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Isotope Geology
RADIOGENIC ISOTOPES IN GEOLOGY

**GEOCHRONOLOGY**
- Age of rocks, minerals and mineralizations
- Age of geological events

**GEOCHEMISTRY**
- Sources of Magmas and Fluids
- Water – rock interaction and magma contamination
CONCEPTUAL MODEL FOR ORE DEPOSITS

source → Age and Nature
migration → Time and Interaction
Geological Control → Type and Timing
Precipitation and Concentration → Time
Preservation → Erosion rates
TEMPORAL RELATIONSHIPS OF MINERALIZATION TO GEOLOGICAL EVENTS

(adapted from Sillitoe, 1999)
What target look first?

CRITERIA FOR MINERAL EXPLORATION PROGRAM
ISOTOPIC SYSTEMS IN ORE DEPOSITS AND OIL SYSTEMS

$^{87}$Rb – $^{87}$Sr

$^{235}$U – $^{207}$Pb
$^{238}$U – $^{206}$Pb
$^{232}$Th – $^{208}$Pb

U - Pb
Pb - Pb

$^{147}$Sm – $^{143}$Nd
$^{176}$Lu – $^{176}$Hf

$^{187}$Re – $^{187}$Os

$^{40}$K – $^{40}$Ar
$^{40}$Ar – $^{39}$Ar
RADIOACTIVE DECAY

\[ ^{87}\text{Rb} \rightarrow ^{87}\text{Sr} \]

Radioactive Element \rightarrow Radiogenic Element

\[ \lambda \]
EQUATION: \[ N = N_0 e^{-\lambda t} \]

**GEOCHRONOLOGICAL EQUATION**

\[ T = \frac{1}{\lambda} \ln(1 + D/N) \]
Age can be calculated in different ways

U-Pb Concordia Diagram

Hydrothermal altered volcanic rocks
El Soldado
Age = 109 ± 6 Ma

Rb-Sr, Sm-Nd, Re-Os and Pb-Pb Isochronic Diagram

Ar-Ar Plateau Age Diagram
**AGE** is related to **TEMPERATURE (Closure Temperatures)**

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>MINERAL</th>
<th>TEMPERATURE (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K – Ar (Ar - Ar)</td>
<td>hornblende</td>
<td>500</td>
</tr>
<tr>
<td>K – Ar (Ar - Ar)</td>
<td>muscovite</td>
<td>350</td>
</tr>
<tr>
<td>K – Ar (Ar - Ar)</td>
<td>biotite</td>
<td>300</td>
</tr>
<tr>
<td>K – Ar (Ar - Ar)</td>
<td>microline</td>
<td>250 - 150</td>
</tr>
<tr>
<td>Rb - Sr</td>
<td>whole-rock</td>
<td>~ 700</td>
</tr>
<tr>
<td>Rb - Sr</td>
<td>muscovite</td>
<td>450</td>
</tr>
<tr>
<td>Rb - Sr</td>
<td>biotite</td>
<td>350</td>
</tr>
<tr>
<td>Sm - Nd</td>
<td>garnet</td>
<td>600</td>
</tr>
<tr>
<td>U – Pb</td>
<td>zircon</td>
<td>≥ 700</td>
</tr>
<tr>
<td>U - Pb</td>
<td>monazite</td>
<td>600</td>
</tr>
<tr>
<td>Re - Os</td>
<td>pyrite</td>
<td>500</td>
</tr>
<tr>
<td>Re - Os</td>
<td>molybdenite</td>
<td>450</td>
</tr>
<tr>
<td>Re - Os</td>
<td>chalcopyrite</td>
<td>400</td>
</tr>
<tr>
<td>Re - Os</td>
<td>sphalerite</td>
<td>350</td>
</tr>
<tr>
<td>FT</td>
<td>apatite</td>
<td>70 to 110</td>
</tr>
</tbody>
</table>
Indirectly mineralization dating
hydrothermal alteration minerals

Sericite
Biotite
Alunite
Illite
Monazite
Hydrothermal zircon
Strongly altered whole-rock
MARMATO GOLD DISTRICT – ECHANDIA SECTOR

<table>
<thead>
<tr>
<th>MINERAL</th>
<th>ROCK</th>
<th>% K</th>
<th>$^{40}$Ar rad. ccSTP/g</th>
<th>$^{40}$Ar atm. (%)</th>
<th>IDADE (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plagiocl.</td>
<td>Porph. Dacitic</td>
<td>1.766</td>
<td>0.38</td>
<td>65.3</td>
<td>5.6 ± 0.6</td>
</tr>
</tbody>
</table>

