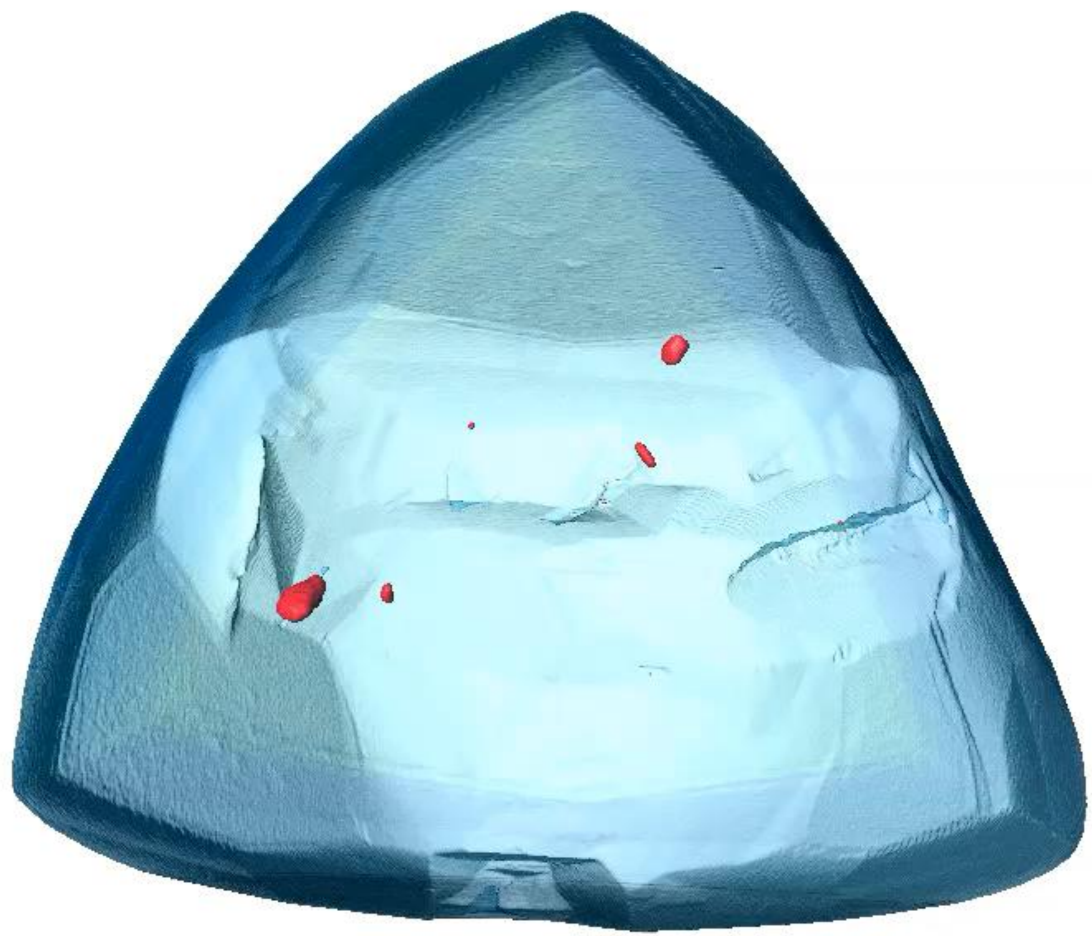
Metals in the Mantle & Cratons

Metallogenesis: How metals become mineralised through space and time



1 carat Orapa diamond (blue) with multiple sulphide inclusions (red) shown as 3D volume rendered false colour image from µCT
Clip available from McDonald et al. (2017)

Hannah Hughes
Malvern U3A Geology Group, Wednesday 12th February

Metals in the Mantle & Cratons

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Critical metals info

Recipe for mineralisation

Chalcophile & Siderophile

Metallogenesis & geodynamics

Composition of magmas & igneous rocks

What is a craton?

Partial melting

Diamond video

Metals in magmas

Craton-specific exploration

Sulphide cooling & homogenisation

Sulphides & metals in the mantle

Presentation intro

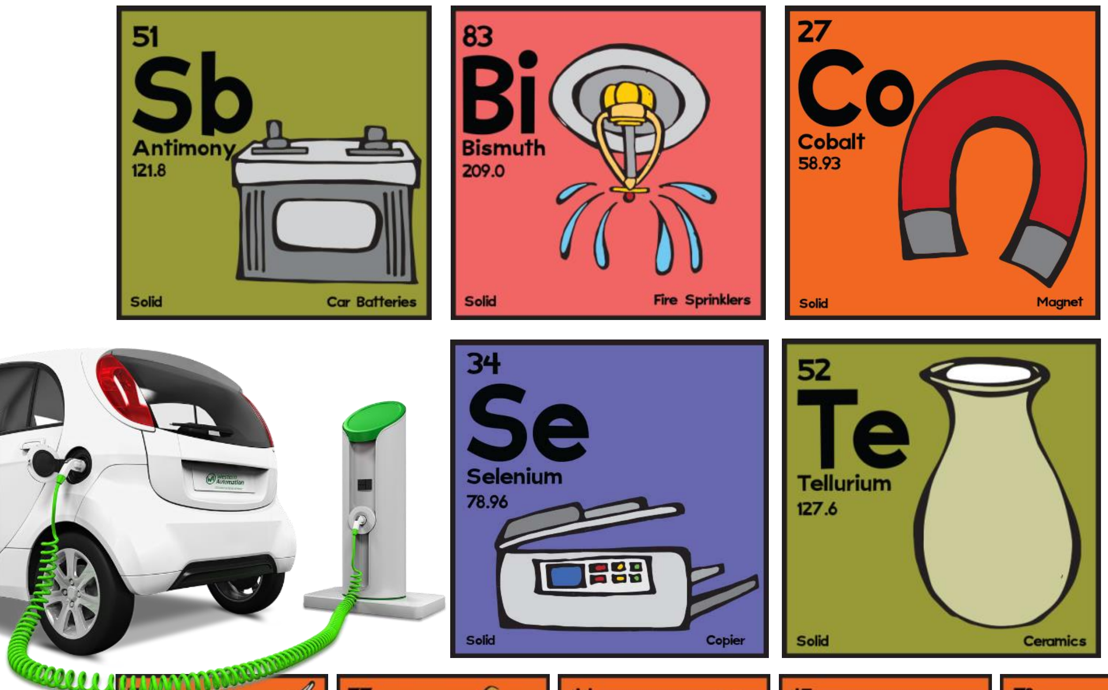
UNIVERSITY OF EXETER

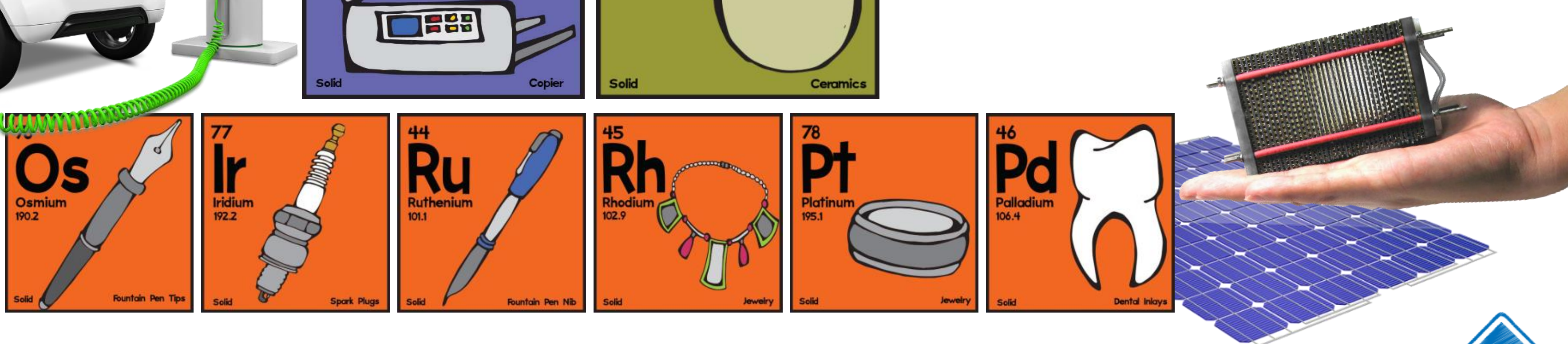
Hannah Hughes

Malvern U3A Geology Group, Wednesday 12^{th} February

Critical raw materials

& green/technology metals





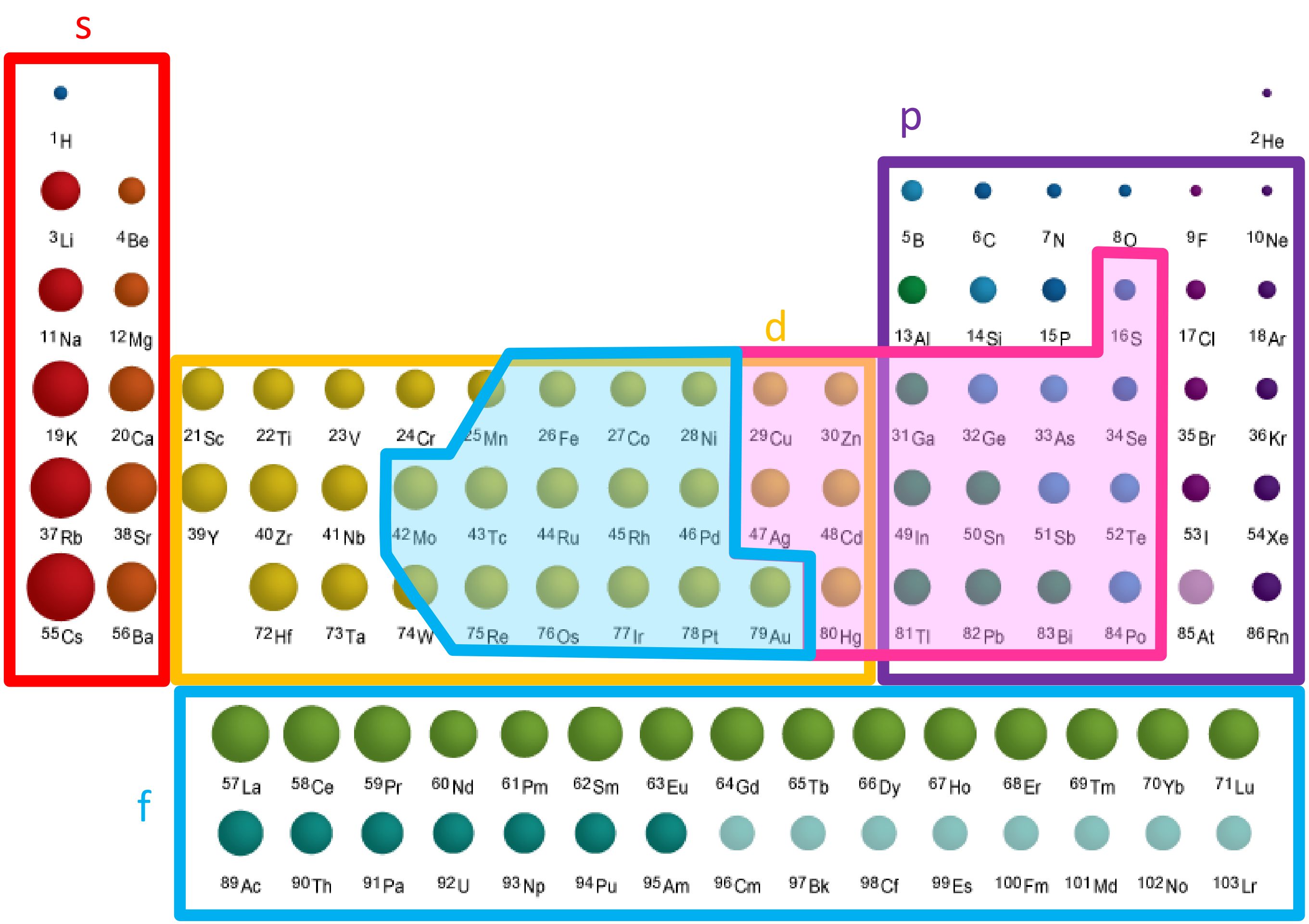
Critical raw materials are those with vulnerable supply due to their production being dominated by one or two countries and susceptible economically / politically driven fluctuations in supply.

Green or 'Technology Metals' are those whose availability are essential for green or digital technology.

This list is not exhaustive and there are a plethora of terms/definitions. [For more information click here.]

Geochemical behaviour

highly siderophile elements and chalcophile elements



Chalcophile elements

(S, Cu, Ag, As, Bi, Cd, Cu, Ga, Ge, Hg, In, Pb, S, Sb, Se, Sn, Te, Tl, Zn)

- ‘ore-loving’ or ‘chalcogen-loving’ (O, S, Se, Te)
- affinity for sulphur or sulphide minerals

Siderophile elements

(Fe, Co, Ni, Os, Ir, Ru, Rh, Pt, Pd, Re, Au, W, Mo)

- affinity for metal
- elevated melting points
- resistant to oxidation
- chalcophile in the absence of metal

A recipe for mineralisation

Mineralisation in the crust is the culmination of many factors from the source region of the magma/metals to the location of 'deposition' of the ore body.

Ore

Pathway

Agent

Whilst the main concentrating events that lead to mineralisation are predominantly crustal processes (e.g., magmatic differentiation, S-saturation, etc) the fertility of the source region is important. The lower the concentration of metals in the source region, the more 'upgrading' is required by later (crustal) processes.

Source

Thus by understanding the principals dictating source composition and fertility, we may feed into mineral exploration models.

