

Geneses of Magmatic Mineral Deposits: Special reference to Cr and Pt mineralization

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Who was I?



- A geologist of the Geological Survey of Japan
- Experience in the study of mineral deposits
- Consultant for mineral exploration



Who am I?

- Professor in Economic Geology, Akita University (2014-Present)
- Faculty of International Resource Sciences



Mining Museum,
Akita University



Faculty of International Resource Sciences, Akita University

- Mining College of Japan, aims to produce personals in the field of mining sectors
 - 120 undergraduate students
- Resource policy course (30)
 - Resource economics, Mining laws, Mining politics, International situation, culture, negotiation, etc.
- Resource earth science course (35)
 - Genesis of mineral deposits,
 - Exploration strategy and technology, etc.
- Resource development & environment course (50)
 - Mining engineering, recycling



Geneses of Magmatic Mineral Deposits

1. What are the mineral deposits?
2. How do the metallic mineral deposits form?
 1. Behavior of elements
 2. magmatic processes
3. Waterberg project in northern Bushveld Complex, SA

Crustal abundance and ore grade

Element	A. Crustal abundance (ppm)	B. Ore (lower limit) (ppm)	Concentration (B/A)
Cu	55	5,000	90
Pb	13	20,000	1,500
Zn	70	25,000	360
Ni	75	10,000	130
Cr	100	100,000	1,000
Pt	0.004	4	1,000



Chalcopyrite (CuFeS_2)

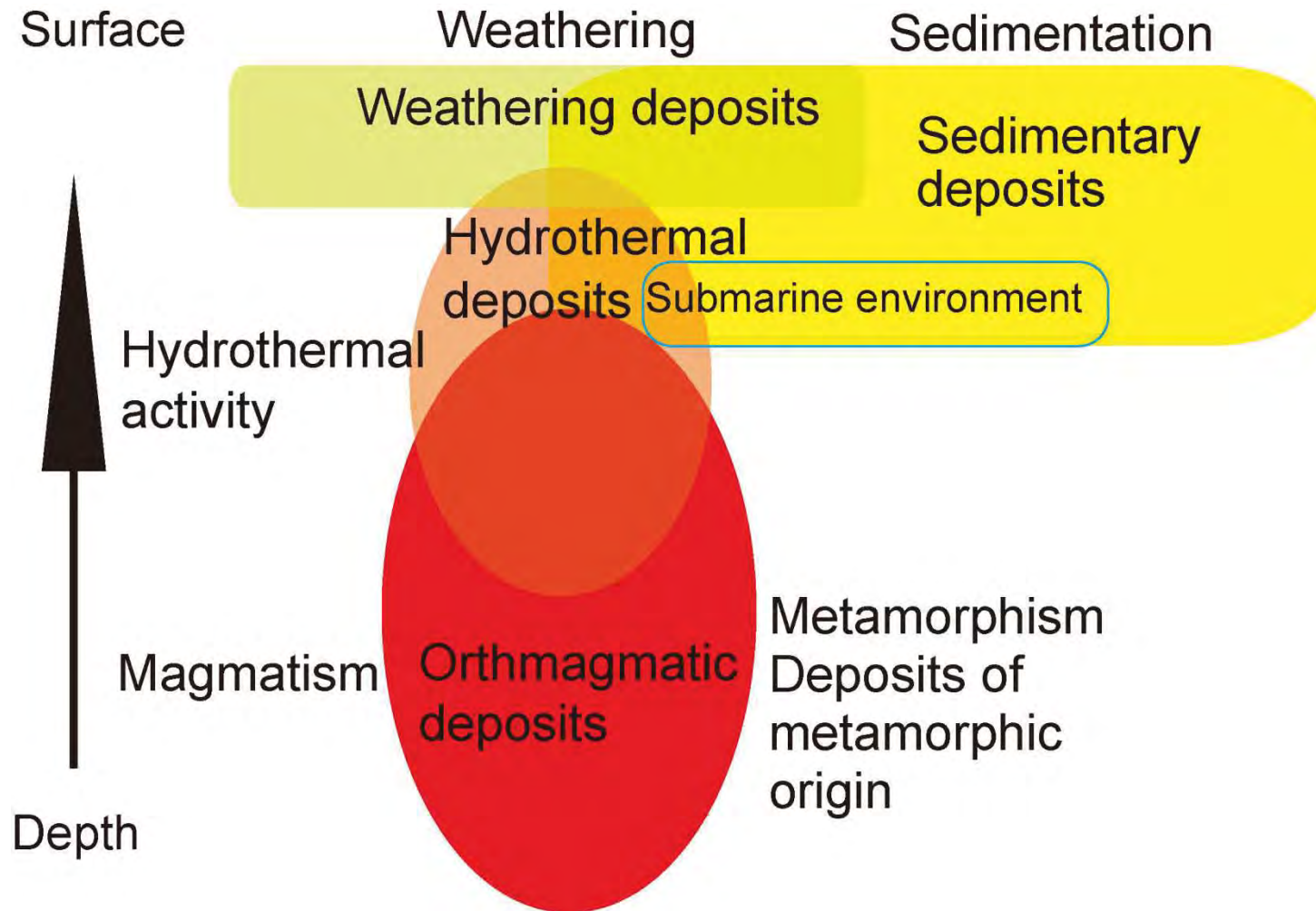


Galena (PbS)



Sphalerite (ZnS)

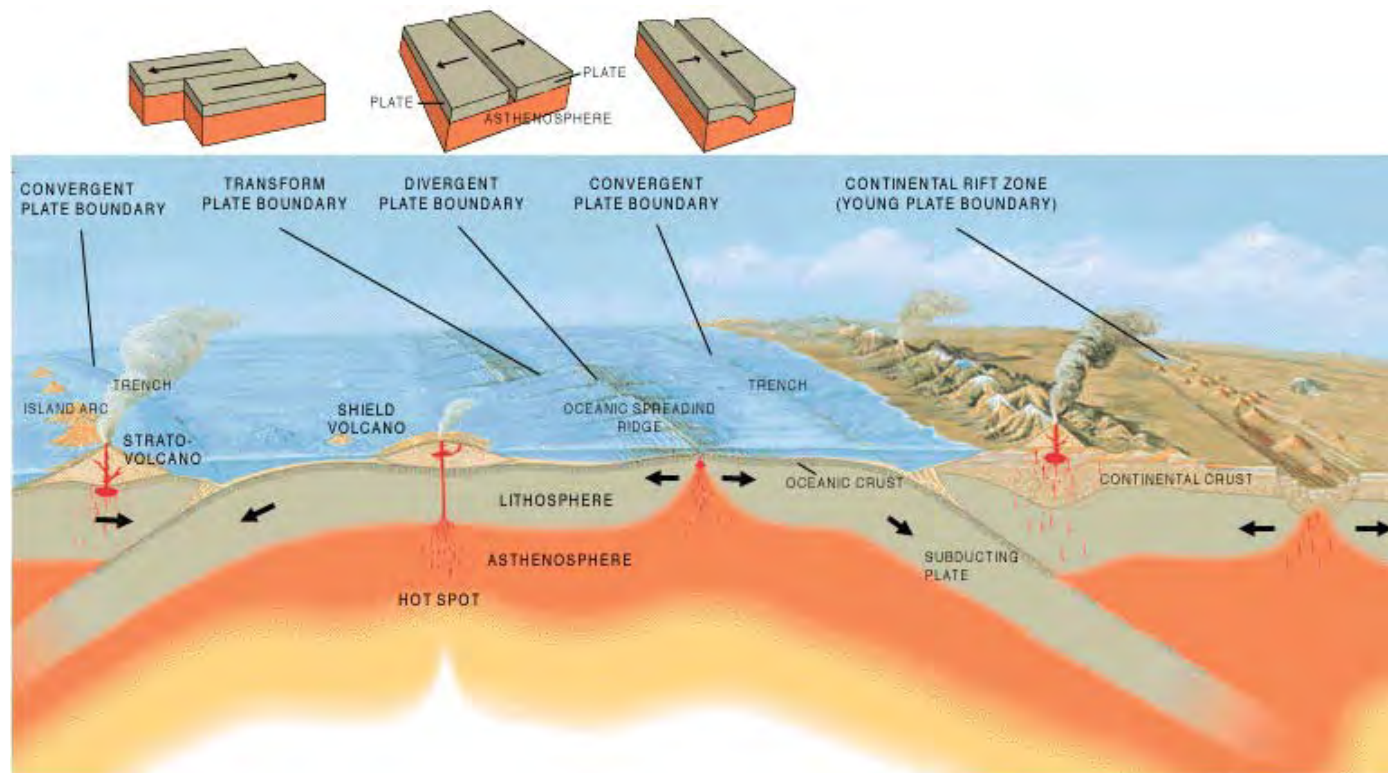
How did the mineral deposits form?



