Felsic magmatism and uranium deposits

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Uraninite (St Sylvestre two micas granite)

URAM 2014, June 23-27 Vienna
### METAL FRACTIONATION FROM ULTRABASIC ROCKS TO GRANITES

<table>
<thead>
<tr>
<th>ppm</th>
<th>Ultrabasic</th>
<th>Basic</th>
<th>Intermediate</th>
<th>Granites</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>0.021</td>
<td>0.75</td>
<td>2.4</td>
<td>3.3</td>
<td>x 160</td>
</tr>
<tr>
<td>Th</td>
<td>0.060</td>
<td>3.5</td>
<td>7.8</td>
<td>17.5</td>
<td></td>
</tr>
</tbody>
</table>

Earth average Th/U = 4

INCOMPATIBLE BEHAVIOR
WHAT IS AN INCOMPATIBLE ELEMENT?

Olivine > Mantle = Silicates

\[
\text{Mg}^{2+} \quad \text{low charge}
\]
\[
\text{small ionic radius} \quad \equiv \text{Ni}^{2+} = 0.69
\]

\[
\text{Th}^{4+} \quad \text{high charge}
\]
\[
\text{large ionic radius} \quad 1 \, \text{Å} \quad \text{(coordinance 8)}
\]

\[
\text{Incompatible with the silicate network}
\]
U INCOMPATIBLE BEHAVIOUR

Several major geochemical, geophysical and metallogenic consequences:

(i) U continuously transferred from the mantle to the Earth crust, & within the continental crust towards its upper part together with Th, K, …

(ii) radiogenic heat production is maximized in the upper crust → radiogenic heat flux production may delineate radioelement enriched crustal blocks,

(iii) the most felsic melts tend to be the most enriched in U,

(iv) granites & rhyolites = primary U sources for the formation of most U deposits

Despite the strongly incompatible behavior of U, deposits dominantly resulting from magmatic processes are rare.

Average granite (U = 3-4 ppm), U mainly in zircon, apatite, monazite, titanite, … from which U cannot be leached by most geological fluids.

Some specific granites have higher U contents permitting crystallization of other accessory minerals from which U can be more or less easily leached for the formation of U deposits → “fertile granites” of Moreau [1966]
U continuously transferred from the mantle to the Earth crust

Which Process has led to such a fractionation?

Mantle
84% Earth vol./ 68% mass

Core
16% Earth volume
31% of its mass

Continental Crust
(0.7% Earth vol.)
1.3 ppm

0.021 ppm U
(Primitive Mantle)

x 60

7 ppb U
(Carbonaceous chondrites)
Partial melting
Fractional crystallisation
Sediment subduction and mantle metasomatism
Mixing with crustal material
Melt/fluid fractionation
Magma aluminous indices to classify magmatic rocks

\[
\frac{\text{Al}}{(\text{Na+K+2Ca})} = \frac{\text{A}}{\text{CNK}} \quad \text{in cations}
\]

= ASI  Aluminium Saturation Index

\[
\frac{\text{Al}}{(\text{Na+K})} \quad \text{ou} \quad (\text{Na+K}) \frac{\text{Al}}{} = \text{AGPAICITY}
\]

why ?

= INDEX OF MAGMA POLYMERISATION
U-rich magma classification using aluminous indices

Some specific granites have higher U contents

**METALUMINOUS**
- High-K
- Calc-alkaline
- A2 Type

**PERALUMINOUS**
- Leucogranites (two micas)
- S-Type

- $\frac{Al}{(Na+K+2Ca)} = 1$ & $\frac{Al}{(Na+K)} = 1$
- when
- Al-Na-K-Ca in feldspars only

**IMPOSSIBLE COMPOSITION FIELD**

**PERALCALINE**
- quartz saturated & undersaturated series
- A1 Type

- $\frac{Al}{(Na+K+2Ca)} > 1$
  - $\Rightarrow$ peraluminous

- $\frac{Al}{(Na+K+2Ca)} < 1$
  - $\&$ $\frac{Al}{(Na+K)} < 1$
  - $\Rightarrow$ peralkaline

- $\frac{Al}{(Na+K+2Ca)} > 1$
  - $\&$ $\frac{Al}{(Na+K)} > 1$
  - $\Rightarrow$ calc-alkaline
Why using aluminous indices for magma classification?
UO$_2$ SOLUBILITY IN GRANITIC MELTS

Peiffert et al., 1996

Peraluminous Peralkaline

Oxygen buffers

$\Delta$ Cu$_2$O - CuO

○ H.M.