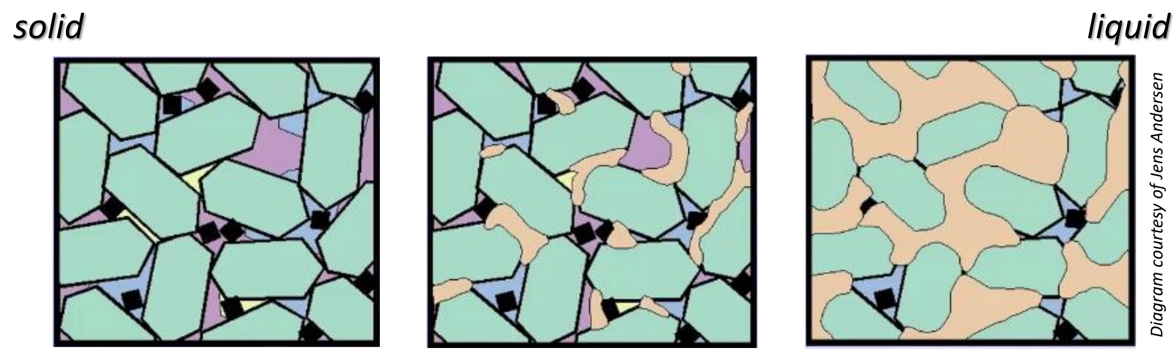
Partial melting of the mantle

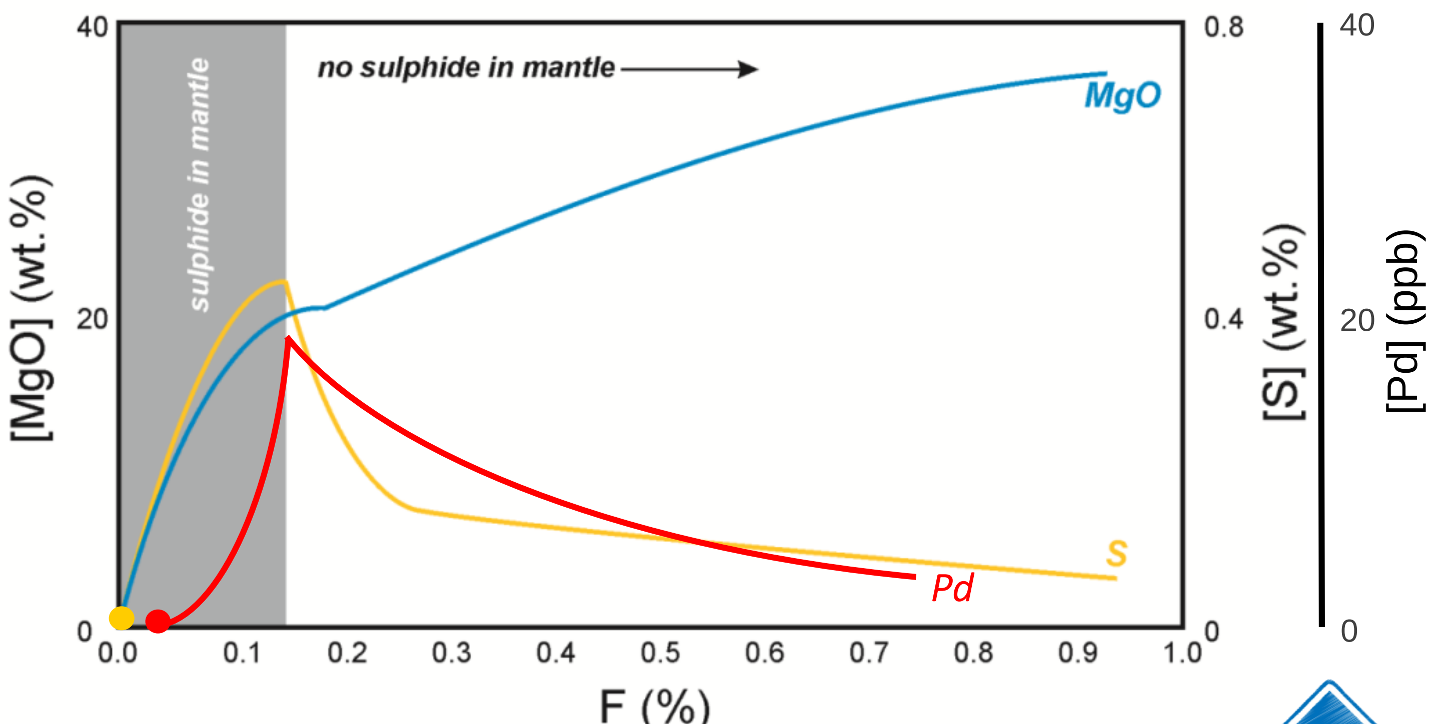
During partial melting, the most fusible minerals will melt first:
clinopyroxene & sulphides

In a partial melting model there will come a point that sulphides will become exhausted in the source.

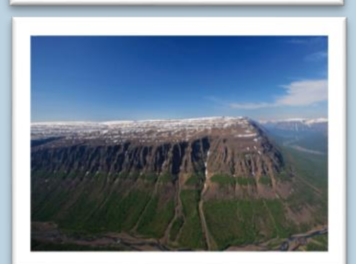
As sulphides host most of the chalcophile elements, they control the budget of these elements in the melts that are formed.

Exhaustion of sulphides means no significant input of chalcophile elements in the melt and/ dilution of these elements with continued melting.





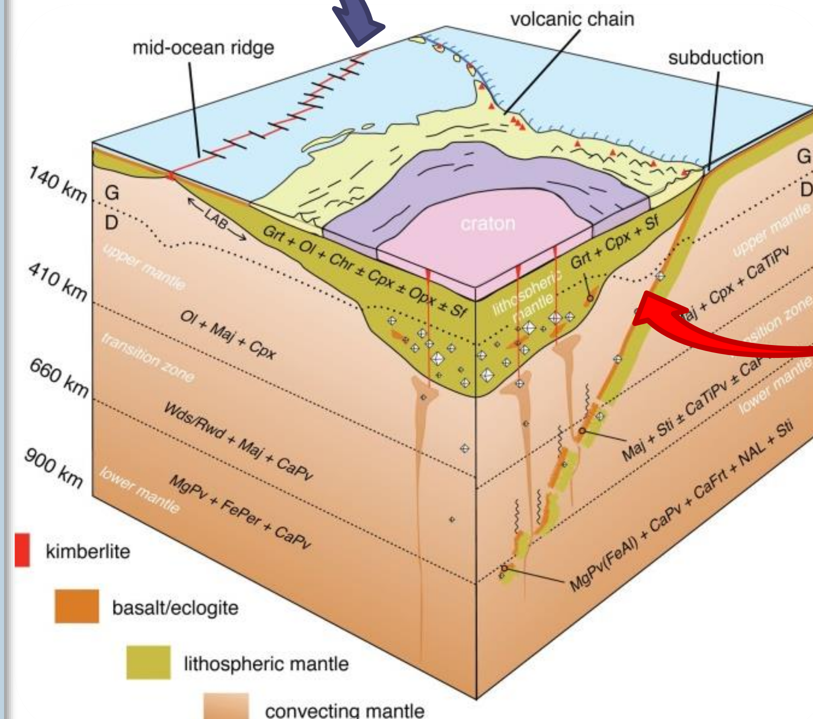
How do we know how much metal is in the mantle?



Modelling

- Meteorites ➔ Mass balance calculations to estimate Bulk Silicate Earth (BSE), etc
- Igneous rocks ➔ 'undo' fractionation via modelling and estimate source composition

… Assumes homogeneity



Empirical

- Mantle xenoliths
- Inclusions in diamonds

Observe and analyse mantle sulphides

… Bewildering detail

Image credits: Tappert & Tappert (2011); Diamina; C. A. Macris; Meteorites.tv; Paul Wignall

Metal budget above subduction zones

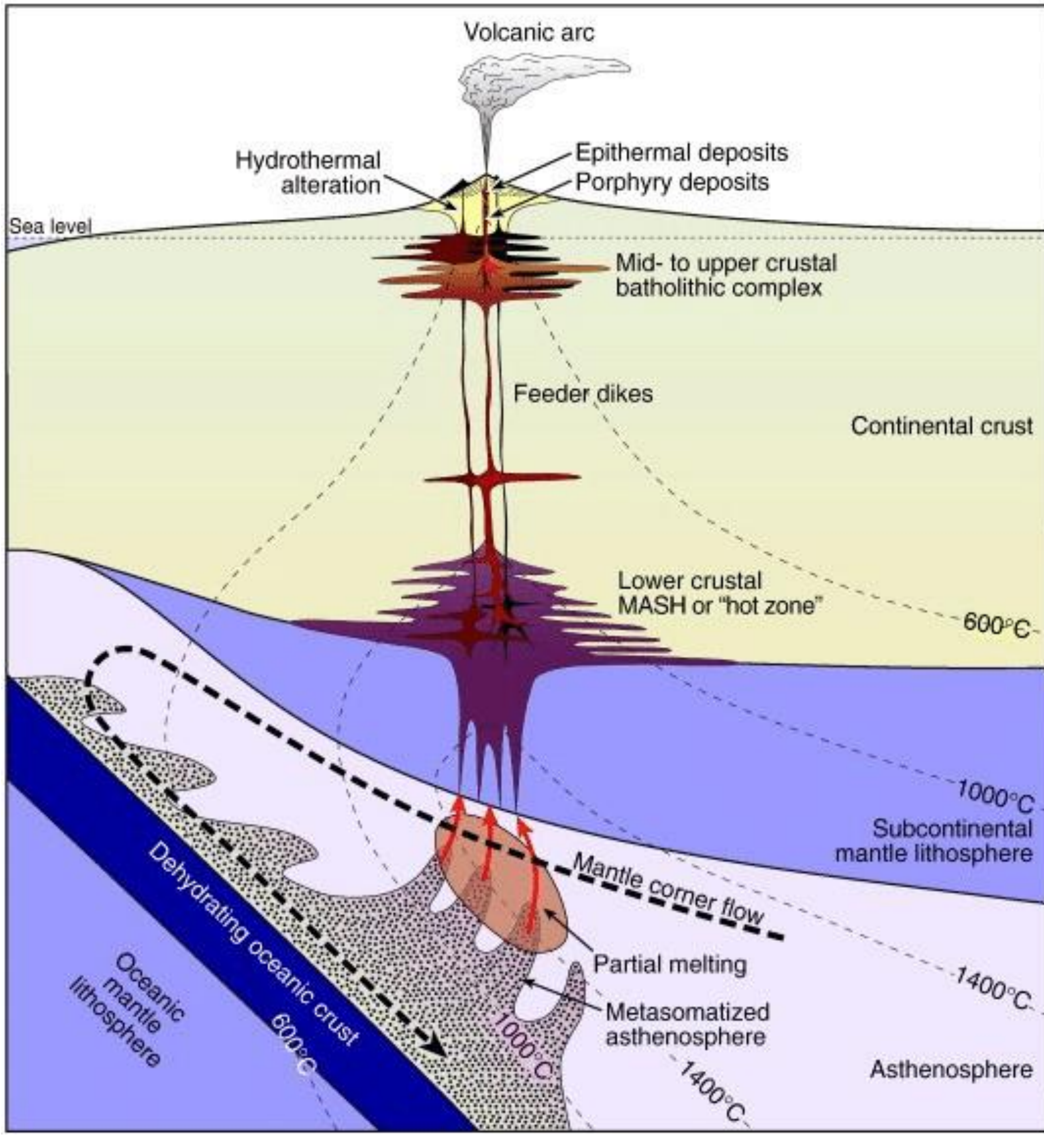


Image : Richards (2011)

Partial melting of mantle peridotites releases base metal sulphides and their metal budget into silicate magma generated…

…But what proportion of these metals become trapped in the lithospheric mantle and lower crust during magma ascent?