Origin of metals

Major sites of magma formation

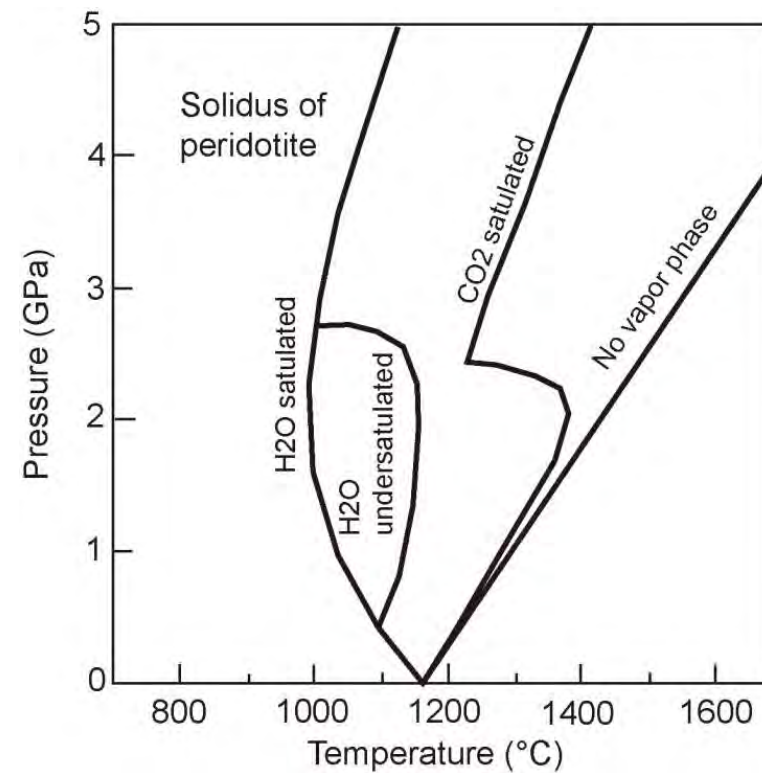
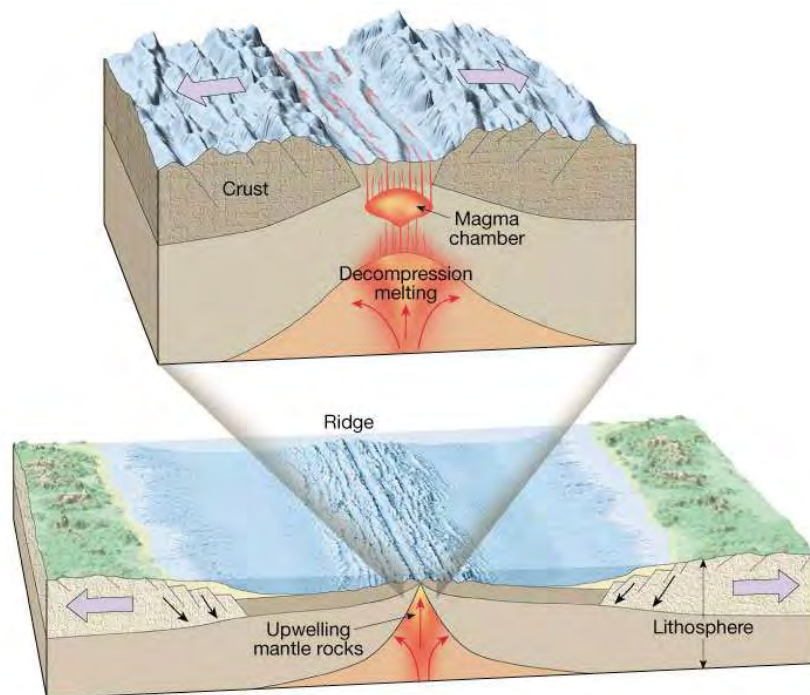
- Oceanic plate spreading ridge
- Oceanic plate subduction zone
- Continental rift zone



Asthenosphere & lithosphere

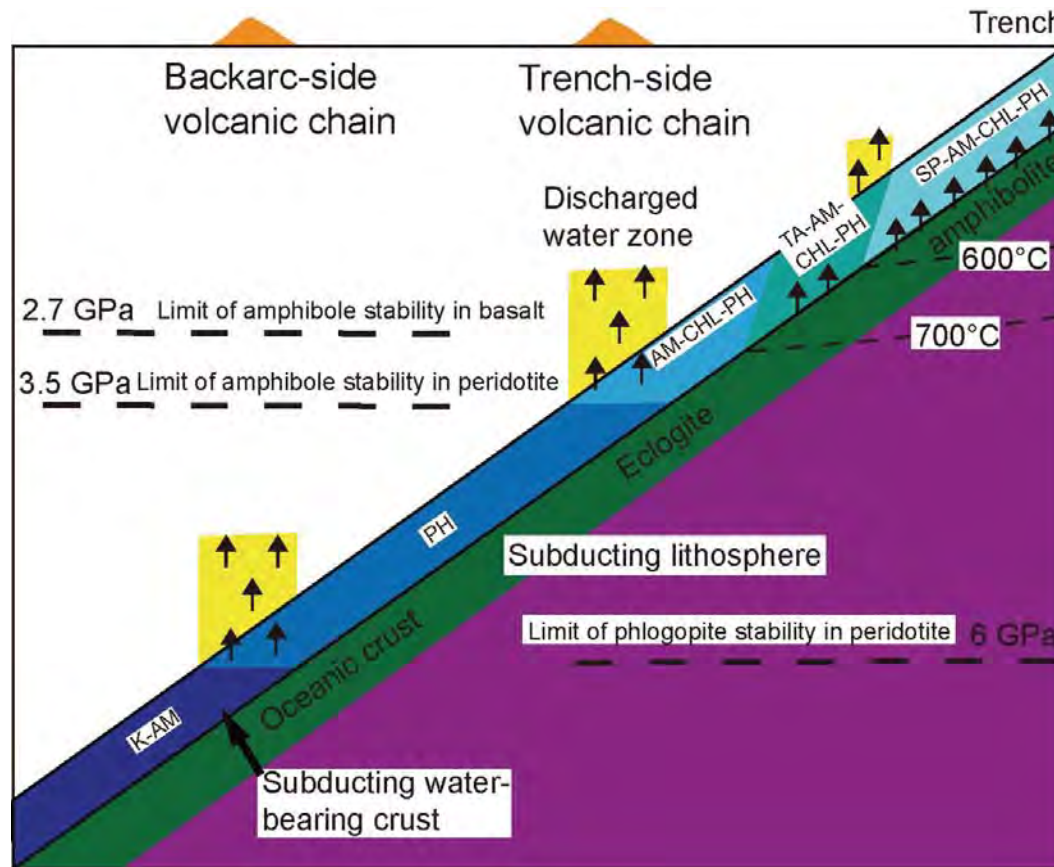
- Asthenosphere is a part of the upper mantle just below the lithosphere. The lithosphere-asthenosphere boundary is conventionally taken at the 1300°C isotherm, above which the mantle behaves in a rigid fashion and below which it behaves in a ductile fashion.
- Seismic waves pass relatively slowly through the asthenosphere compared to the overlying lithospheric mantle. This decreasing in seismic waves velocity from lithosphere to asthenosphere could be caused by the presence of small percentage of melt in the asthenosphere.