□ Ni - NiO

U (ppm) in the silicate melt

10 ppm

100 ppm

1 wt%

780°C

2 kbar

Peiffert et al., 1996

$\text{Na}^+\text{K}/\text{Al}$

$\text{Na}_2\text{CO}_3$

$\text{HCl}$

$\text{NaCl}$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$
MONAZITE SOLUBILITY IN SILICATE MELTS

\[ \frac{\text{(Na+K+2Ca)}}{\text{(Al.(Al+Si))}} \]

\[ \ln(\sum \text{REE}/0.83) \]

from Montel, 1986
THREE TYPES OF U – RICH ACIDIC MAGMAS

● PERALKALINE MAGMAS
  ● Na+K > Al
  ● Riebeckite, Aegyrine, Avfedsonite
  ● betafite, thorite, complex U,Th,REE,Zr minerals
  ● Strongly enriched in U, Th, REE, Zr, ...

● METALUMINOUS HIGH-K CALC-ALKALINE MAGMAS
  ● Al < Na+K+2Ca
  ● Amphibole, Pyroxene, biotite
  ● Allanite, U-thorite, titanite, ± Th-rich uraninite, magnetite
  ● Enriched in U, Th, REE

● PERALUMINOUS FELSIC MAGMAS
  ● Al > Na+K+2Ca
  ● Al-biotite, Muscovite, ± sill, andalusite, garnet, topaz, tourmaline
  ● Low-Th uraninite, monazite, ilmenite
  ● Enriched in U, poor in Th, REE, Zr ...
**PERALKALINE MAGMAS**

Na + K > 1 + high T $\Rightarrow$ highly depolymerized

Very high solubility of accessory minerals

Very high U, Th, Zr, REE, Nb, Ta, ... contents continuously enriched in the residual melts

**Volcanic rocks:** U in the glassy matrix

**Granites/Syenites:** crystalliz. of a complex mineral paragenesis: zircon, U-Th-Zr silicophosphates, Nb-Ta oxydes, ...

U in refractory sites

Very good U-source

Bad U source / high extraction cost

Ex.: - Streltsov (Russia) - McDermitt (USA)

Ex.: - Ilimaussaq, Groenland (syenites) - Bokan Mountain Alaska (granites)

\[ \text{Th} \; \text{Th/Th=1} \; \text{Th/Th=4} \; \text{Th/Th=10} \]
Ilimaussaq (Greenland) peralkaline complexe

U mineralization in the most fractionated part where fluid oversaturation occurred

⇒ simultaneous enrichment in: U, Th, Zr, REE, Nb, Ta, F ...

U in steenstrupine: Silicophosphate of U, Th, Zr, REE, Nb, Ta

220,000 t U @ 250 ppm
Variscan granite

U-deposit projection

Caledonian granite

Marbles

U-deposit projection

GEOLOGIC MAP OF THE STRELTSOVSKY ORE FIELD

280 000t U in 18 deposits

5 km
U loss evaluation from U-contents of melt inclusions (acidic volcanics compared to altered rhyolites)

STRELTSOV caldera

Average altered Streltsovky rhyolite

Magmatic inclusions Streltsovky (Russia)

Magmatic inclusions Dornot (Mongolia)

U-loss = 10-13 ppm

Average GRANITE

Th/U = 10

Th/U = 100

Average crustal ratio

Th/U = 2

Th/U = 1

U ppm

Th ppm
Conceptual model for U deposits related to peralkaline magmatism

Intracontinental sedimentary basin

pyroclastic tuffs

U1
Mantle:
- Primitive: U0
- Depleted: U-1
- Enriched: U1

Partial melting

Crystal fractionation

Magma chamber

Underplated basalts

Crust assimilation

Moho

U1

Sedimentary basin complex

pyroclastic tuffs

Basement plutonic complex

caldera

Cauldron subsidence

syn-caldera zoned plutonic complex

1 2 3 4 5

U6 U5 U4 U3 U2

U1

Underplated basalts

Partial melting

Crystal fractionation
melt inclusions
Melt inclusion geochemistry from sandstone
PERALUMINOUS MAGMAS