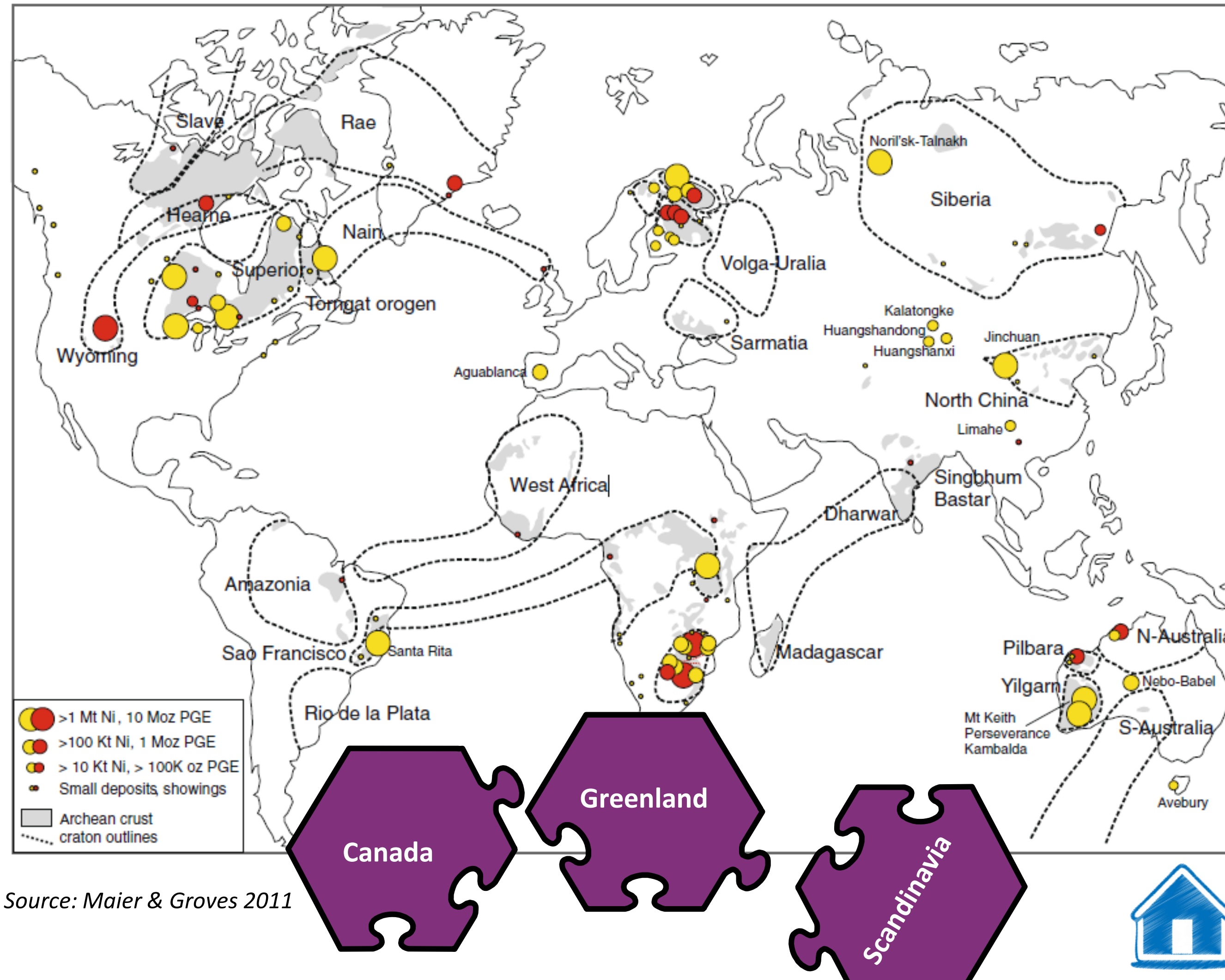
Pyroxenite xenoliths are material from the melting, assimilation, storage and homogenization ('MASH') zone overlying subduction environments.

Lower crust or upper mantle – what is their metal basket?

Metallogenesis
Spatial patterns for mineralisation

- ✓ Association with **Archaean crust/ cratons**
    - Ni-Cu-PGE deposits preferentially located near craton margins
- ✓ Association with **mantle plumes**

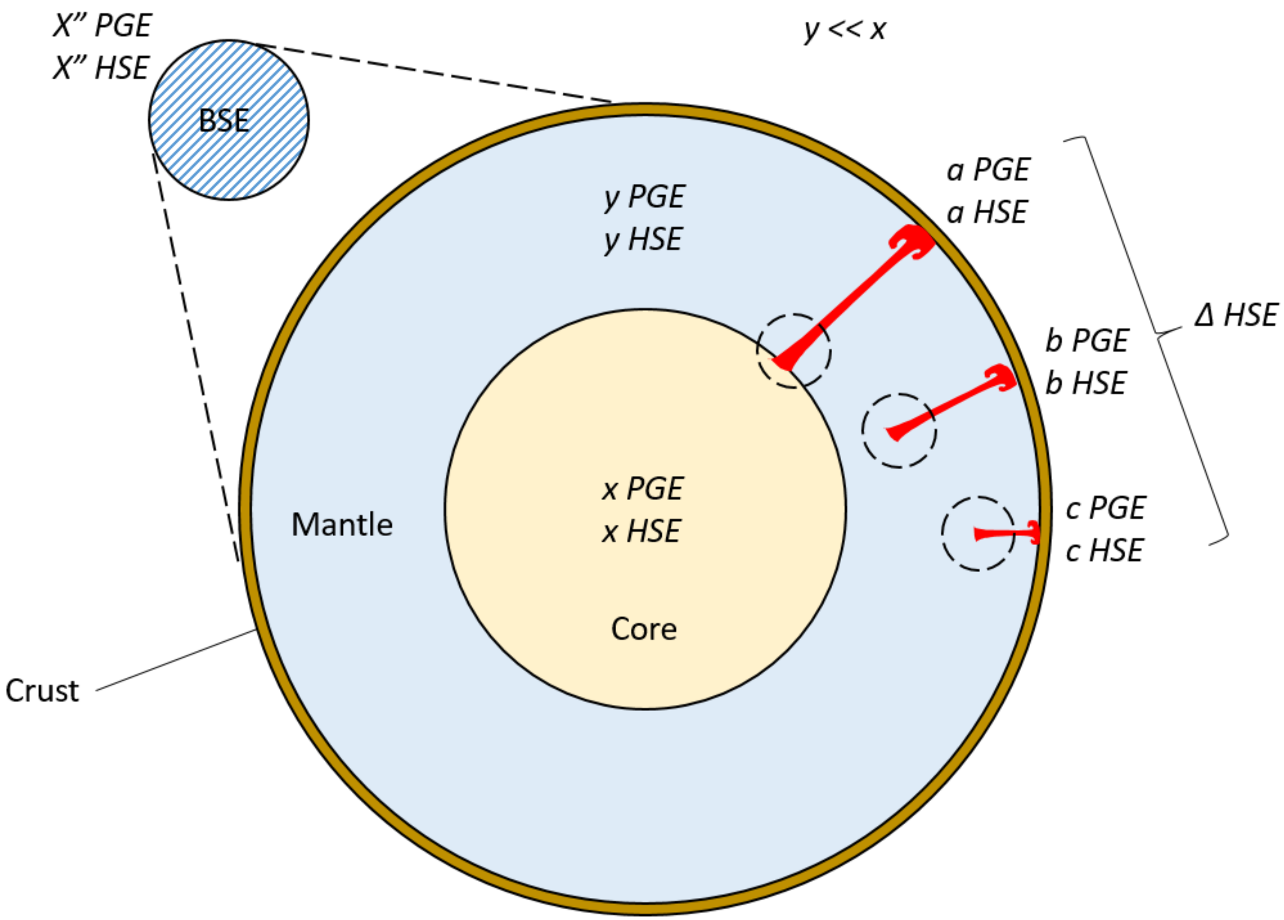
Is this a biased preservation potential of Archaean/ Palaeoproterozoic large layered intrusion deposits **(in a stabilized cratonic setting)?**
… or chemical/physical interaction between the plume and craton?



Source: Maier & Groves 2011

Source region metal concentrations

Mass balance for deep plume:
Incorporating ~ 0.5% outer core material = 2.5 – 3 x mantle concentration of PGE in plume material
Andersen et al. (2002)



Work of Jordan J. Lindsay

The concentration of metals in the source region that is being melted will differ – whether this be the lithosphere or asthenosphere (shallow or deep).

Is the concentration of chalcophile elements consistent throughout the asthenosphere?

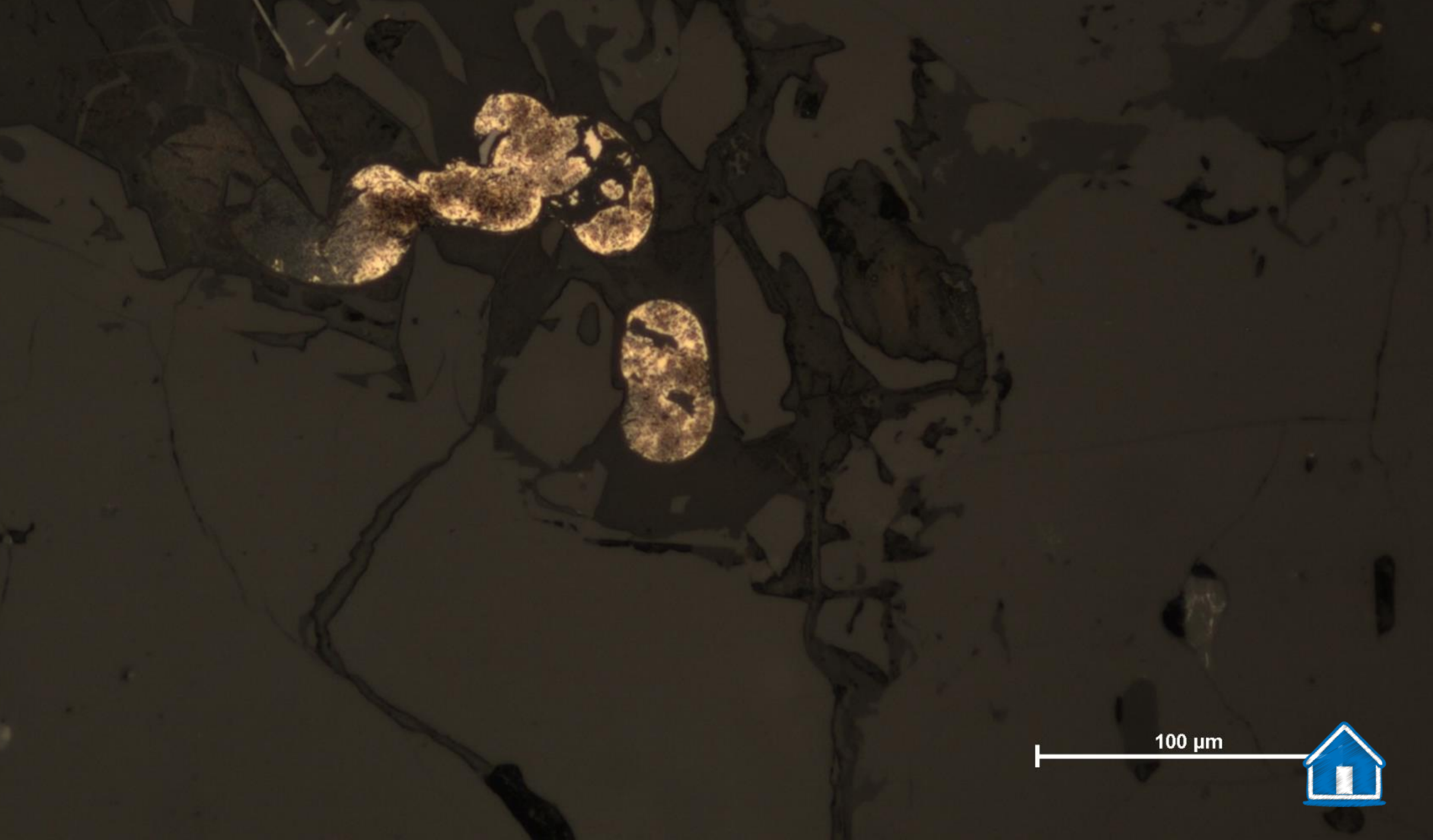
There is even a debate as to whether deep mantle plumes may incorporate components of outer core material. Highly siderophile (and thus chalcophile) elements exist in much higher concentrations in the core than the mantle.

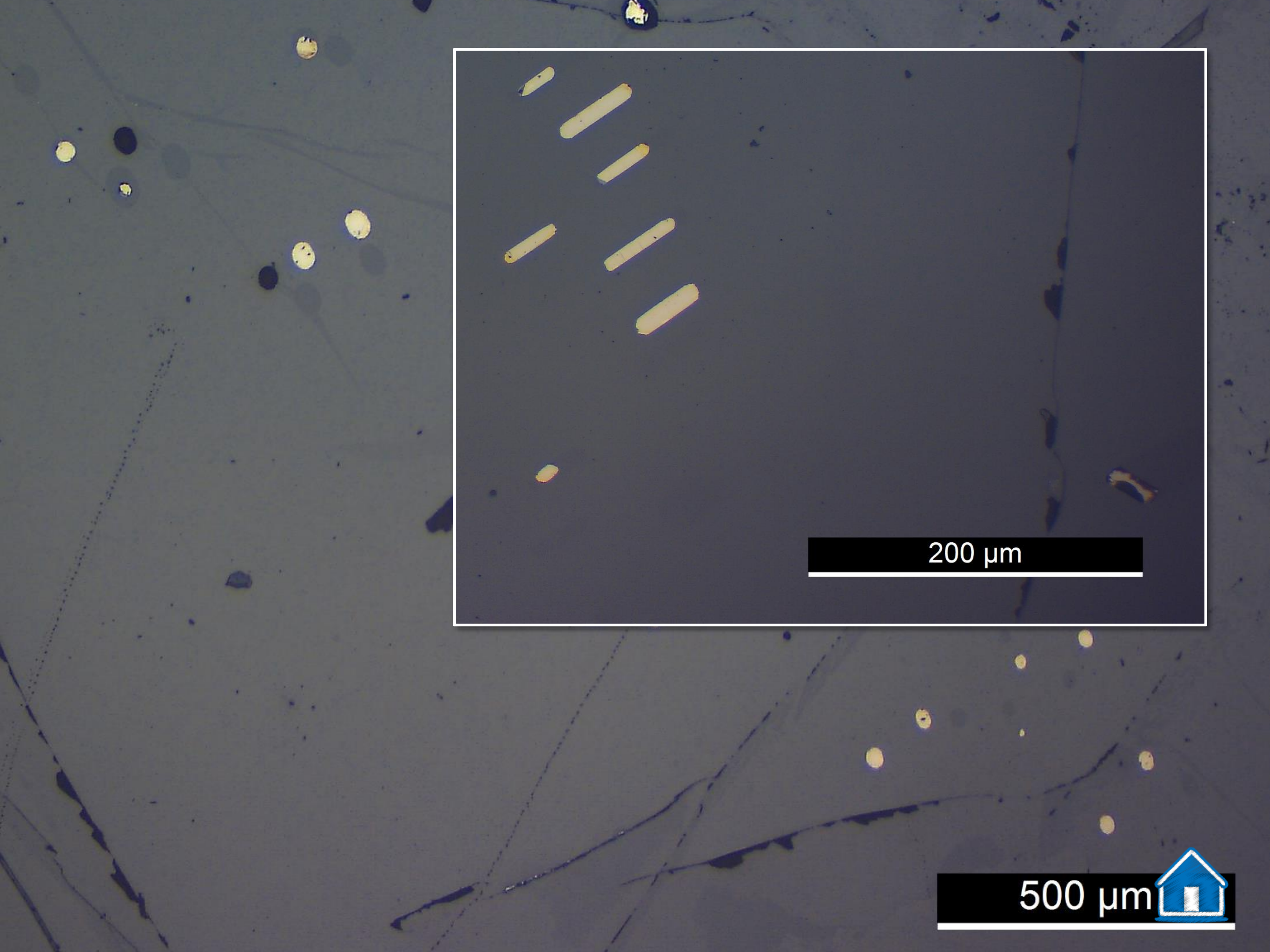
If deep plumes 'tap' into outer core material (originating from the D" Layer) this could significantly upgrade their fertility for some metals.