Origin of magma at spreading center



Tatsumi (1995)

Dehydration of water from peridotite



AM: amphibole,
CHL: chlorite,
PH: phlogopite,
SP: serpentine,
TA: talc

Tatsumi (1995)

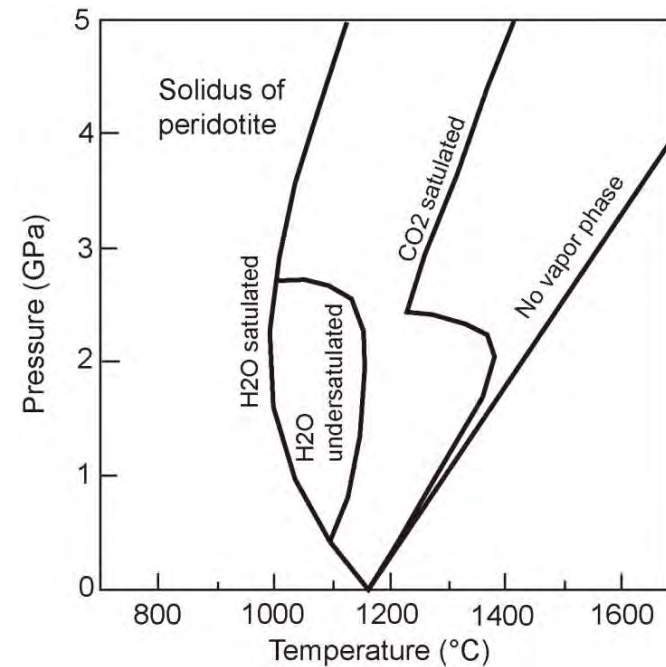
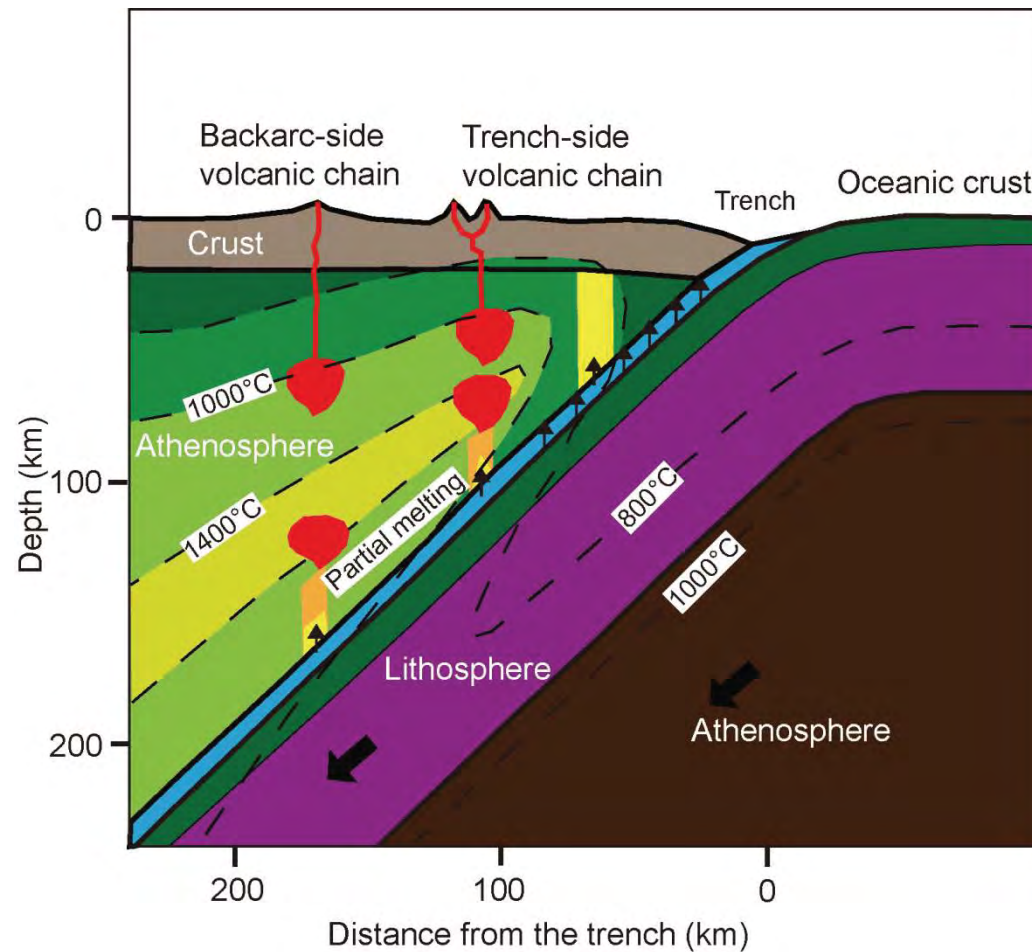


Anthophyllite

Enstatite

Quartz

Origin of magma at subduction zone



Tatsumi (1995)

Incompatible elements

- Elements that are unsuitable in size and/or charge to the cation sites of the minerals, defined by the partition coefficient between rock-forming minerals and melt being much smaller than 1.
- During the fractional crystallization of magma and magma generation by the partial melting, elements that have difficulty in entering cation sites of the minerals are concentrated in the melt phase of magma.
- Two groups of incompatible elements: One includes elements having large ionic radius, such as K, Rb, Ca, Sr, Ba (called **LILE**, or large-ion lithophile elements), and the other includes elements of large ionic valences (or high charges), such as Zr, Nb, Hf, REE, Th, U and Ta (called **HFSE**, or high field strength elements).

Ionic radius and valences

Group	Element	Valence state	Radius (A)
Compatible	Fe	+2, +3	0.63-0.78
	Cu	+1,+2	0.46-0.73
	Zn	+2, +4	0.60-0.89
Incompatible (LILE)	K	+1	1.37-1.64
	Ca	+2	1.00-1.34
	Ba	+2	1.35-1.61
Incompatible (HFSE)	Zr	+4	0.8-1.03
	Nb	+3,+4,+5	0.72-0.74
	Hf	+4	0.58-0.83
	Ta	+3,+4,+5	0.72-0.92
	U	+3,+4,+5,+6	1.03-0.52

