbody>
</table>

(Rombach & Newberry, 2001)
SHOTGUN TEXTURES

A - Stockwork
C - Breccia
D - UST/brain rock
Au-Bi – 0.73

(Rombach & Newberry, 2001)
OUTLINE OF EXAMPLES IN SHORTCOURSE

1. Type-examples

2. Porphyry-style examples

3. Shallow-level examples

4. Pogo
TINTINA GOLD BELT

Fort Knox, Ryan Lode & True North
Kaltag Fault
Donlin Creek
Shotgun
Farewell Fault
Denali Fault
Kaltag Fault
Kula (85Ma)
Kula (56Ma)
Farallon (100Ma)

Major gold deposits
Gold occurrences

Tintina Gold Belt
Tombstone Plutonic Suite
Tungsten Plutonic Suite

(Flanigan et al., 2000)
DONLIN CREEK (28 M.oz.)

- Exploration
  - Placer gold 1909
  - Lode ore found 1940 above placer fields
  - Ongoing exploration 1970-1990’s
  - Rock chip & soil sampling (>250ppb over ore)
  - RC & diamond drilling

(Ebert et al., 2000)
DONLIN CREEK

• Geology & mineralization
  – Rhyolite dykes hosted in reduced flysch sediments
  – Magmatism & mineralization 71 to 66 Ma
  – Fault controlled NE & NW strike-slip
  – Narrow Au-As-Sb-Hg veins in dykes>sediments
  – Ore within NNE extensional fracture zone
  – Epithermal/epizonal characteristics

(Ebert et al., 2000)
DONLIN CREEK VEINS
DONLIN CREEK MAGMATIC MODEL

(Ebert, 2001)
TINTINA GOLD BELT

- Donlin Creek
- Fort Knox, Ryan Lode & True North
- Kaltag Fault
- Kula (85Ma)
- Kula (56Ma)
- Kula (100Ma)
- Dublin Gulch
- Pogo
- Brewery Creek
- Kuganqa Fault
- Farewell Fault
- Denali Fault
- Tintina Fault
- Tintina Gold Belt
- Tombstone Plutonic Suite
- Tungsten Plutonic Suite
- Major gold deposits
- Gold occurrences

(Flanigan et al., 2000)
BREWERY CREEK (1.4 M.oz.)

- Exploration
  - Discovered in 1987
  - Soil geochemistry
  - >25ppb over 12km strike
  - Reserve trend ~12 major gold zones
  - Open pit mining between 1997 & 2001

(Diment, 1996)
BREWERY CREEK

• Geology
  – 80 % ore hosted in Tombstone suite intrusions
  – 20 % hosted in Cambrian-Carboniferous sediments
  – Reserve trend comprises
    • Lies outside magnetic high (aureole/intrusion)
    • E-W monzonite
    • Normal, dip-slip E-W, NW & NNE brittle faults
    • Veins & ore trend E-W with NNE component

(Lindsay, 2002)
BREWERY CREEK MAP

(Lindsay, 2002)
(Hart et al., 2000)
BREWERY CREEK CROSS SECTION

Reserve Trend

CANADIAN DEPOSIT
(adapted from Diment, 1995)

(Diment, 1995; Lindsay, 2002)
BREWERY CREEK GRADE TRENDS

(Lindsay, 2002)
BREWERY CREEK

• Ore
  – Mineralization in monzonite, 3 vein stages
    1) pyrite-quartz-carbonate-roscoelite
    2) arsenopyrite-carbonate-quartz-gold
    3) stibnite-quartz-carbonate-adularia
  – Only oxide ore processed (weathering ~10-30m)
  – Hypogene gold in arsenopyrite & arsenian pyrite

(Mark, 2002)
BREWERY CREEK PARAGENESIS
POGO (> 5 M.oz.)

- Exploration
  - Geochemical sampling Goodpaster River 1981
  - Au, As, W anomalies in Pogo & Liese Creeks
  - Soil sampling & surface-exploration 1993
  - >100ppb Au in soils anomaly 2km²
  - Drilling soil anomaly 1994 – Liese zone
  - Drive developed 1999-2000
  - Pour first gold end 2005

(Smith et al., 1999)
POGO

View to North

- Topo relief - 830m (1225m - 400m ASL)
- Deepest Drilling is 230m ASL returned 2.5m @ 7.16 g/t Au at L3 level.
- 1500m relief from deep bottom drilling to Top Hill 4021

(Roberts, 2005)
POGO

- Host rocks
  - L. Proterozoic - M. Paleozoic gneiss
    - Amphibolite facies
      - M. Cretaceous granite dykes, aplites & pegmatites
        - Reduced I-type, 15% vol.
      - Post-mineralization dolerites
  - Age
    - U-Pb 107 to 93 Ma – Intrusions
    - Ar-Ar ~91-92 Ma - Mica alt
    - Re-Os ~104Ma - Molybdenite

(Smith et al., 1999; Selby et al., 2002)
POGO (> 5 M.oz.)