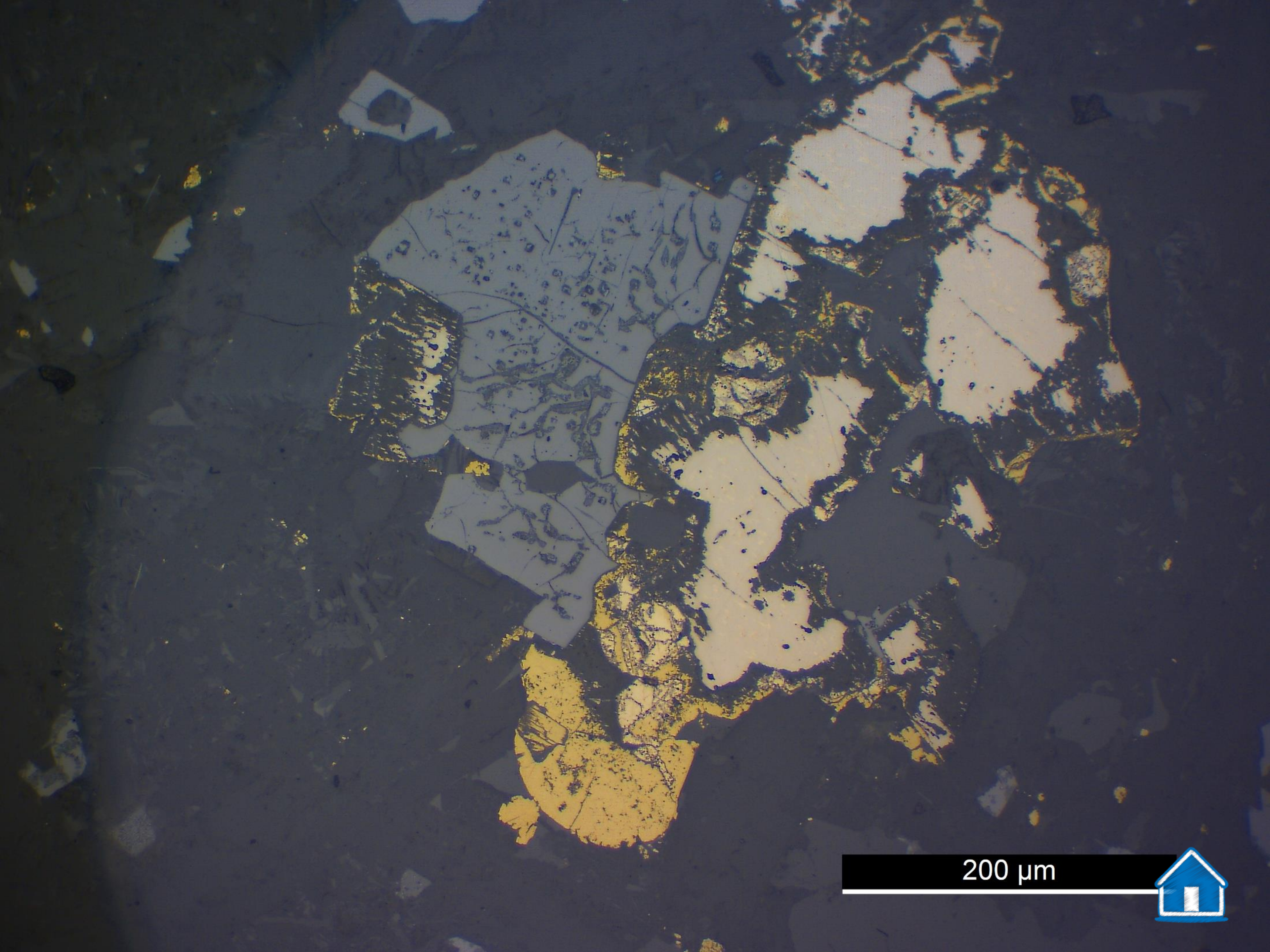
The empirical approach

Close up view of sulphide inclusion within 1 carat Orapa diamond (3D volume rendered false colour image from µCT). Inclusion approx. 80µm wide.
Clip available from McDonald et al. (2017)

There are mantle sulphides and then there are mantle sulphides…



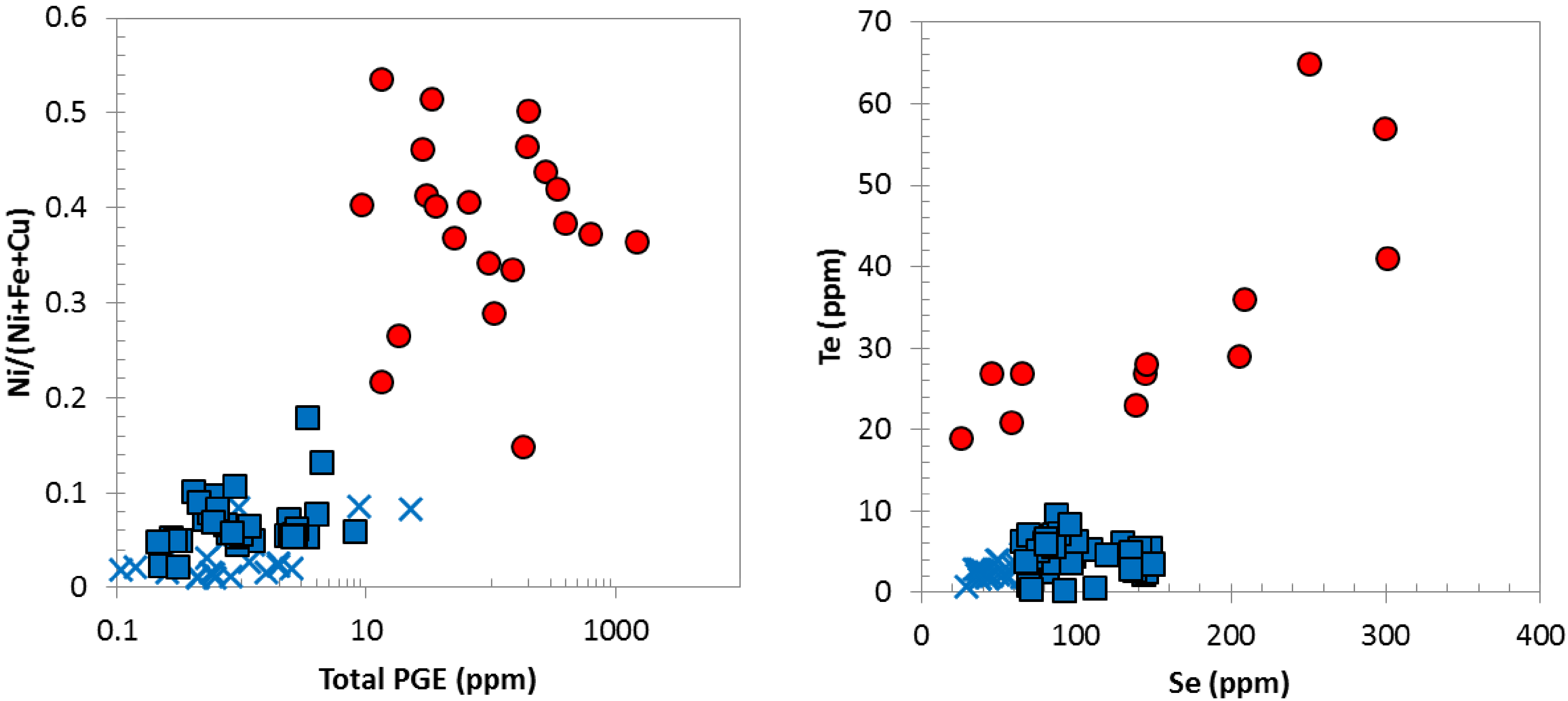

200 µm
500 µm


200 µm

Sulphide inclusions in diamond

Peridotite (P-type) vs Eclogite (E-type)

McDonald et al. (2017)

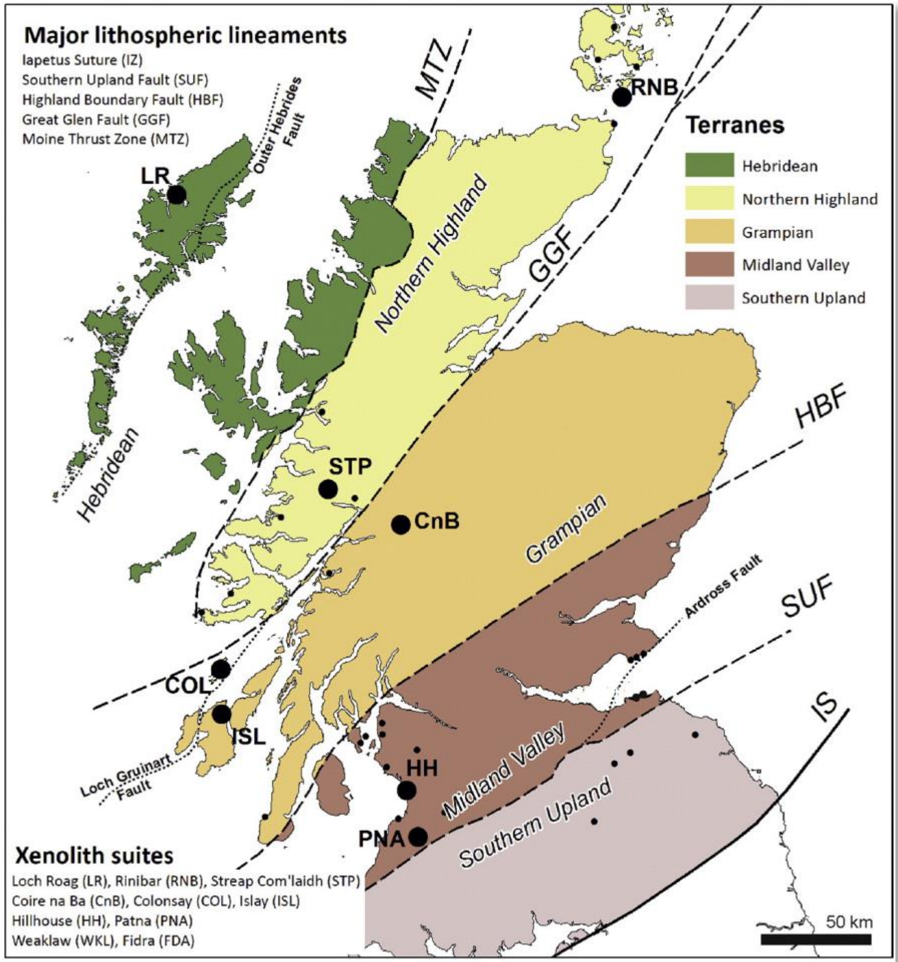


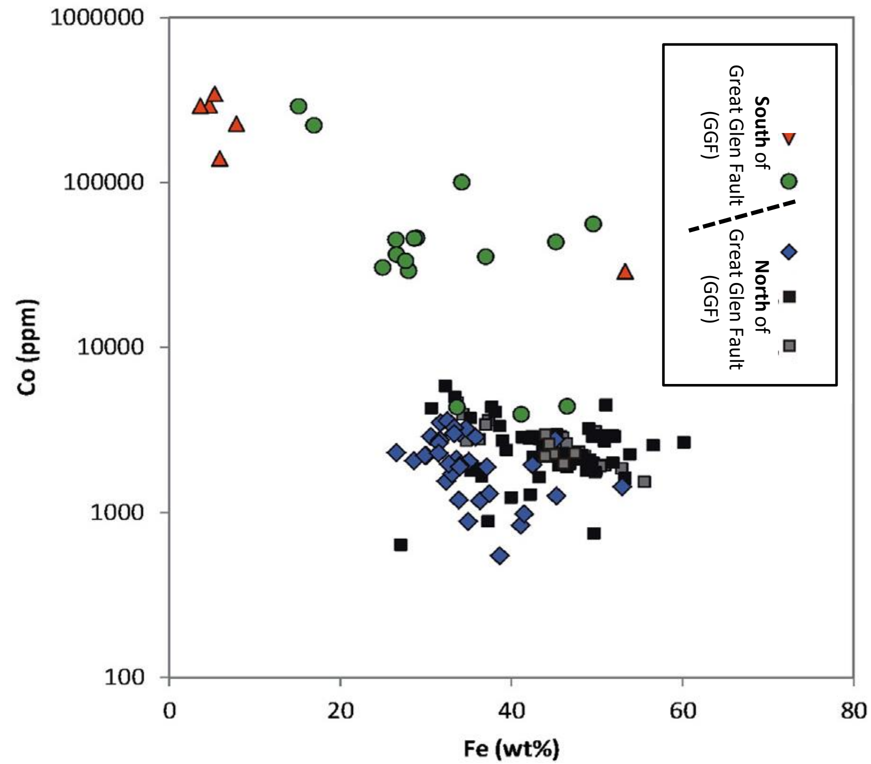
Diamonds may be P-type (derived from a peridotite) or E-type (derived from an eclogite). Both P- and E-type diamonds may have sulphide inclusions.