LILE: large-ion lithophile elements,
HFSE: high-field-strength elements

transition-row elements

REE

LILE

HFSE

Si

P

Ta, Nb

Hf

Ti, W, Zr, Pb

U, Th

Cr

Al

Fe

Co, Zn

Ni

Cu

Mn

Mg

Pt

Mg

Fe

Li

Ca

Na

Eu

Sr

Pb

Ba

K

Rb

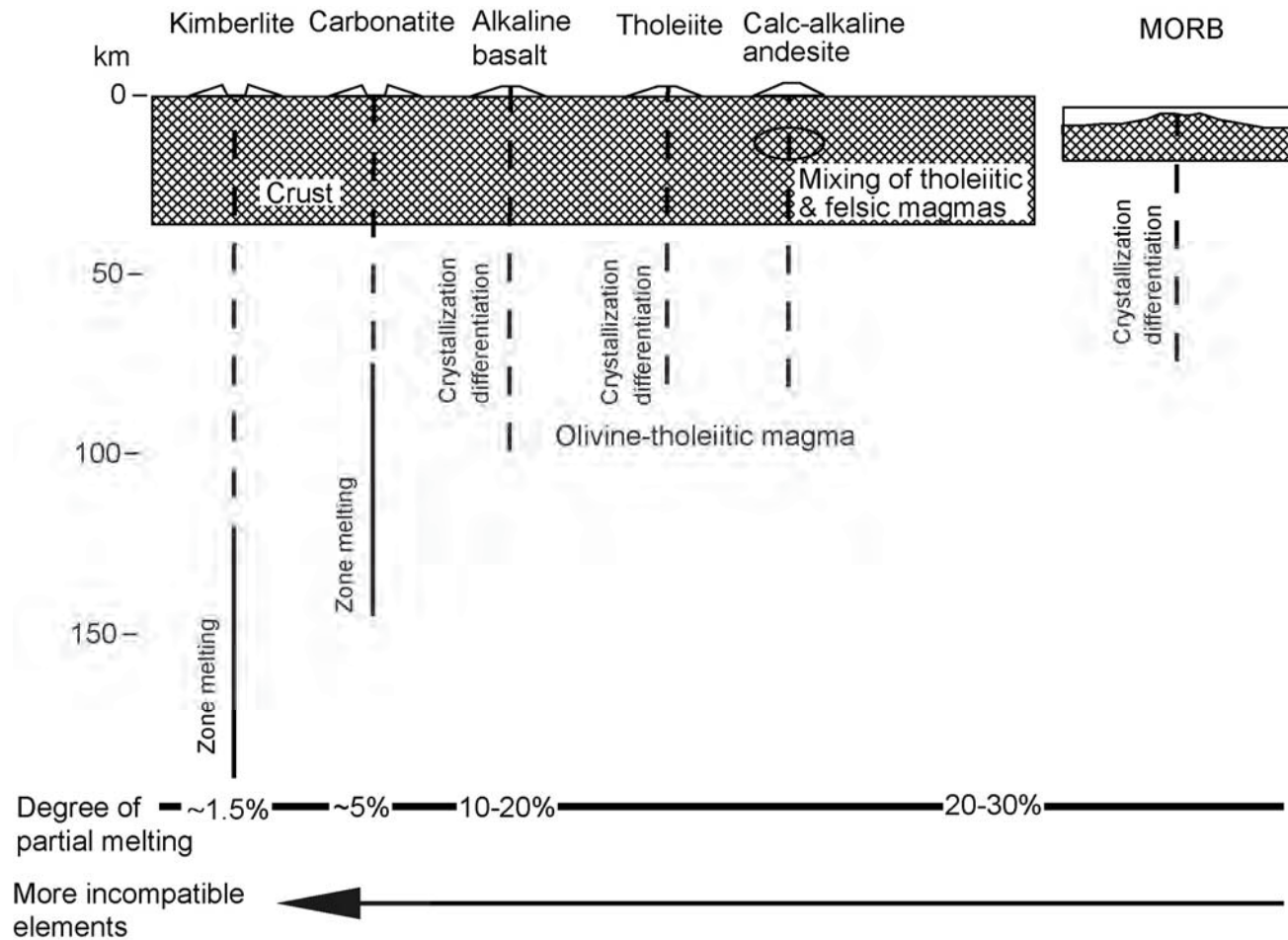
Cs

La

La

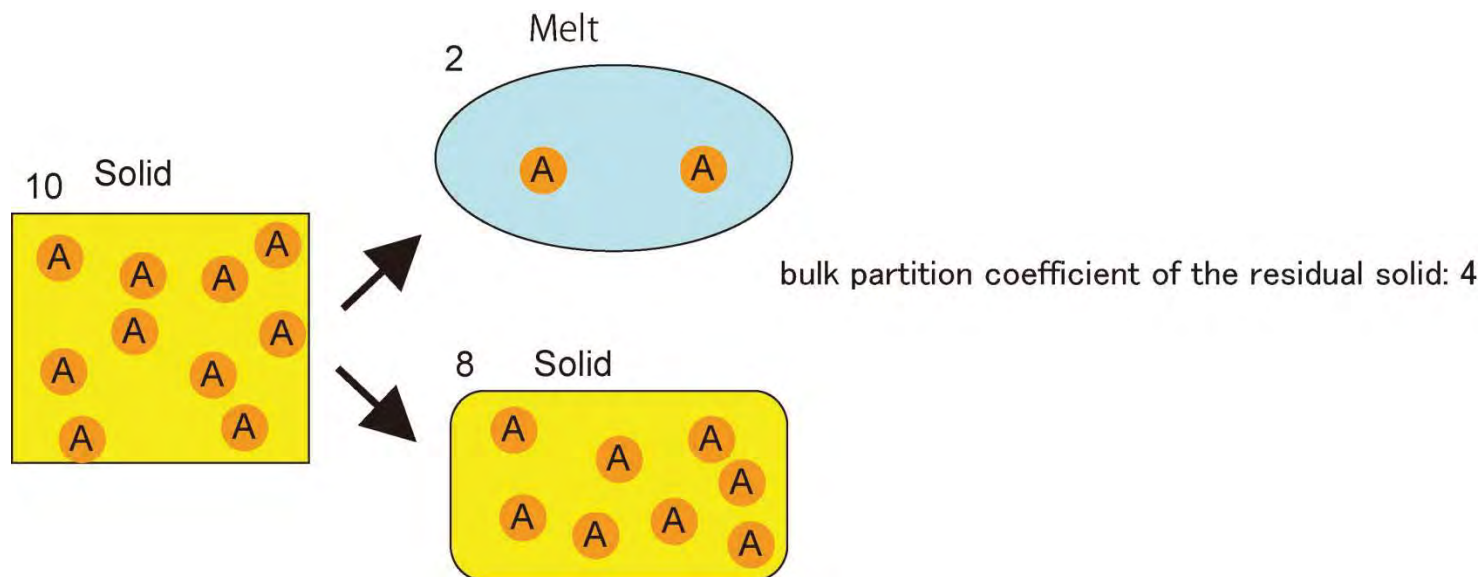
Ridely (2013)

Magma type and degree of partial melting

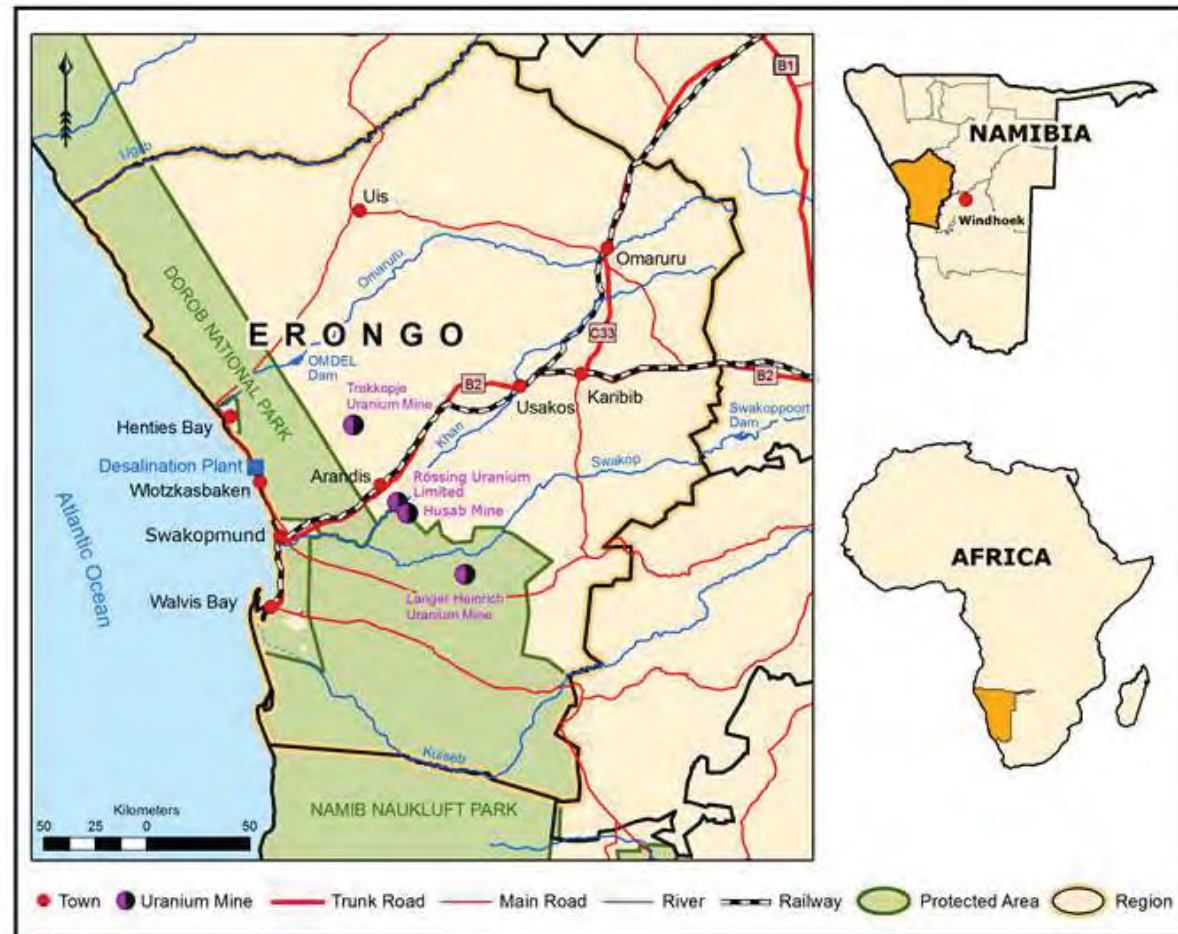


Partition coefficient

- partition-coefficient (D) is the ratio of concentrations of a compound in a mixture of two immiscible phases at equilibrium. These coefficients are a measure of the difference in solubility of the compound in these two phases.