Ar – Ar Biotite, (Vinasco 2001)
Marmato stock: 6.7 ± 0.1 Ma
Cauca Romeral Shear Zone: 5.6 ± 0.4 Ma

Tassinari et. al., 2008
HYDROTHERMAL ALTERED VOLCANIC ROCKS

El Soldado

AGE = 109 ± 6 Ma

Sr/87Sr = 0.7048 ± 0.0003

El Soldado - Chile
Mantle Type Cu Mine

Sr/87Sr

Tassinari & Munizaga unp.
HIDROTHERMAL ALTERATION MINERAL ASSEMBLAGE
Rb –Sr Technique

Age = 364.4 ± 3.6 Ma
Initial $^{87}$Sr/$^{86}$Sr = 0.74606 ± 0.00028
ZIRCONS FROM THE MINERALIZED METAGRAYWACKE (MINA III – LEVEL 600)

Hydrothermal zircon

2165 ± 47 Ma

500 - 450 Ma

Jost et. al. 2010
U-Pb HYDROTHERMAL Monazite SHRIMP AGE
Cuiaba and Morro Velho gold mines

U–Pb SHRIMP monazite ages of the giant Morro Velho and Cuiabá gold deposits, Rio das Velhas greenstone belt, Quadrilátero Ferrífero, Minas Gerais, Brazil

Lobato et. al. 2007
Directly mineralization dating
Ore and Gangue minerals

Sulfides
(Py.; Cpy.; Sph.; Ga.; Pyrt.; Cov.; Moly)

Schellite

Magnetite

Tourmaline

Fluorite

Garnet

Chromite
El Toqui Zn Deposit - Chile

\[ \frac{^{87}Rb}{^{86}Sr} \]

\[ \frac{^{87}Sr}{^{86}Sr} \]

\[ T(Ma) = 99.1 \pm 1.9 \]

\[ Ro = 0.70597 \pm 0.00011 \]

\[ MSWD = 0.9323 \quad R = 0.9996 \]
Produtos Lixiviados de MAGNETITAS - SALOBO 3A

Carajás Mineral Province

Idade = 2112 ± 12 Ma
MSWD = 1.8

Tassinari et. al. 2003
Pb-Pb Stacey & Kramers Model Age

Serra dos Carajás – Gradaús prospect

Stacey & Kramers Curve

Py

Cpy

2729 Ma
2500 Ma
2168 Ma

Pb-Pb Stacey & Kramers Model Age
primary pyrite and secondary calchopyrite
Serra dos Carajás – Gradaús prospect

2700
2500
2300
2100
14.4
14.6
14.8
15.0
15.2
15.4
13.2 13.6 14.0 14.4 14.8
206Pb/204Pb
207 Pb/204 Pb
2729 Ma
2168 Ma
Lusitanica Sedimentary Basin, Portugal

Stacey and Kramers Pb-Pb model age

- **152 Ma**: Distension and reactivation of preexisting faults associated with the development of basin rifting.
- **59 Ma**: Stage of inversion of the sedimentary basin.
- **30 Ma**: Second Stage of inversion of the sedimentary basin.

Ferreira (2017)
Vaal Reef pyrite isochron

$2.99 \pm 0.11 \text{ Ga (MSWD} = 0.77)$

$\frac{^{187}\text{Os}}{^{188}\text{Os}}$ vs. $\frac{^{187}\text{Re}}{^{188}\text{Os}}$

$0.124 \pm 0.037$

Kirk et. al. 2003
Sm-Nd isochron diagram illustrating data from scheelite (CaWO₄) from lode Au deposits associated with an shear zone system in Zimbabwe

Age = 2668±64 Ma

initial $^{143}$Nd/$^{144}$Nd ratio = 0.50918±0.00010

Darbyshire et. al. (1996)
Chromitite and gabbro of the Tapo Ultramafic Massif
Central Peru

Tassinari et. al. 2010
Pyrite may armour K-bearing mineral inclusions from alteration induced by Ar loss
Figure 1. Photomicrograph showing muscovite inclusions in pyrite grains from (A) Mount Charlotte sample MC1 and (B) Kanowna Belle sample GD1.
Figure 2. A: $^{40}$Ar/$^{39}$Ar step-heating age spectrum for matrix muscovite from Mount Charlotte sample MC1.