There appears to be a systematic difference in the metal budget of P- and E-type diamond sulphide inclusions.

- ● Bulanova et al 1996 - Yakutian P-type diamonds
- × Aulbach et al 2012 - Diavik Mine (Slave Craton) E-type diamonds
- ■ McDonald et al. (2017) Orapa E-type diamonds

Cobalt: terrane-scale trends





In situ **analyses of sulphides from spinel lherzolite mantle xenoliths in Scotland show two trends:**

- **North** of the Great Glen Fault (GGF*) have **ppm** levels of Co.
- **South** of the GGF have **wt.%** levels of Co.

**The GGF is the crustal lineament dividing marginal cratonic terranes to the N from off-craton terranes to the S.*

Hughes et al (2016)

… over to you

head back to the main menu & choose what to discuss …

Critical raw materials
& green/technology metals

more info…

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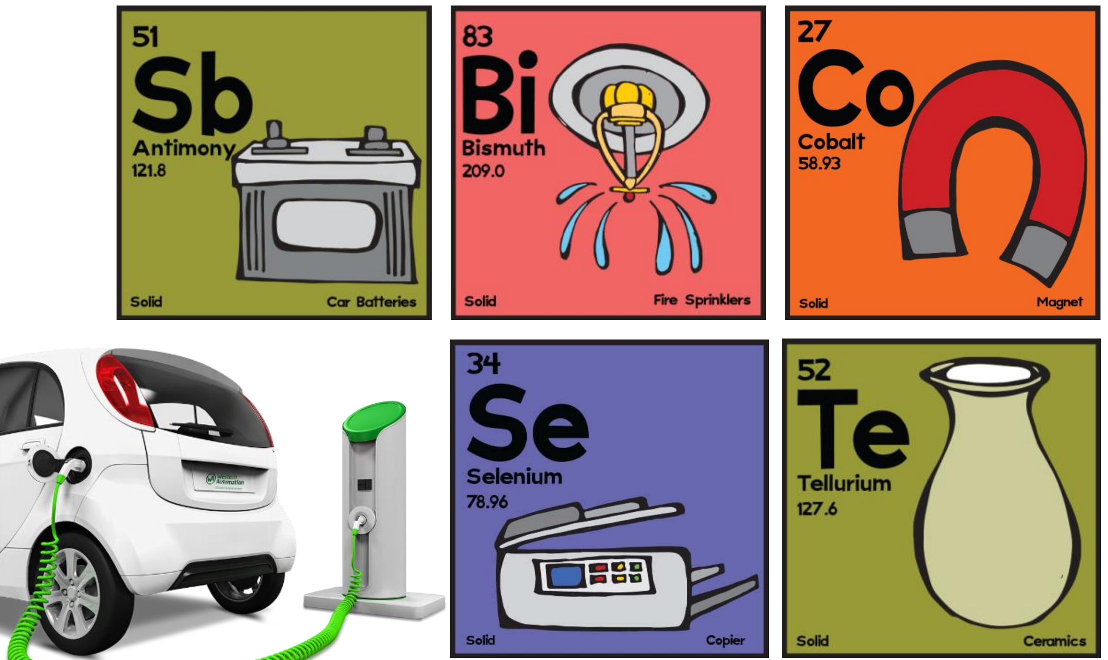

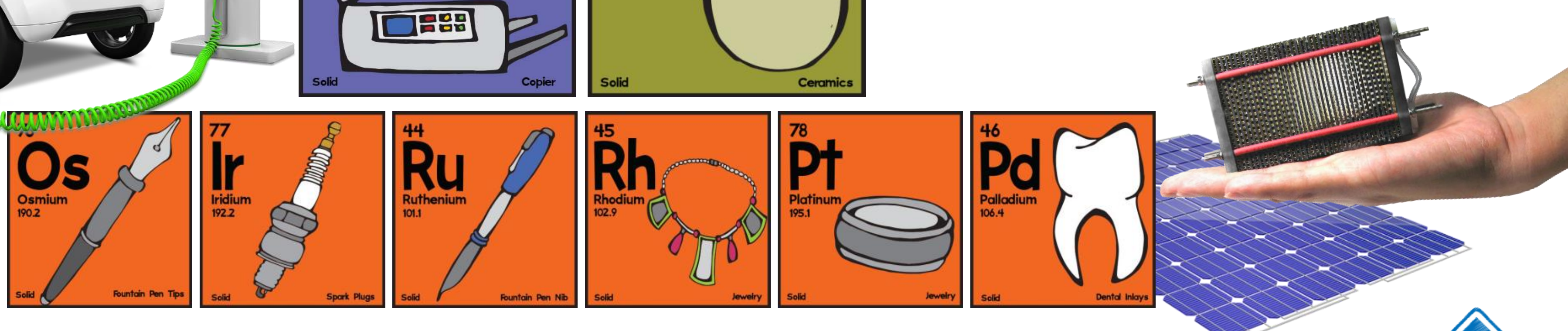

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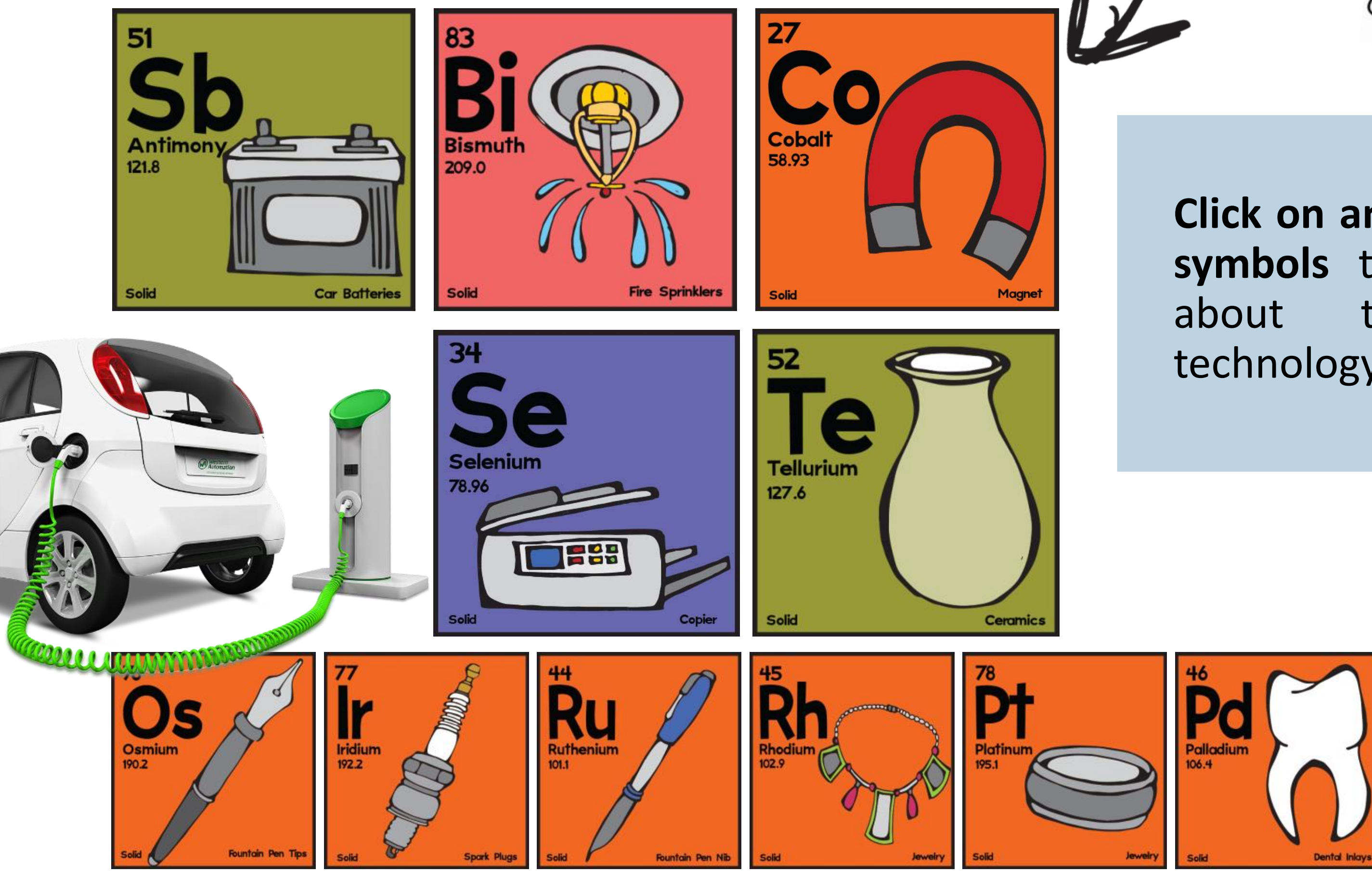
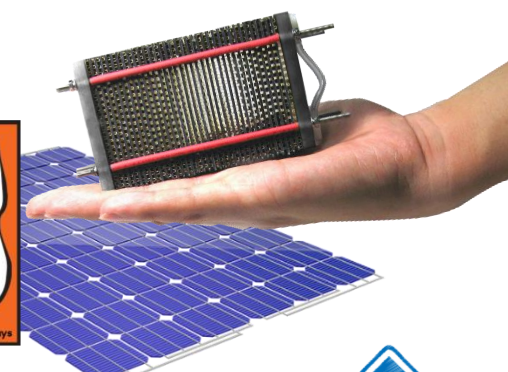
Critical metals

... fun facts



Click on any of the chemical symbols to find out more about their uses in technology and our lives



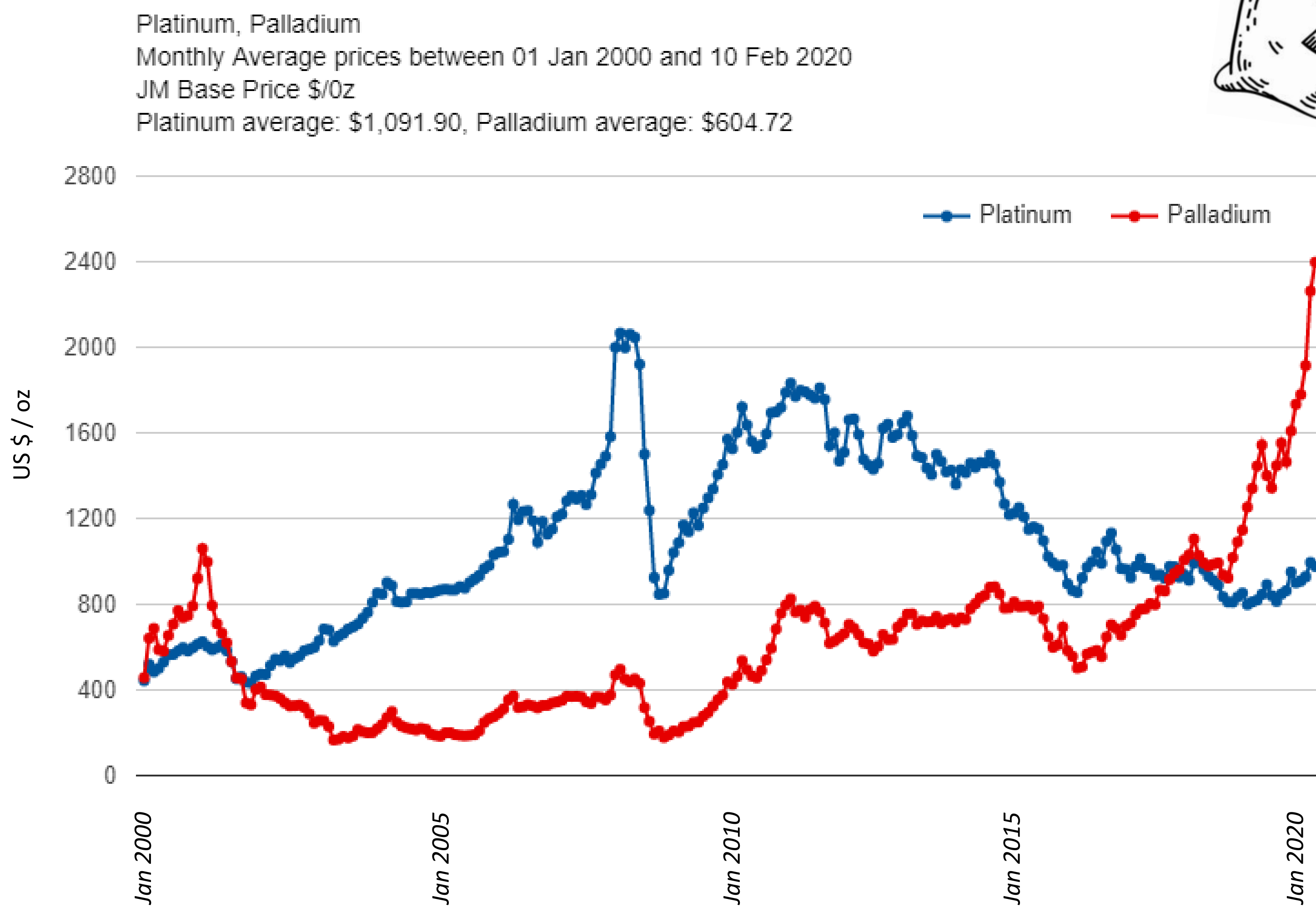
For more info see http://www.rsc.org/periodic-table