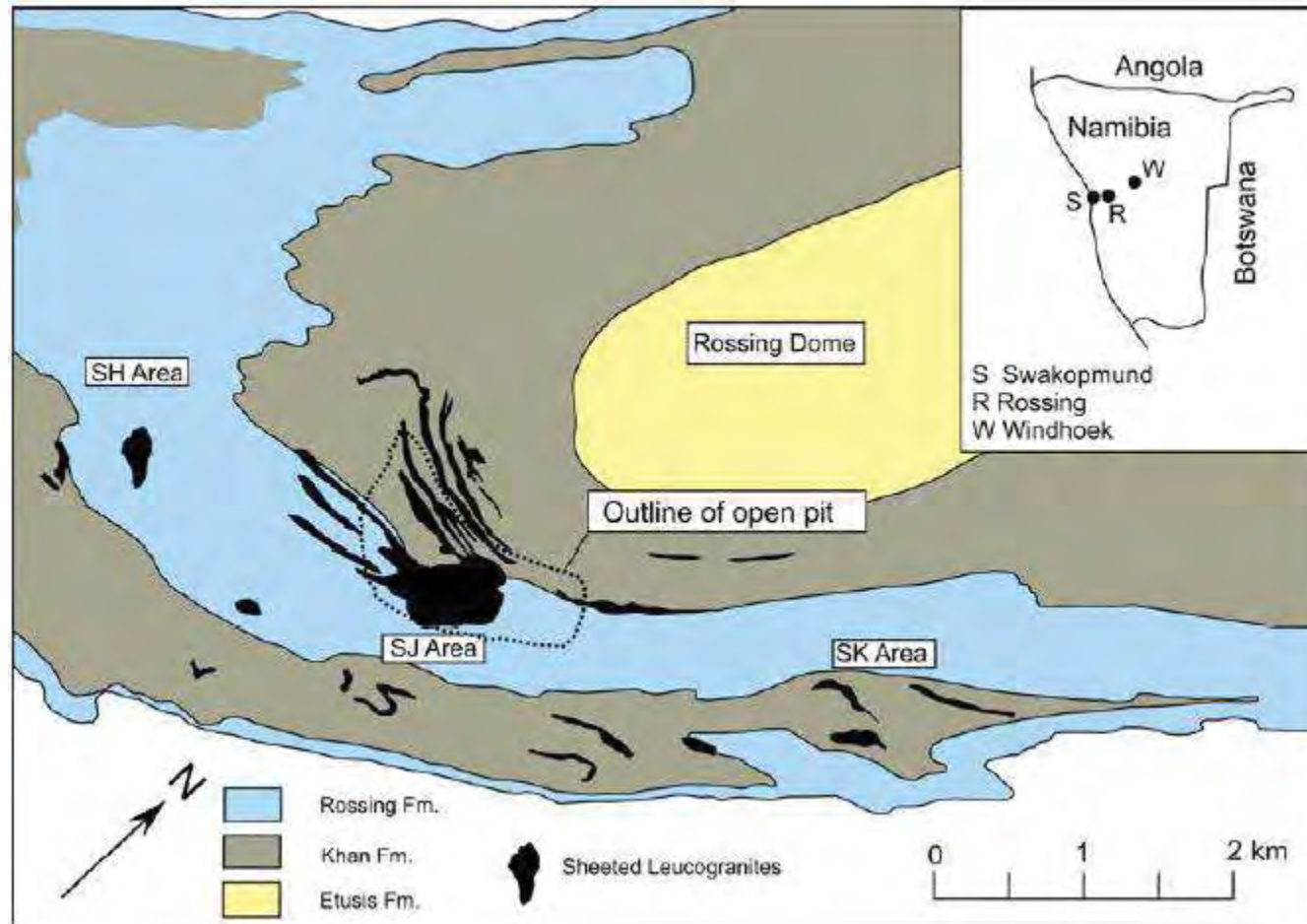
Rossing U deposit



Rossing uranium deposit, Namibia

- Rossing U deposit
 - World largest U deposit
 - Discovered in 1928, Explored in late 1950's, Production from 1976
 - 125,862 t U produced until 2013
 - Associated with leucogranite
 - major ore mineral: uraninite (UO_2) disseminated in the granite
 - The granite formed by partial melting from metamorphic rocks
 - Grade: 0.031% (310ppm) U_3O_8

Rossing deposit geology

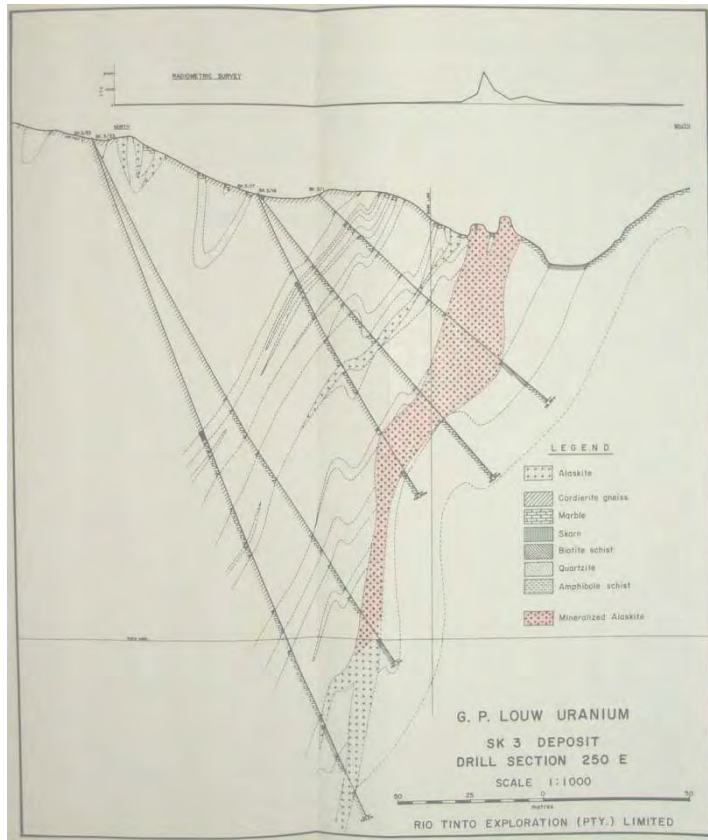


Smith (1961)

Open pit of the Rossing Mine



Occurrence of Rossing leucogranite

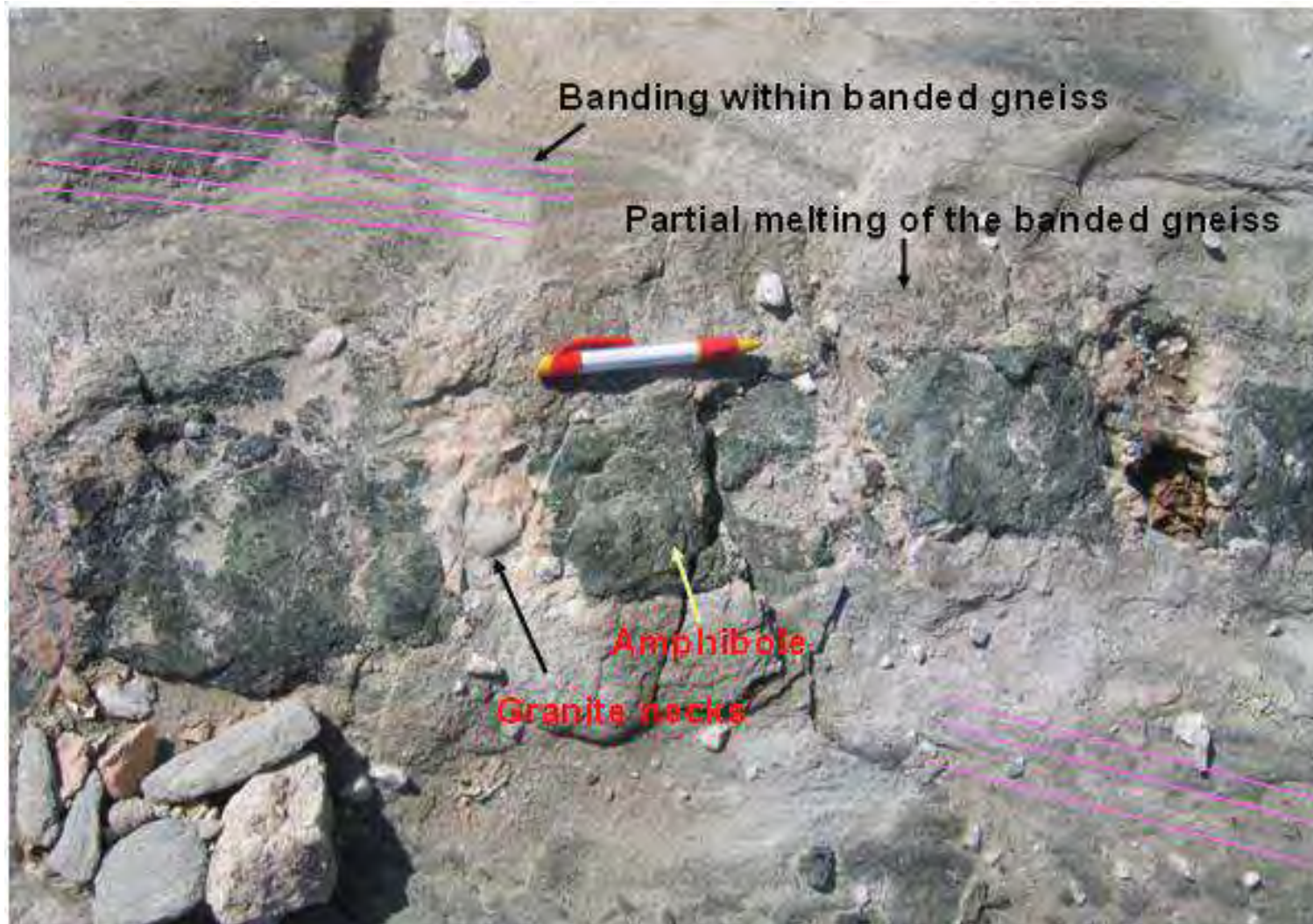


Louw (1979)