Highly polymerized: A/CMK > 1 + low T

Accessory minerals low solubility

low Th, Zr, REE,... contents
continuously depleted in the residual melts

Early crystallization of monazite and zircon:
With limited amount of U

U enriched in residual silicate melts (up to some tens of ppm)

Volcanic rocks: RARE FERTILE U-SOURCE
Ex.: - Macusani (Peru)

Granites: U >> as low-Th URANINITE
FERTILE U-SOURCE
Ex.: - St Sylvestre (Limousin)
- Erzgebirge (Germany)
GRANITE RELATED DEPOSITS OF THE MID-EUROPEAN VARISCAN BELT

> 300,000 t U @ 0.2 %
CUSANI YELLOW CAKE

30,000 t U @ 0.02
HIGH-K CALC-ALKALINE MAGMAS

Intermediate: A/CNK ~ 1 + moderately high T

Accessory minerals intermediate solubility

high U, Th, Zr, REE, Nb, Ta, ...
constant or decreasing in the residual melts

High Ca-contents

Monazite not stable

REE in Ca-minerals:
- amphibole, allanite, titanite

Volcanic rocks
Variable fertility
According to glass/accessory mineral ratio

Granites
Th > U
Allanite + U-thorite
BARREN if not metamict

Ex.: Ben Lomond (Australia)

Ex.: Hotagen (Sweden)

U > Th
± uraninite ± fertile
Granite breccia

Roxby Dawns granite

Geologic Map of the Olympic Dam Iron Oxide Cu-Au +U (REE) (IOCG) deposit

2.100 Mt U

2 U-rich sources

high-K calc-alkaline magmas
Associated with high-K calc-alkaline metavolcanic gneisses of the Aillik Group U mineralization associated with hematization + albitization
ANATECTIC PEGMATOIDS

Partial melting of U rich metasediments and/or metavolcanics

Low A/CNK : ~ 1.1 + low T

Accessory minerals intermediate solubility

high U and/or Th and/or Zr and/or REE and/or Nb, Ta, ... depending of the nature of the source
constant or decreasing in the residual melts

Uraninite ± Monazite ± Allanite ± Uranothorite ± Zircon ± Nb-Ta minerals ± ...

Ex.: Rössing (Namibia)
ANATECTIC PEGMATOIDS

Cross-section of the Rossing alaskite body geology & boreholes (drill section zero)

LEGEND
- Scree & alluvium
- Uraniferous alaskite
- Upper marble
- Conglomerate
- Schist
- Lower - cordierite - biotite gneiss
- Gneiss
- Lower marble
- Biotite - amphibole schist
- Upper pyroxene - hornblende gneiss
- Pyroxene garnet gneiss
- Lower pyroxene - hornblende gneiss

NOSIB ROSSING

250,000 t U @ 300 ppm

after Berning, 1986
U-Th relationships in the Rossing Alaskites & metsediments

Cuney, 1981
U - Th FRACTIONATION IN THE 3 TYPES OF U – RICH ACIDIC MAGMAS

Complex U-Th-REE minerals

Av. granite

Th/U=10
Th/U=4
Th/U=1

monazite
Th/U=10
Th/U=4
Th/U=1
Th/U=0.1

uraninite

allanite
Th/U=10
Th/U=4
Th/U=1
Th/U=0.1

Av. granite

U (ppm)

Th (ppm)

Peralkaline

Peraluminous

Metaluminous
CONCLUSIONS

Three types of U-rich felsic magmas identified:

- **Peralkaline (fractionated A1-type)**
  - Weakly fertile granites (U in highly refractory phases)
    - Examples: Ilimaussaq (Groenland), Bokan Montain (Alaska)
  - Highly fertile volcanics if high glass/crystal ratio
    - Example: Stretlsovka (Russia), Dornot (Mongolia)

- **Metaluminous high-K calc-alkaline (A2-type)**
  - Fertile granites if uraninite-rich or metamict accessories for vein & sedimentary deposits
  - Fertiles volcanics if large glass/crystal ratio
    - Examples: Source for Olympic Dam deposit

- **Peraluminous felsic**: + Anatectic pegmatoids
  - Uraninite bearing granites
    - Very fertile for vein type deposits & sec. dep. in sedimentary basins
    - Example: Variscan belt (Europe), Yenshanian belt (China), …
  - Peraluminous volcanics:
    - Fertile for vein type deposits, rare
    - Example: Macusani (Peru)