Metal prices

Gold price

Metal prices

Platinum & Palladium price



Critical metals

... fun facts

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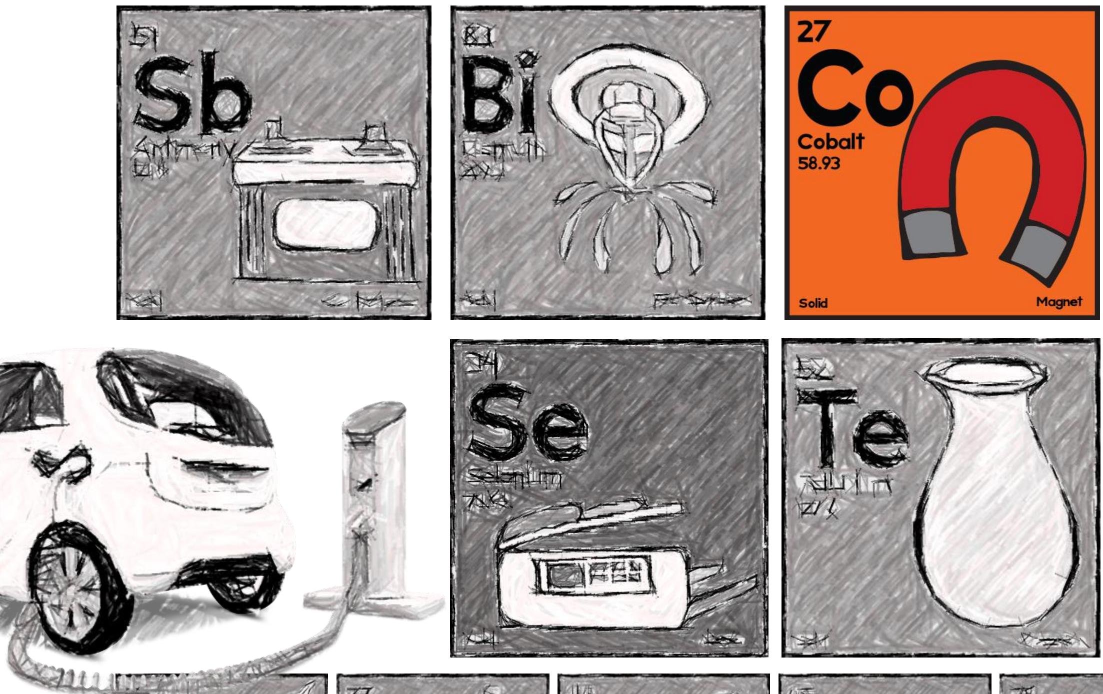
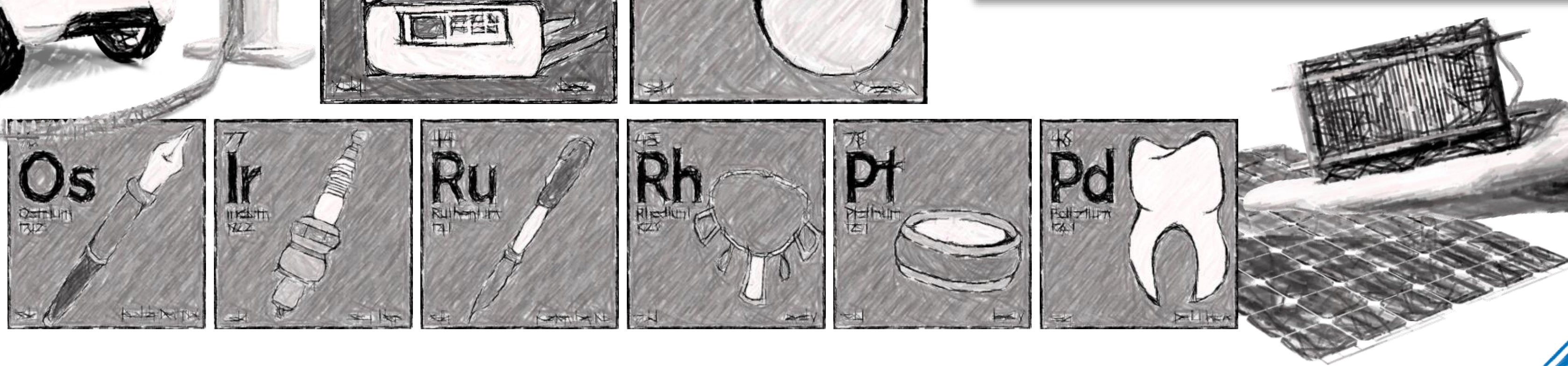
Choose your next critical metal...



Co is used to make **magnets** (particularly powerful when alloyed with Al and Ni). Co alloys are also used in **jet turbines** and **gas turbine generators**. Co metal is used in **electroplating** and Co salts as a **pigment**. Radioactive ^{60}Co is used in **cancer treatment**. Of course of major interest for green technology, Co is a fundamental component in many **batteries** and **energy storage systems**.



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Critical metals

... fun facts

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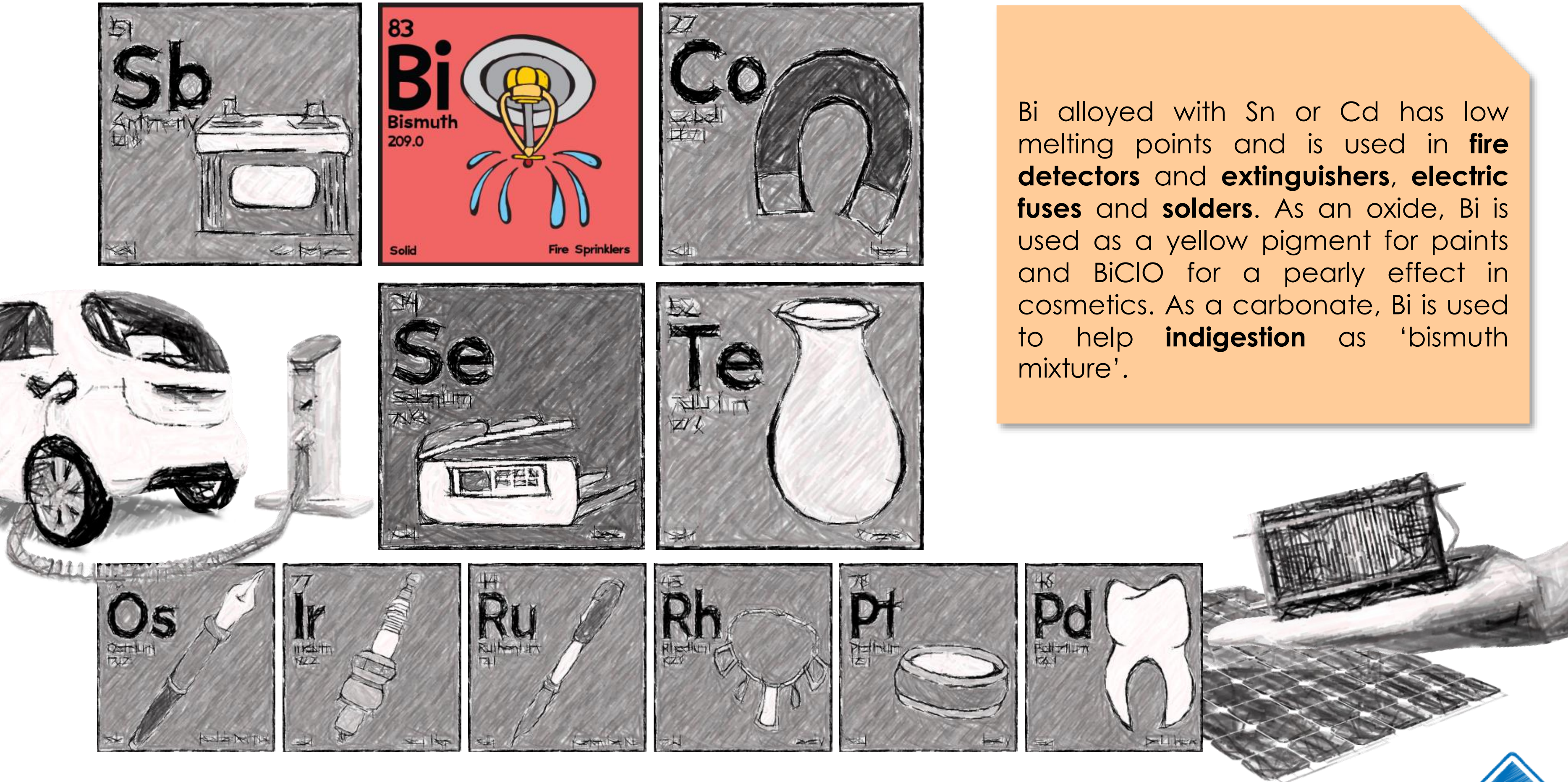

Bi alloyed with Sn or Cd has low melting points and is used in **fire detectors** and **extinguishers**, **electric fuses** and **solders**. As an oxide, Bi is used as a yellow pigment for paints and $BiClO$ for a pearly effect in cosmetics. As a carbonate, Bi is used to help **indigestion** as 'bismuth mixture'.

For more info see http://www.rsc.org/periodic-table

Critical metals

... fun facts

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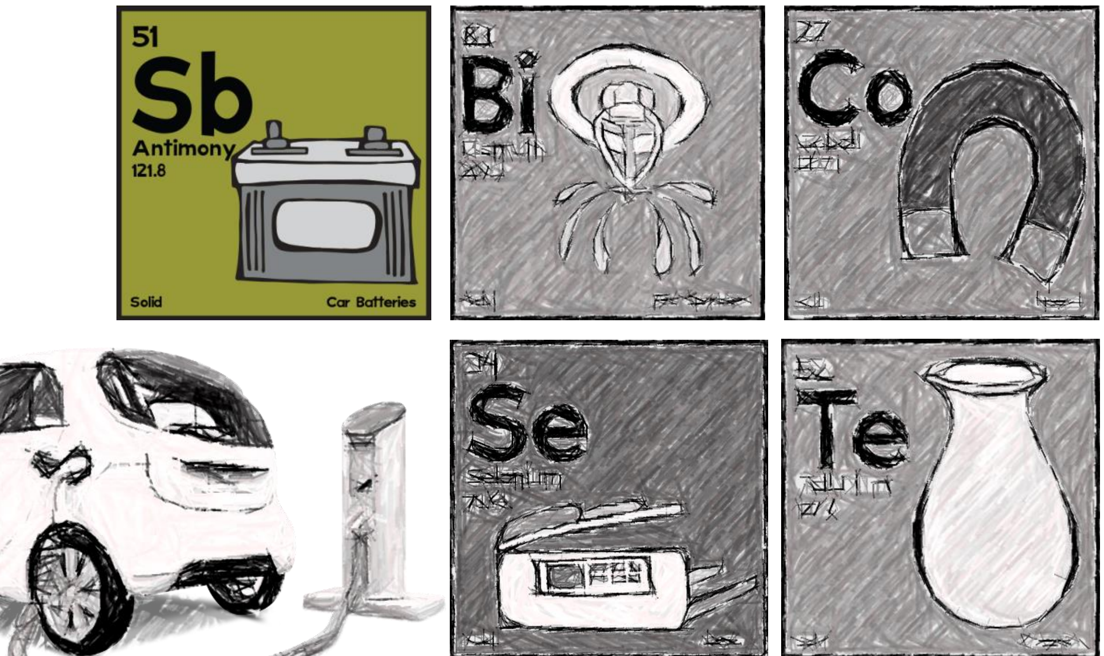
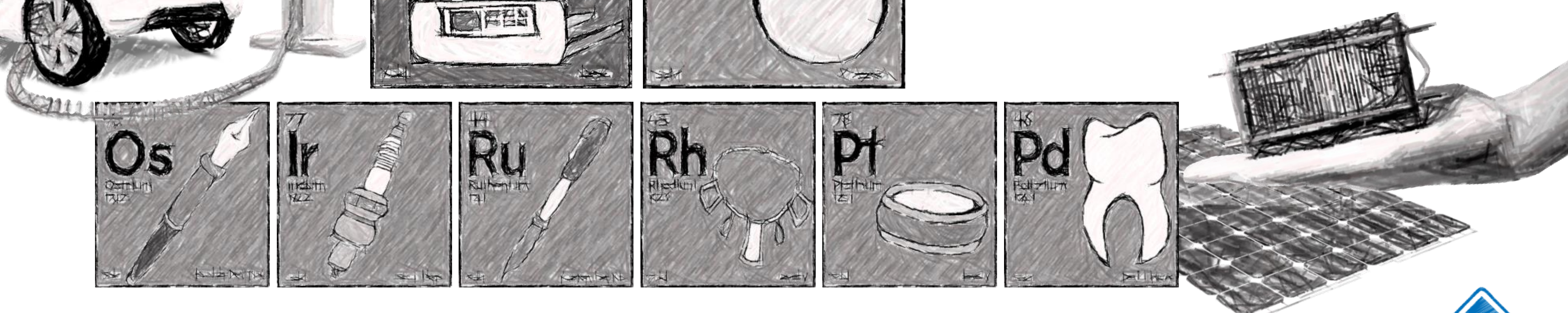


Sb is used in **semiconductor devices**, such as **infrared detectors** and **diodes**. A Pb-Sb is used in some **batteries**. Sb compounds are also used to make **flame-retardant materials**, **paints**, **glass** and **pottery**.