Abraham (2009)

Partial melting of amphibolite

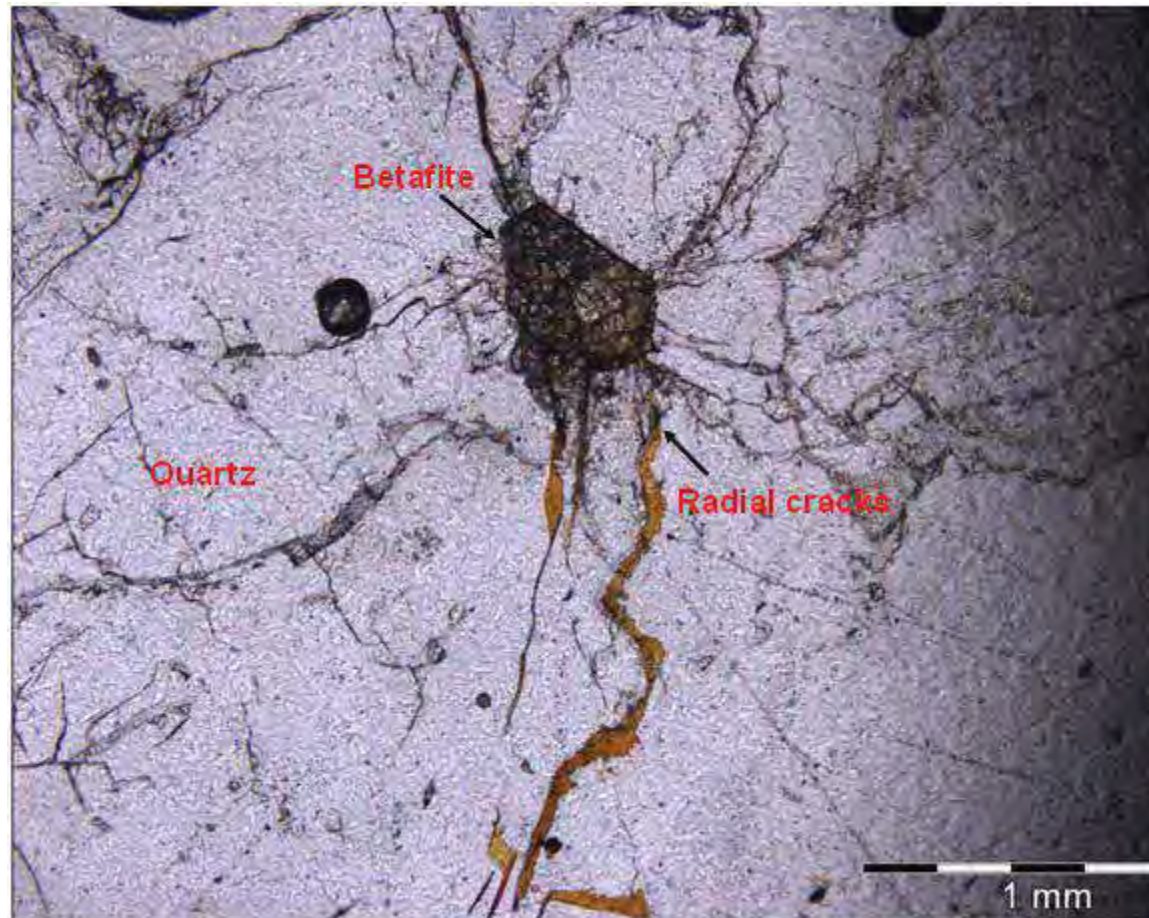




Uranophane $\text{Ca}(\text{UO}_2)_2(\text{SiO}_3\text{OH})_2 \cdot 5\text{H}_2\text{O}$

**Rössing Uranium Mine,
Swakopmund, Namibia**

Occurrence of granite at Rossing Deposit

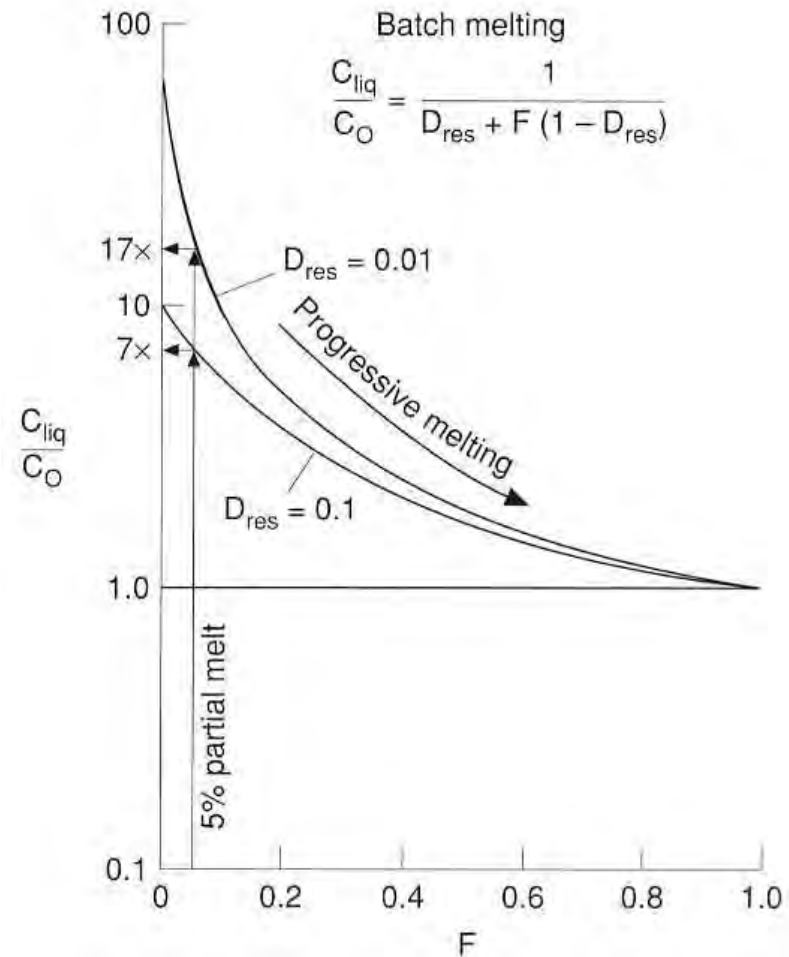


Betafite: $\text{U}^{4+}(\text{Nb,Ti})_2\text{O}_6\text{OH}$

Abraham (2009)