Phillips D, Miller J M Geology 2006;34:397-400

Matrix muscovite

Pyrite muscovite

AGE = 2564 ± 9 Ma

AGE = 2595 ± 19 Ma

AGE = 2594 ± 8 Ma
What can be done with radiogenic isotopes beyond ages?

- $^{87}\text{Sr}/^{86}\text{Sr}$
- $^{147}\text{Sm}/^{143}\text{Nd}$
- $^{206}\text{Pb}/^{204}\text{Pb}$
- $^{208}\text{Pb}/^{204}\text{Pb}$
- $^{188}\text{Os}/^{187}\text{Os}$

These isotopes are used to study the relationship between source and fluid-rock interaction. The isotope composition is given by:

$$\text{ISOTOPE COMPOSITION} = \text{Source} + \text{fluid-rock interaction}$$
ONE OF THE MOST USEFUL, CONSERVATIVE, AND STABLE ELEMENTS FOR ISOTOPIC STUDY IN SEDIMENTARY ROCKS (CARBONATES AND EVAPORITES)

\[ \frac{\text{Sr}^{87}}{\text{Sr}^{86}} \]
ISOTOPIC MODELLING FOR MINERAL EXPLORATION: MISSISSIPPI VALLEY TYPE MINERALIZATIONS

- **Important Ore Deposits**
  (Kentucky + Tenesse + Virginia)

- **Small Deposits (No economic)**
  (NW Ohio)

Kessen et. al. 1988
MISSISSIPPI VALLEY DISTRICT

No Economic Mineralizations

$^{87}\text{Sr}/^{86}\text{Sr}$

- Host carbonates
- MVT ore minerals

0.709

- pugh
- Aug.
- Lima
- Wt.rock

Mining Occurrences
MISSISSIPPI VALLEY DISTRICT

Economic Mineralizations

$^{87}\text{Sr}/^{86}\text{Sr}$

Ore minerals

Host Carbonates

Mines

cave  salem  gratz  Masc.  Aust.
ISOTOPIC MODELLING FOR MINERAL EXPLORATION OF Cooper Porphyry Deposits

Sr ISOTOPES AS INDICATOR OF THE POTENTIAL SIZE OF DEPOSIT

BHP's Escondida Mine in Chile
Zongo-San Gaban Zone [38-40Ma crustal ramp]

Clark, 1993, modified

<table>
<thead>
<tr>
<th>Ma</th>
<th>$S_{r_1}$</th>
<th>t Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>0.7082</td>
<td>&lt;50,000 (+Pb, Zn and Ag)</td>
</tr>
<tr>
<td>41</td>
<td>0.7064</td>
<td>&lt;200,000?</td>
</tr>
<tr>
<td>37</td>
<td>0.7061</td>
<td>&lt;100,000</td>
</tr>
<tr>
<td>36</td>
<td>0.7058</td>
<td>&lt;100,000 (+Mo)</td>
</tr>
<tr>
<td>37</td>
<td>0.7043</td>
<td>10,000,000</td>
</tr>
<tr>
<td>32</td>
<td>0.7044</td>
<td>+43,000,000</td>
</tr>
<tr>
<td>34</td>
<td>0.7040</td>
<td>22,500,000</td>
</tr>
<tr>
<td>41</td>
<td>0.7041</td>
<td>5,700,000</td>
</tr>
<tr>
<td>44</td>
<td>0.7053</td>
<td>SMALL</td>
</tr>
</tbody>
</table>
Os Isotopes: $^{187}\text{Os}/^{188}\text{Os}$ vs. Tonnes Porphyry Cu Deposits – CHILE

crustal contamination

Mathur et. al., 2000
MINERALIZATIONS

Mpodozis & Kay (2000)
ISOTOPIC MODELLING FOR MINERAL EXPLORATION OF PGE

Bathopele Mine – Anglo American, SA
PGE magmatic deposits

- Manto derived silicated magmas
  - Low S content in the mantle

S and PGE concentration

- Mafic magmas contaminated by Felsic magmas

S + PGE concentration should be close to the limit between contaminated and non-contaminated zones
Merensky Reef

Crustal Contamination
Mafic – Ultramafic bodies

Hypotetical Situation
Nd Isotopes mineralization fluid sources

\[ \epsilon_{Nd, CHUR} = \left[ \frac{^{143}Nd}{^{144}Nd}_{sample} \right] - \left[ \frac{^{143}Nd}{^{144}Nd}_{CHUR} \right] \times 10^4 \]
RANGE OF $\varepsilon_{\text{Nd}}$ VALUES (Mina III - CRIXAS)

- **Pyrrhotite**
- **Arsenopyrite**
- **Metakomatiite** (Arndt et al. 1989)
- **Metabasalt**
- **Metagraywacke**
- **Carbonaceous Schist**

$\varepsilon_{\text{Nd}}$ (2.2 Ga) vs. $\varepsilon_{\text{Nd}}$ range from -4 to +4.