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Critical metals

… fun facts

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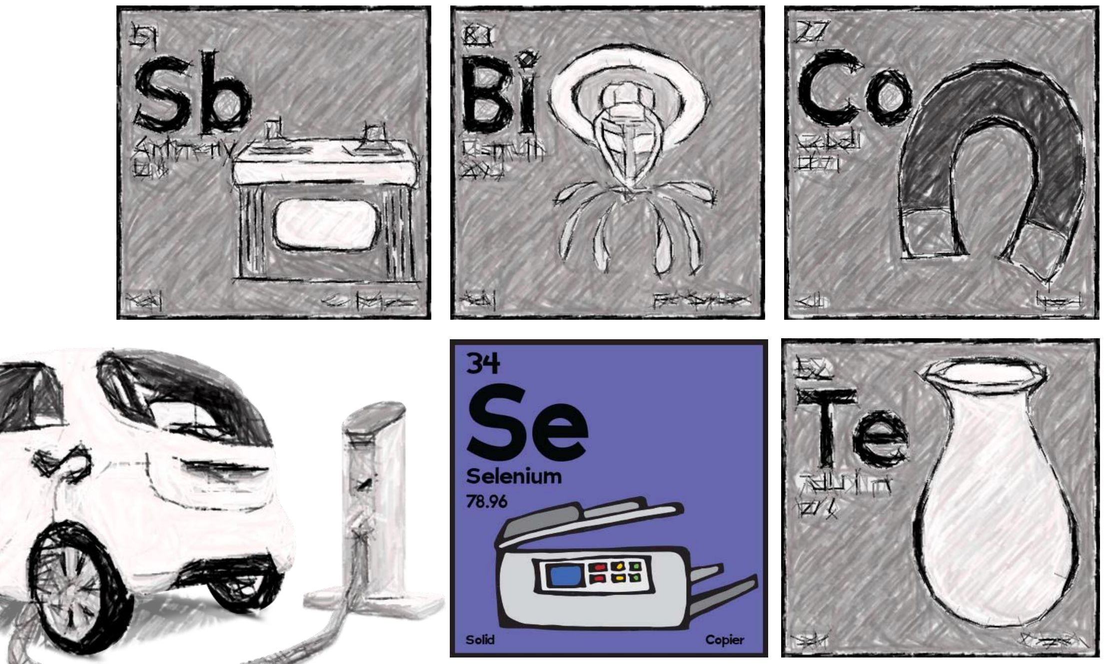

Se is currently mostly used in **glass** making (to reduce transmission of sunlight or as a pigments). It's also toxic to scalp fungus and thus used in some anti-dandruff shampoo. As a critical metal, Se is both photovoltaic (converts light to electricity) and photoconductive (electrical resistance decreases with increased illumination) so it's a fundamental component in **photocells / solar cells** (and photocopiers!)

For more info see http://www.rsc.org/periodic-table

Critical metals

... fun facts

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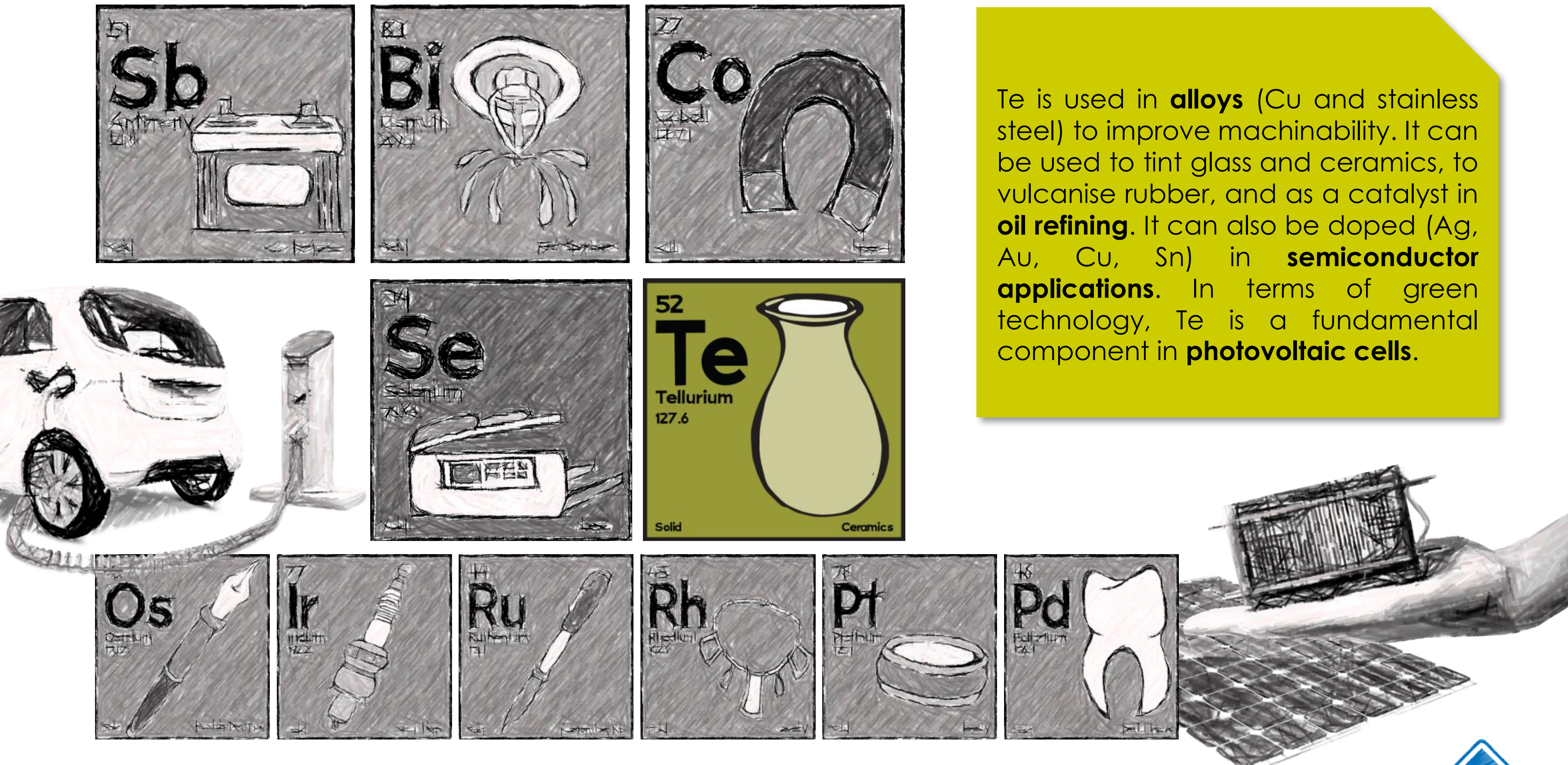

Te is used in **alloys** (Cu and stainless steel) to improve machinability. It can be used to tint glass and ceramics, to vulcanise rubber, and as a catalyst in **oil refining**. It can also be doped (Ag, Au, Cu, Sn) in **semiconductor applications**. In terms of green technology, Te is a fundamental component in **photovoltaic cells**.

For more info see http://www.rsc.org/periodic-table

Critical metals

… fun facts

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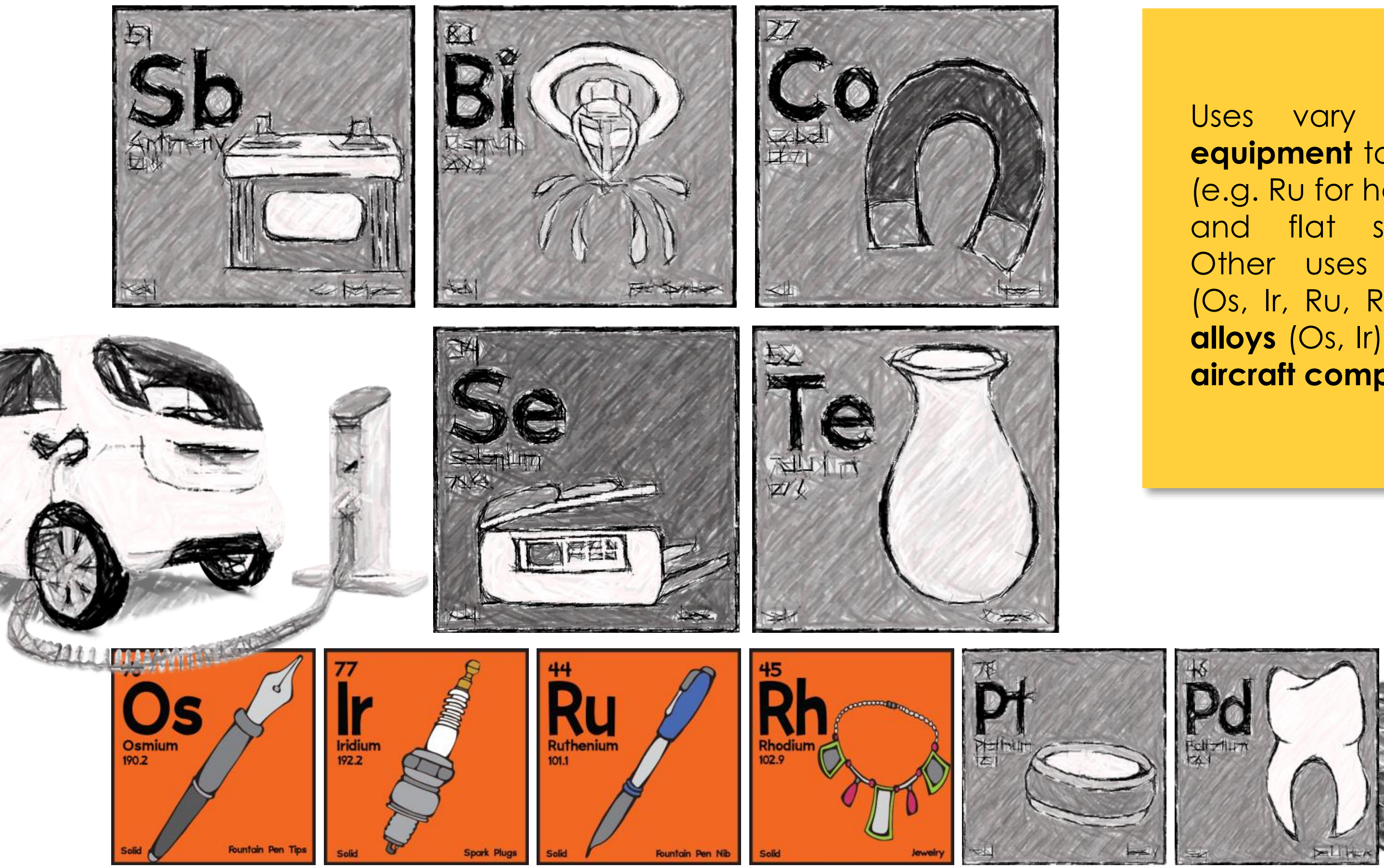
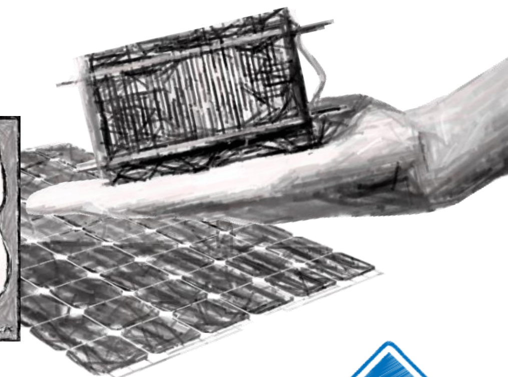


Uses vary from **glass-making equipment** to **magnet technology** (e.g. Ru for hard disk manufacture and flat screen technology). Other uses include **electronics** (Os, Ir, Ru, Rh), **high-temperature alloys** (Os, Ir), **solar cells** (Ru), and **aircraft components** (Rh).