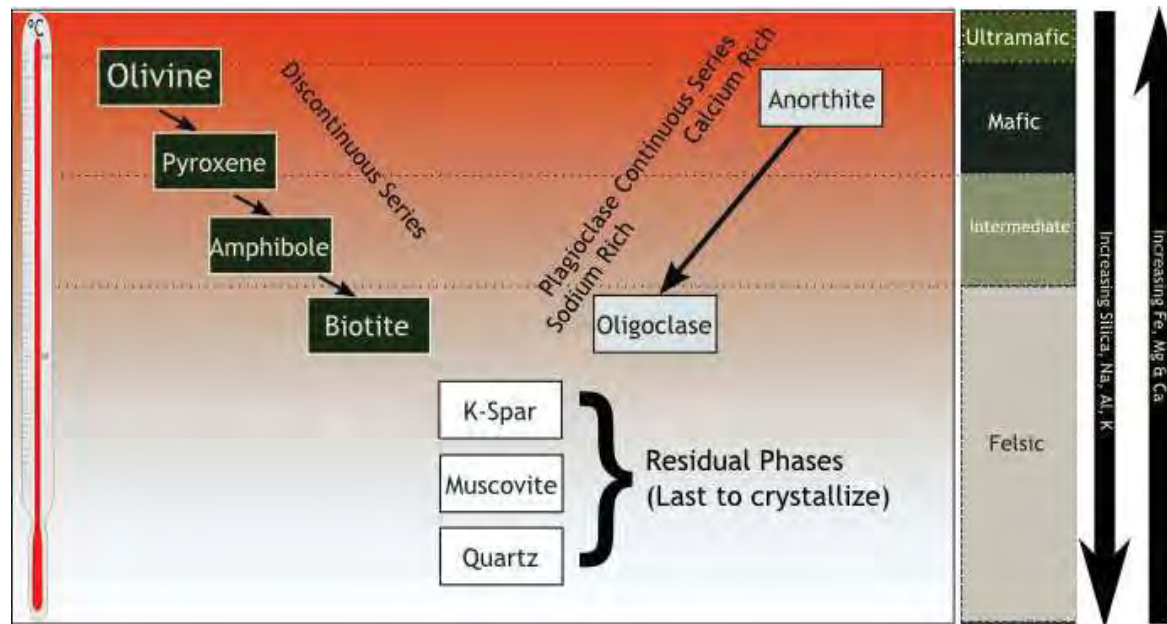
U concentration at Rossing

- U content of host rocks : 10ppm
- D_{res} : 0.01-0.1
- 5% partial melt ($F=0.05$)
- Concentration of U into granite melt: 7~17 times, 70-170ppm
- How 310ppm U concentration can be realized?



Crystal fractionation

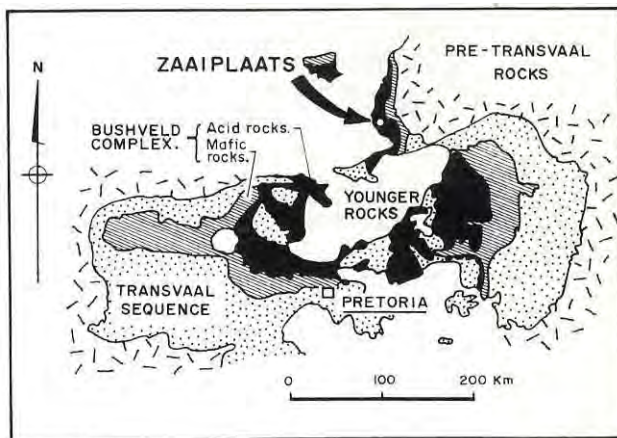
- Crystal fractionation is the removal and segregation from a melt of mineral precipitates.
- During the process of crystal fractionation, melts become enriched in incompatible elements. Textures of rocks provide insights, as documented in the early 1900s by Bowen's reaction series.



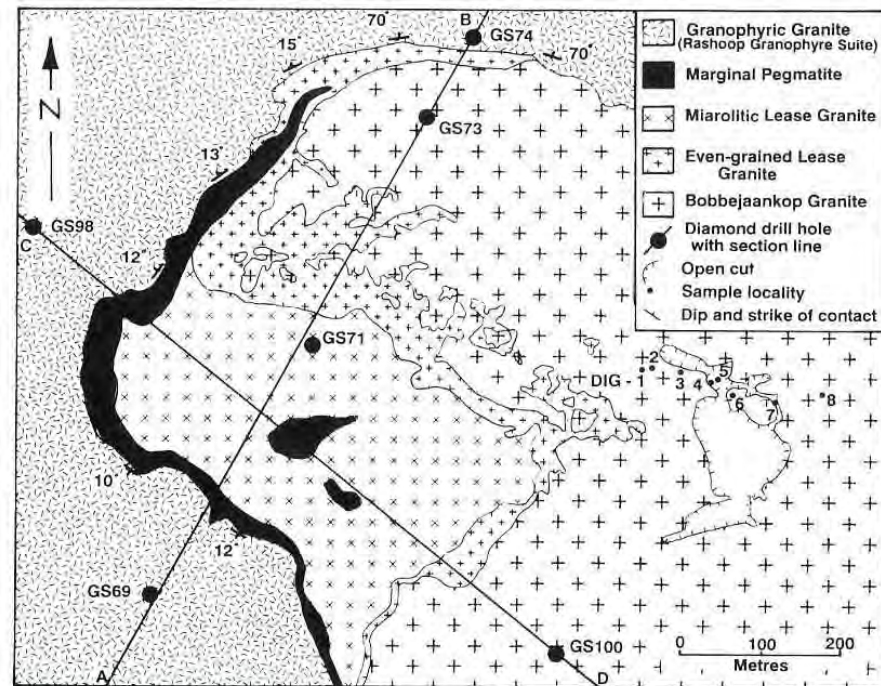
Bowen's reaction series

Zaaiplaats Sn deposit, South Africa

- Zaaiplaats Sn deposit
 - Hosted in granite of the Bushveld Complex
 - Cassiterite (SnO_2) disseminated in granite

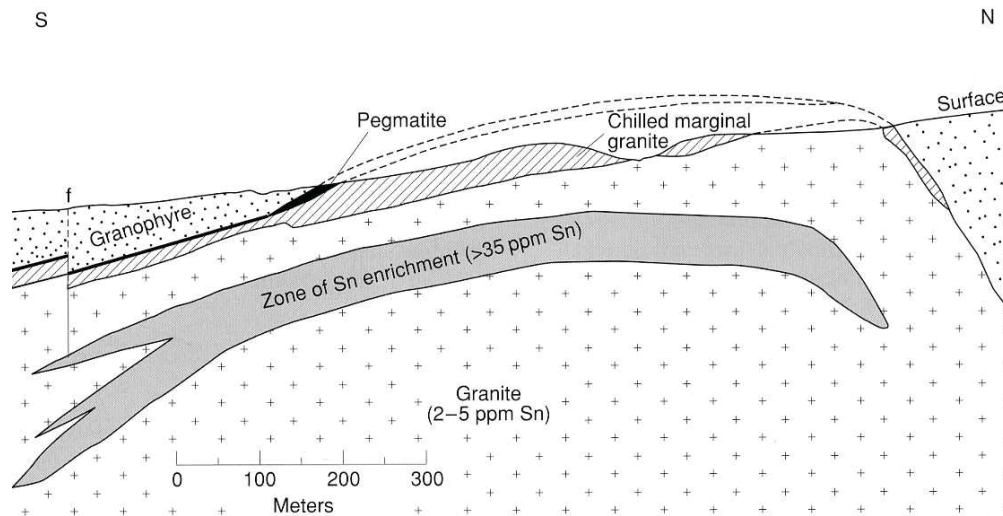


McNaughton et al. (1993)

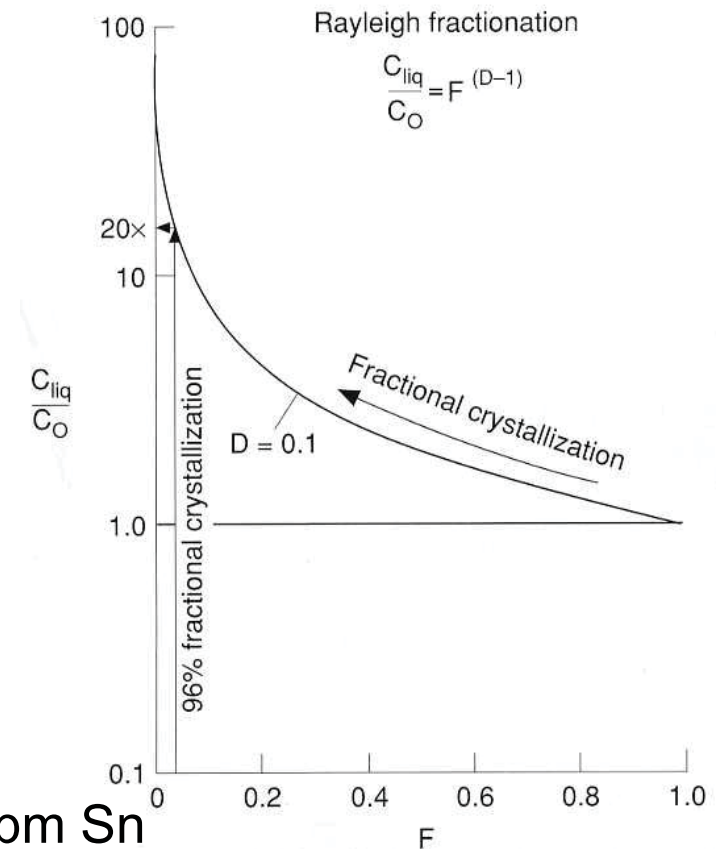


Zaaiplaats geology map
(McNaughton et al., 1993)

Zaaiplaats Sn mineralization



- Unmineralized granite : 8-14ppm Sn
- Cassiterite (SnO_2) in orebody: 270 ppm Sn
- Fractional crystallization concentrated Sn
- Sn is incompatible $D=0.1$.