(Smith et al., 1999; Selby et al., 2002)
POGO

- Ore
  
  Sulphide ~3%
  
  Reduced assemblage: Po-Lo-Apy-Py-Ccp
  
  Au-Bi-Pb-Te-Ag-S phases; Au:Bi 0.89

![Graph showing Au vs. Bi concentrations with a line indicating a ratio of 0.89.](image-url)
OVERVIEW

• Part 1: Classification, nomenclature & deposit comparison

• Part 2: Examples: Tintina Gold Province

• Part 3: Other examples & exploration
Late Paleozoic gold deposits, Tien Shan

(Yakubchuk et al., 2002)
Gold deposit model
Tien Shan

Taror 3 M.oz.
Amantaitau 4 M.oz.
Murontau 175 M.oz.
Jilau 3 M.oz.
Zarmitan 11.3 M.oz.

(Yakubchuk et al., 2002)
KIDSTON (4 M. oz.)

- Regional Geology
  - Kennedy Igneous Province
  - Mid-Carboniferous-Permian intrusions
  - I-type granites, crustally derived
  - Similar tectonic setting to TGB?
  - Regional Au-Sn-W-Bi-Mo-As-Sb

(Baker & Andrew, 1991)
KIDSTON

• Deposit Geology
  • Magmatic-hydrothermal breccia pipe
  • Intrudes Proterozoic granitoid & gneiss
  • Gold in breccia & sheeted veins
  • Rhyolite sills & dykes
  • Py-Po-Sph-Ccp-Mo-Gal-Apy-Bi; zoned
  • Deeper Mo-W mineralization
  • Ser-Carb-Qtz alteration

(Baker & Andrew, 1991)
KIDSTON TEXTURES
TIMBARRA (0.4 M.oz.)

- Geology & Mineralization
  - Zoned granite pluton (250-245 Ma)
  - Age ore & alteration = intrusion
  - Disseminated Au-Bi-Ag-Te-(Mo-As-Sb)
  - Sulfide < 1%; Apy-Py-Moly-Au-Bi-Te-Ag
  - Magmatic-hydrothermal transition

(Mustard, 2001)
TIMBARRA MAP

Legend

- Drake Volcanics
- Spherulitic flow-banded Rhyolite Dyke
- Fine to medium grained porphyritic Granite Stock
- Palelithic, monographic Granite Stock
- Medium to coarse grained porphyritic altered Stock
- BPG - Strongly Porphyritic Granite (Carapace)
- VFG - Very fine grained Granite (Carapace)
- VFG - Very fine grained Granite (Internal)
- FMG - Fine to medium grained Granite (Carapace)
- FMG - Medium to fine grained Granite (Carapace)
- MCG - Medium to coarse grained Granite (Main Type)
- MPG - Moderately porphyritic Granite (Main Type)
- Fine to medium grained Granite (Transitional Type)
- Medium to very coarse grained Granite (Main Type)
- Medium to coarse grained Granite (Main Type)
- Medium to coarse grained Granite (Border Type)

(Mustard, 2001)
TIMBARRA CROSS SECTION

(Mustard, 2001)
TIMBARRA GRANITE FACIES & Au

(Mustard, 2001)
## TIMBARRA PARAGENESIS & FLUIDS

<table>
<thead>
<tr>
<th>Process</th>
<th>Late Magmatic</th>
<th>Transitional Magmatic-Hydrothermal</th>
<th>Hydrothermal</th>
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<td><strong>Mineralization Style</strong></td>
<td>Stage 1</td>
<td>Stage 2a</td>
<td>Stage 3</td>
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<td>Miarolitic cavities</td>
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<td>Aplitite dykes</td>
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<tr>
<td>Pegmatite veins</td>
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<td>Vein-dikes</td>
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<td>Quartz-moly veins</td>
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<td>Fractures (Au)</td>
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<td>Comb veins</td>
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<td>Chalcedonic veins</td>
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<td>Hematite staining</td>
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<td>Melt Inclusions</td>
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<td>High XCO2</td>
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<td>Mod-Low XCO2</td>
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<tr>
<td>Mod-Low Salinity H2O</td>
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(Mustard, 2001; Mustard, 2000)
### SUMMARY CHARACTERISTICS

<table>
<thead>
<tr>
<th>Shallow (&lt;3km, &lt;1 kbar)</th>
<th>Style</th>
<th>Alteration</th>
<th>Metals</th>
<th>Fluids</th>
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</thead>
<tbody>
<tr>
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<td>• veinlets, stockwork, breccia</td>
<td>• clays, carb, fsp</td>
<td>• As, Sb, Hg, Bi, Te</td>
<td>• brine, CO₂-vapour, late H₂O</td>
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<tr>
<td></td>
<td>• dikes, stocks, sills</td>
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</table>

Strong evidence for major magmatic input, epithermal/porphyry style characteristics

<table>
<thead>
<tr>
<th>Deep (&gt;3km, &gt;1 kbar)</th>
<th>Style</th>
<th>Alteration</th>
<th>Metals</th>
<th>Fluids</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>• sheeted, disseminated</td>
<td>• fsp, carb</td>
<td>• W, Mo, Bi, Te</td>
<td>• CO₂-H₂O, some late brine</td>
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<tr>
<td></td>
<td>• stocks, plutons</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Baker, 2002)
IMPLICATIONS