Tassinari et al. In prep.
The Re-Os systematics of gold and sulfides from the Witwatersrand basin were utilized to determine whether the gold is detrital or was introduced by hydrothermal solutions from outside the basin.
GOLD
Placer or Hydrothermal Model?

Kirk et. al. 2003
Re-Os Isochron

Vaal Reef pyrite isochron

$2.99 \pm 0.11 \text{ Ga (MSWD = 0.77)}$

$0.124 \pm 0.037$

Kirk et al. 2003
Pb ISOTOPES

IMPORTANT TOOL IN MINERAL EXPLORATION

- COMPARISON OF MINERAL DEPOSITS
- CHARACTERIZATION OF ROCKS SOURCE OF FLUIDS
- CRITERIA TO PRIORITIZATION

OF GEOCHEMICAL / GEOPHYSICAL ANOMALIES OR TARGETS
MAGMATIC ARCS AND SELECTED METALLOTECTS

Triassic-Jurassic
San Lucas-Norosí Metallotect (early Jurassic)
El Bagre Metallotect (mid to late Jurassic)

Late Cretaceous to early Paleocene
Antioquia Metallotect
Late Miocene
Middle Cauca Metallotect
ORE Pb-Pb ISOTOPE RESULTS

San Lucas-Norosí Metallotect
(early Jurassic)

El Bagre Metallotect
(mid to late Jurassic)

Antioquia Metallotect
(late Cretaceous – Early Paleocene)

Middle Cauca Metallotect
(late Miocene)

Leal Mejia et. al., 2009
Epithermal Porphyry (?) System

Conceptual Porphyry Cu-Au Deposit Model (after Sillitoe, 1995)

- Chalco-alteration
- Advanced argillic alteration
- Low sulphidation vein
- High sulphidation massive sulphide lode
- Porphyry alteration with porphyry Cu-Au mineralization
- Porphyry stock
- Sub-volcanic basement
isotopic compositions of fluids and rocks may indicate relative contributions from crustal versus mantle sources.
Lead isotope signatures of epithermal and porphyry-type ore deposits from the Romanian Carpathian Mountains

Marcoux et. al. 2002
MARMATO GOLD DISTRICT - COLOMBIA
Pb isotopic variations
Marmato Gold District - Colombia

Melo, 2015
Pb ISOTOPES APPLYED TO MINERAL EXPLORATION

• GENERAL CONCEPT

• A MINERAL OCCURRENCE THAT HAS THE SAME ISOTOPIC SIGNATURE AS A ECONOMIC DEPOSIT, WITHIN THE SAME DISTRICT OR GEOLOGICAL PROVINCE, MAY BE ECONOMIC TOO.
lead isotopes applied to VMS mineral exploration

Example: Elliot Bay District, SW Tasmania (Gulson, 1986)

MINERALIZATION TYPES:
- Stratiform Massive Sulfide
- Pb-Zn disseminated sulfide, with low gold content
- Sulfide bearing quartz veins
PROCEDURES

- Establishment of the Pb isotopic composition of all the mineralization styles of the most important deposit in the district (Isotopic Data-Base)
  \[ \frac{^{206}\text{Pb}}{^{204}\text{Pb}} ; \frac{^{207}\text{Pb}}{^{204}\text{Pb}} ; \frac{^{208}\text{Pb}}{^{204}\text{Pb}} \]

- To measure the Pb isotopic composition of the areas with geochemical and geophysical anomalies
  - Soil samples were collected from the C horizon in trenches 5 meters deep
Base metal exploration of the Mount Read Volcanics, western Tasmania; Pt. II, Lead isotope signatures and genetic implications

Brian L. Gulson and Patricia M. Porritt

Economic Geology April 1987 v. 82 no. 2 p. 291-307
Pb isotopic compositions for the main mineralized zone (VMS)

Gulson and Porritt, 1987
Pulverized samples from drill core and from the trench

Gulson and Porritt, 1987
Red Hills prospect
pulverized samples from drill core

Gulson and Porritt, 1987
Isotopic Analysis Program Costs

Applied to Mineral Exploration and Oil and Gas Exploration

~ US$ 10,000 – 15,000