CASSITERITE
Solomon's Temp



CASSITERITE
Groenfontein 227 KR,
Potgietersrus

Pegmatite



How do the compatible elements (e.g. Platinum) become concentrated?

Goldschmidt classification

Lithophile elements

- Al, B, Ba, Be, Br, Ca, Cl, Cr, Cs, F, I, Hf, K, Li, Mg, Na, Nb, O, P, Rb, Sc, Si, Sr, Ta, Th, Ti, U, V, Y, Zr, W, Lanthanides
- Lithophile elements are those that remain on or close to the surface because they combine readily with oxygen, forming compounds that do not sink into the core.

Siderophile elements

- Au, Co, Fe, Ir, Mn, Mo, Ni, Os, Pd, Pt, Re, Rh, Ru
- Siderophile (from *sideron*, "iron", and *philia*, "love") elements are the high-density transition metals which tend to sink into the core because they dissolve readily in iron either as solid solutions or in the molten state.
- They form stronger bonds with carbon or sulfur than oxygen, but even these are not strong enough to separate out with the chalcophile elements.

Goldschmidt classification

Chalcophile elements

- Ag, As, Bi, Cd, Cu, Ga, Ge, Hg, In, Pb, Po, S, Sb, Se, Sn, Te, Tl, Zn
- Chalcophile elements are those that remain on or close to the surface because they combine readily with sulfur and/or some other chalcogen other than oxygen, forming compounds which do not sink into the core.

Atmophile elements

- H, C, N, noble gases
- Atmophile elements (also called "volatile elements") are defined as those that remain mostly on or above the surface because they are, or occur in, liquids and/or gases at temperatures and pressures found on the surface.

Magmatic deposits

- Magmatic deposits form from primary magmatic processes (cooling and crystallizing magmas). They are hosted within the rocks from which they formed. Deposits may form as a result of
 - Concentration of ore elements by very low degree of partial melting
 - Accumulation and concentration of ore minerals in magma chambers during crystallization
 - Separation of two immiscible melts in a magma
 - Extreme fractionation during progressive crystallization

Processes of metal concentration in magma

- Cumulate in magma chamber
- Crystal fractionation
- Magmatic immiscibility

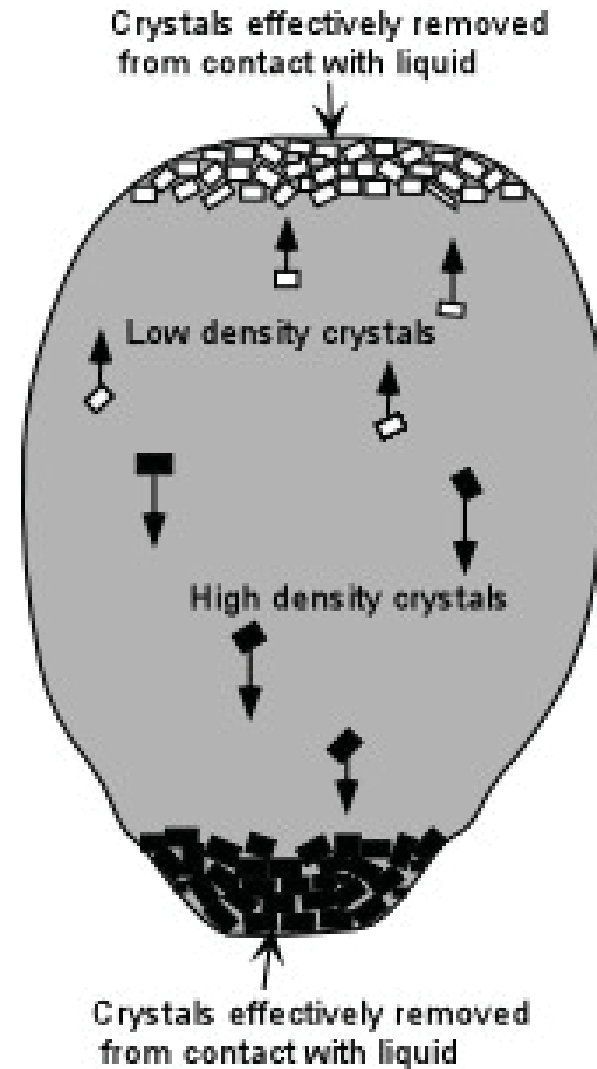


Examples of magmatic deposits

- Layered and podiform deposits
- Titanomagnetite deposits
- Platinum group deposits
- Nickel sulfide deposits
- Peralkaline Ta-Nb, Zr, REE deposits
- Carbonatite REE, Nd, Fe, P deposits

Cumulate rocks

- Cumulate rocks formed by the accumulation of crystals from a magma either by settling or floating.
- Cumulate rocks are the product of precipitation of solid crystals from a fractionating magma chamber.
- Accumulation occurs on the floor of the magma chamber, although they are possible on the roofs if anorthite plagioclase is able to float free of a denser mafic melt.





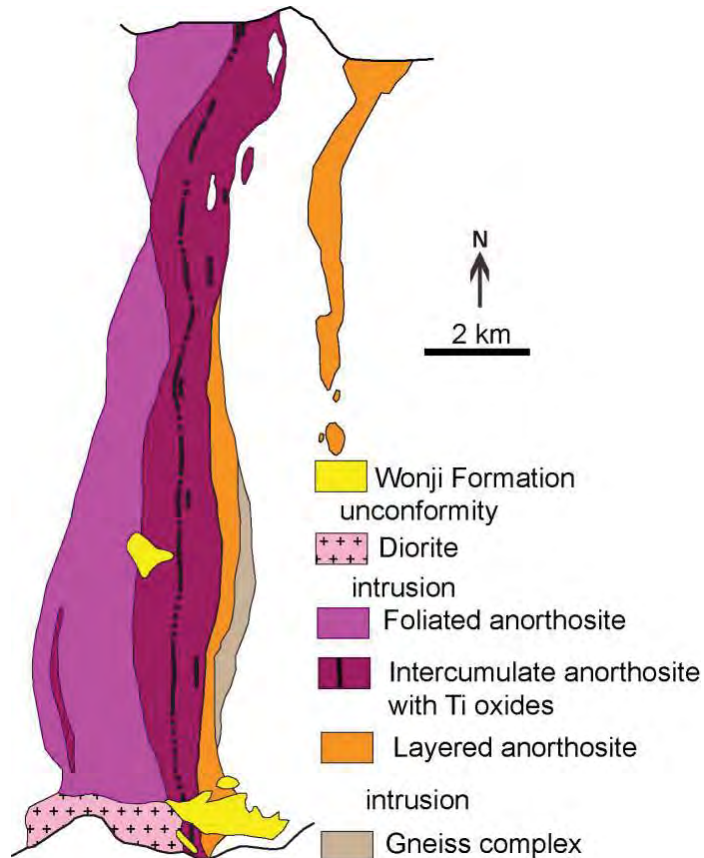
Cumulate texture in anorthosite, Lower Zone of the Bushveld complex, South Africa. Major constituent minerals are olivine (specific gravity: 3.2-4.4), pyroxene (3.2) and plagioclase (2.5-2.7).

Mineral deposits associated with cumulate processes

- Anorthosite-ilmenite deposits
 - occur as layered units in mafic-ultramafic differentiated intrusions. Concentration of Ti oxides occur in anorthosite suites.
 - Stand Hill deposit, NE Canada
- Stratiform chromite deposits
 - Hosted in ultramafic layered intrusions composed of cumulus crystals
 - Consist of thin but laterally continuous layers of chromitite, a term used for massive chromite containing >50% cumulus chromite.
 - Bushveld Complex, South Africa; Great Dike, Zimbabwe, Stillwater Complex, USA, etc.

Hadong ilmenite deposit, Korea

- Ilmenite orebody is 2-10m thick and 14 km long in anorthosite .
- Resources: Probable reserves 2,000Mt@4.0-6.7% TiO_2



Jeong et al. (1989)

Silicate and oxide mineral cumulates

- Silicate mineral cumulates
 - Some anorthosite intrusions contain such pure anorthite concentrations that they are mined for feldspar.
- Oxide mineral cumulates
 - Oxide mineral cumulates form in layered intrusions when fractional crystallization has progressed enough to allow the crystallization of oxide minerals.



Hadong ilmenite [FeTiO₃] deposit, Korea