• IRG possess range in characteristics

• Variation in part reflects depth of emplacement

• Magmatic carbon dioxide critical role
  • High pressure devolatilization
  • Effect on other volatiles
  • Volatile composition varies with depth

• Continuum of deposit types reflect depth & fluid composition

• Exploration criteria will vary between deep, shallow, proximal, distal
ROLE OF BISMUTH

• Au-Bi-W-Mo-As geochemistry
• Spatial & temporal link to intrusions
• In detail spatial & temporal differences
  • W early
  • Au-Bi late
• Main ore zones spatially separate
• Re-emphasizes Bi association
ROLE OF BISMUTH

- Bi significant in ppt. Au
- Bi low melting point (274°C), dec. with inc. pressure
- Bi will ppt. as a liquid rather than solid
- Experiments @ 300°C show strong partitioning Au in Bi liquid
- Bi may concentrate Au in fluids with very low Au contents
- Low melting point Bi, Au-Bi will be late

(Douglas et al, 2000)
APPLICATION OF KEY EXPLORATION CHARACTERISTICS

- Vertical & lateral zonation about mod-reduced granitic intrusions

- Set of pathfinder elements including Au, Bi, Te, As, W, (Mo, Sn, Sb)

- Variety of target types within IRGS
EXAMPLE OF IRGS EXPLORATION CHARACTERISTICS: NORTH QLD

• Reviewed mineral occurrence data sheets & 1:500,00 scale maps (Hogdkinson Province)

• Regional Scale: Tectono-Magmatic Setting
  – Continental arc environment
  – Numerous W-Sn-Mo-Bi-As & Au occurrences
  – Permo-Carb Kennedy Igneous Provence (KIP)
EXAMPLE OF IRGS EXPLORATION CHARACTERISTICS: NORTH QLD

• Regional Scale: Intrusive types
  – Wide range of granite suites
  – Including mod reduced I-types & transitional I-S to S types
  – Highly fractionated components
  – Magmatic-hydrothermal transition textures
EXAMPLE OF IRGS EXPLORATION CHARACTERISTICS: NORTH QLD

- Regional Scale: Variety of crustal levels exposed
  - Contact aureole development (& P-T information)
  - Presence/absence syn-intrusive volcanic rocks
  - Mineral occurrence styles

- Local Scale: Mineral Occurrence Data & Past Exploration
  - Past Au exploration focussed on Kidston-breccia styles &/or porphyry Cu-Au systems
  - Wider range of IRGS styles not widely tested
  - W-Bi-As-(Mo,Sn) prospects poorly tested for Au
EXAMPLE OF IRGS EXPLORATION CHARACTERISTICS: NORTH QLD

• Local Scale: Target Criteria
  – Spatial associated with mod-red I-type KIP intrusives
  – Geochemistry of mineral occurrences (including placer)
    • Au-Bi ±(W-Sn-Mo-Cu-Pb-As) – highest potential
    • Au-W (Bi commonly n/a)
    • Bi±(W-Sn-Mo±Cu - no recorded Au – commonly n/a)
    • Au-As-Sb – distal from intrusives, mesothermal-epithermal
  – Target type
    • Shallow (Donlin Creek-style); Mod-Deep proximal (Fort Knox-style);
      Mod-Deep distal (Pogo-style)
(modified from Garrad & Bultitude, 1999)
EXAMPLE OF IRGS EXPLORATION CHARACTERISTICS: NORTH QLD
EXAMPLE OF IRGS EXPLORATION CHARACTERISTICS: NORTH QLD

M2: 0.5ppm Au, 140ppm Bi

M5: 8.6ppm Au, 657ppm Bi
EXAMPLE OF IRGS EXPLORATION CHARACTERISTICS: NORTH QLD

![Graph showing the relationship between Au (ppb) and Bi (ppm).](image)
EXAMPLE OF IRGS EXPLORATION CHARACTERISTICS: NORTH QLD

T14 (1.26 ppm Au; 20.71 Bi) Quartz-muscovite vein with narrow muscovite (greisen-like) alteration halo Tinaroo Creek

T18 (2.42 ppm Au; 58 ppm Bi) Quartz-muscovite pegmatite-like vein
CONCLUSIONS I

• IRGS have a coherent, useable set of empirical exploration characteristics

• Critical features include
  – Vertical & lateral zonation about mod-reduced granitic intrusions
  – Set of pathfinder elements including Au, Bi, Te, As, W, (Mo, Sn, Sb)
  – Variety of target types within IRGS
CONCLUSIONS II

• Belts known for magmatic related W-Mo-Sn systems are high priority target areas
  – Au-(Bi-W) placer occurrences provide good indicator
  – Such regions commonly lack thorough testing of IRGS model
  – Commonly not sampled for Au & Bi

• Many regions can be regionally evaluated quickly through database searches & GIS approaches