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Critical metals

... fun facts

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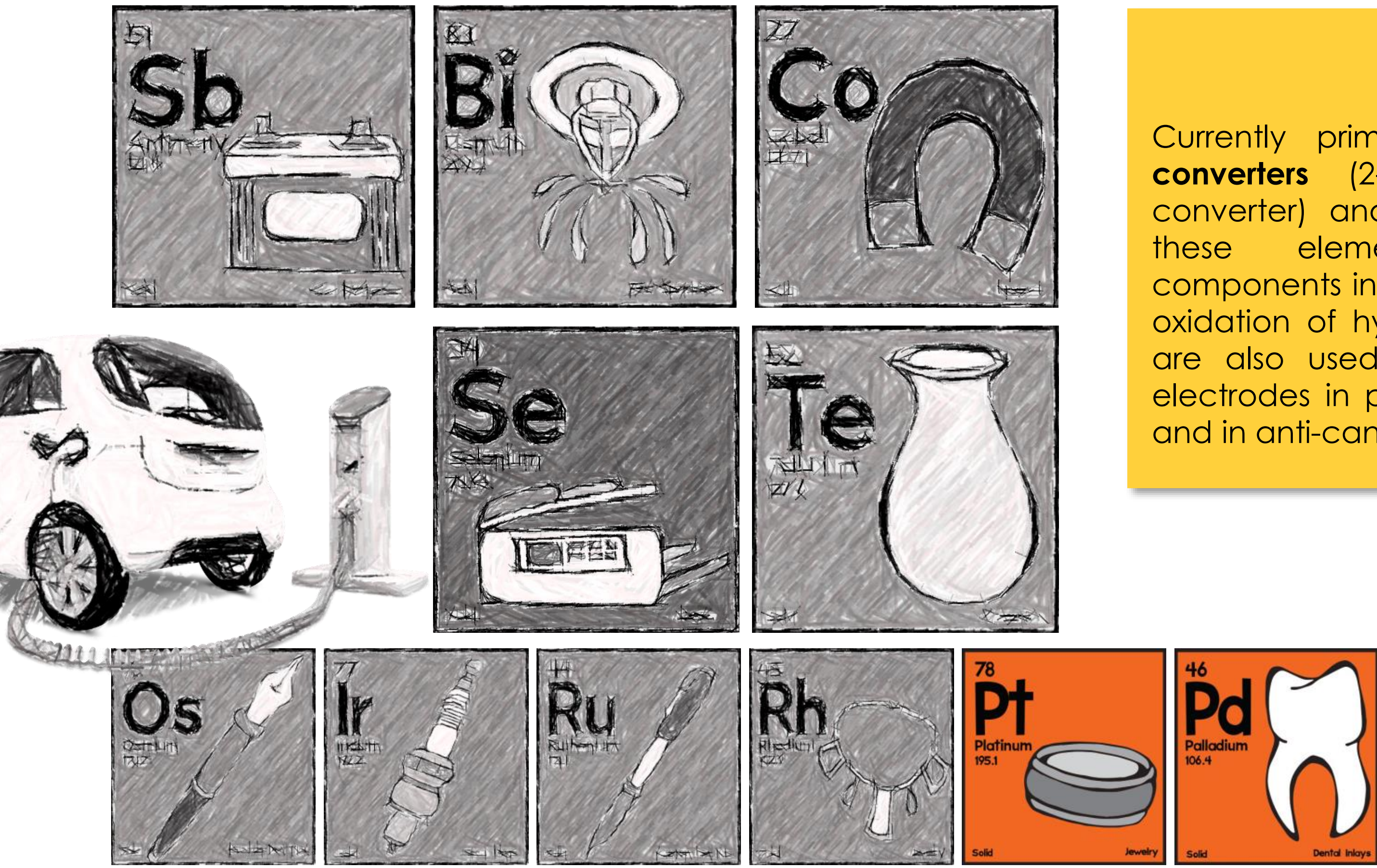
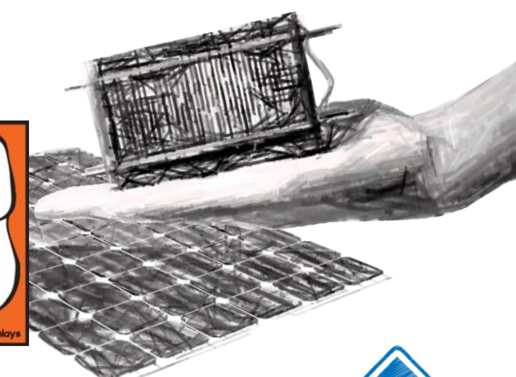


Currently primarily used in **catalytic converters** (2-4 g used per cat. converter) and as **industrial catalysts**, these elements are important components in **fuel cells** to catalyse the oxidation of hydrogen (> 28 g !). They are also used in **medicine** (dentistry, electrodes in pace makers/defibrillators and in anti-cancer drugs).



For more info see http://www.rsc.org/periodic-table

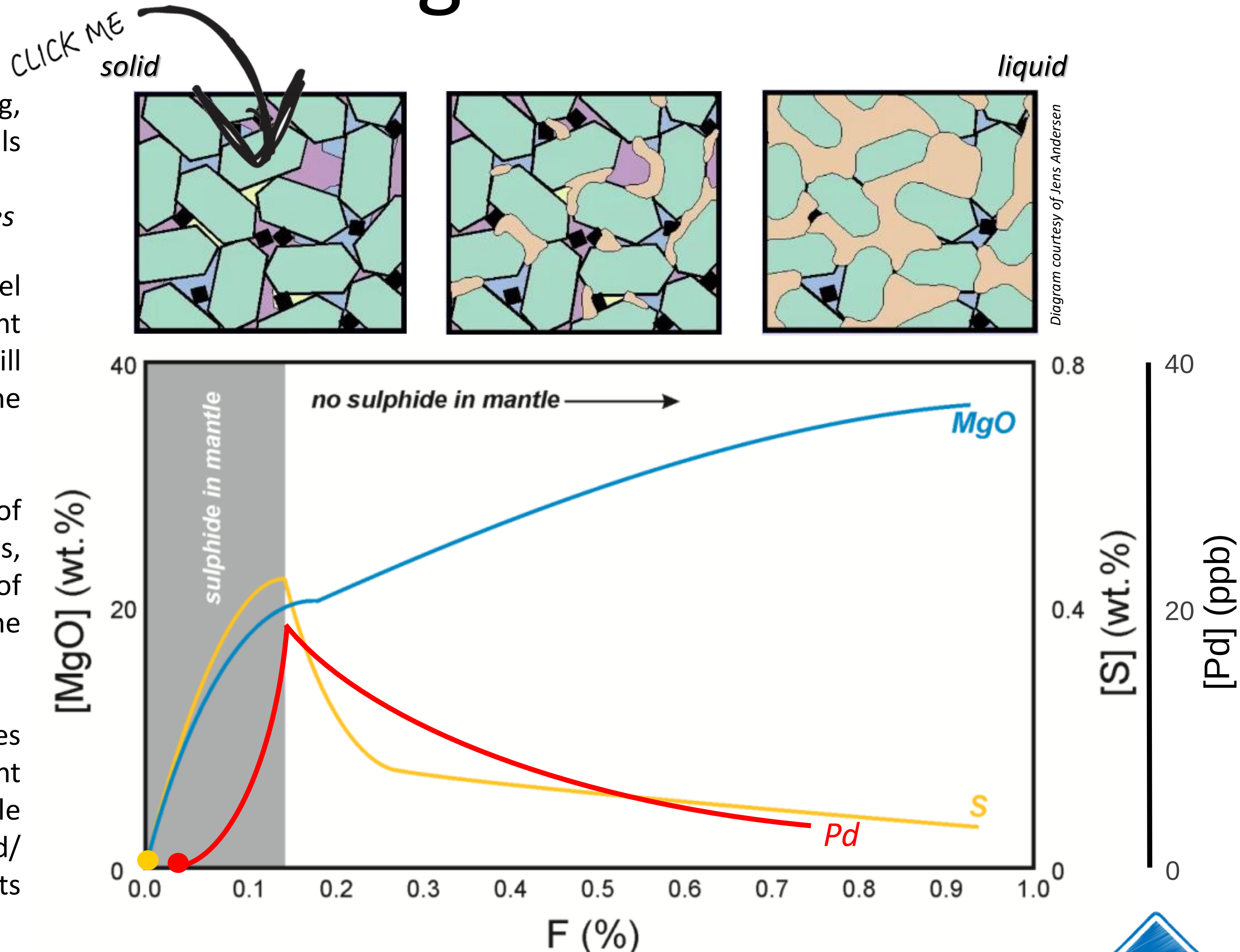
Partial melting of the mantle

During partial melting, the most fusible minerals will melt first: *clinopyroxene & sulphides*

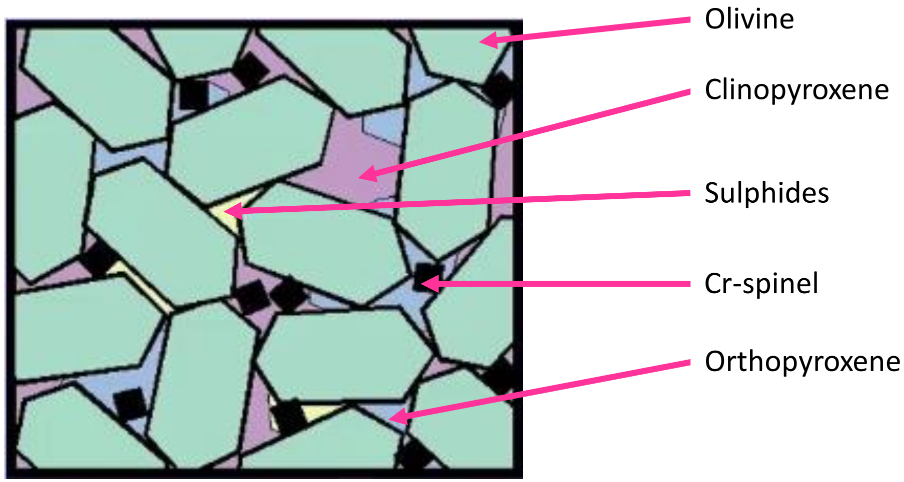
In a partial melting model there will come a point that sulphides will become exhausted in the source.

As sulphides host most of the chalcophile elements, they control the budget of these elements in the melts that are formed.

Exhaustion of sulphides means no significant input of chalcophile elements in the melt and/ dilution of these elements with continued melting.



Partial melting of the mantle



- Sulphide minerals are the main host of chalcophile elements.
- In terms of the platinum-group elements (PGE), sulphides predominantly host Pt, Pd and Rh (the Pd-group PGE, PPGE).
- Sulphides may also host Au (although there is evidence that this can be as nanonuggets outside of sulphides).
- Sulphides can host Os, Ir and Ru although alloys and/or Cr-spinel may play a significant role in controlling the abundance of these elements (the Ir-group PGE, IPGE).

CLICK ME

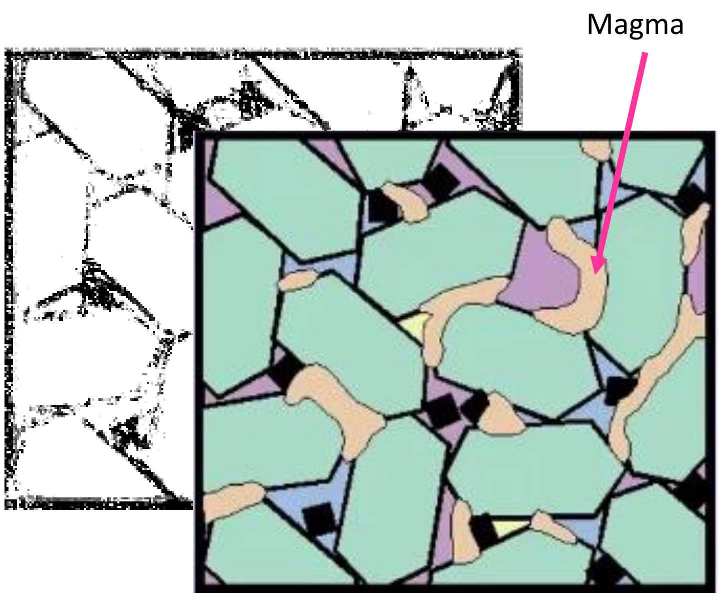
more info…

CLICK ME

Back to partial melting info…

Diagram courtesy of Jens Andersen

Partial melting of the mantle



- In this box model, sulphides are shown as only being interstitial phases (between silicates and oxides). This means that during partial melting their metal budget may be added to the magma that is forming.
- We know from mantle xenoliths that sulphides often occur as inclusions within other minerals, for example olivine, garnet or pyroxenes. Depending on what they are included within, the metal budget of the sulphides may not be accessible to the magma generated during partial melting.
- Hence, just because a mantle rock may have (critical) metal-rich sulphides (and/or a metal enriched bulk composition) doesn't mean that the metal budget from that mantle rock can enter the magma.

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more info…

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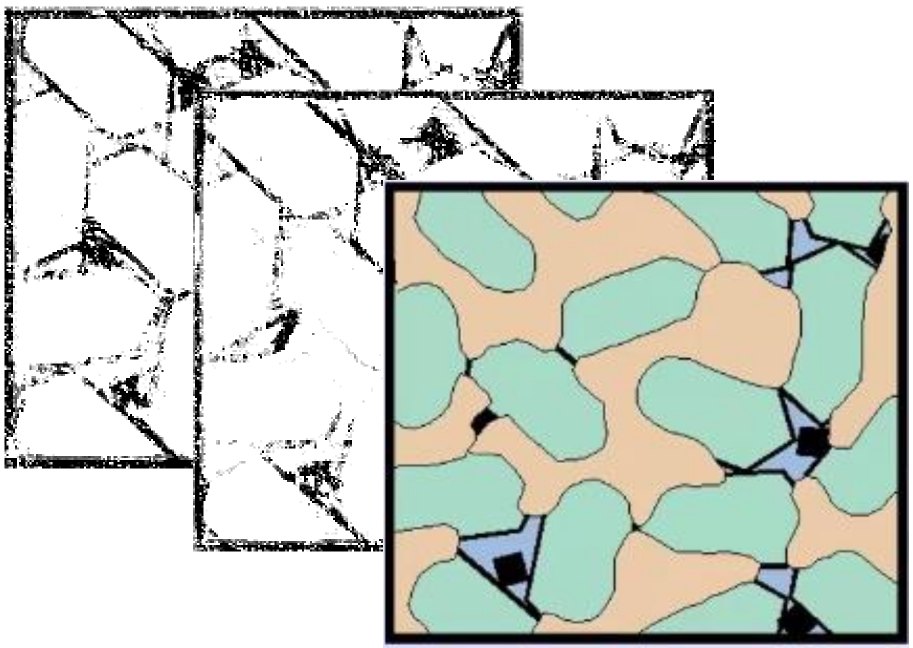
Back to partial melting info…

Diagram courtesy of Jens Andersen

Partial melting of the mantle



- If sulphides are included in less fusible minerals (such as olivine) their metal budget may not be released to the magma until a considerable degree of partial melting of the mantle.

- There are many other controls besides, including the P, T and fO_2 of melting, that may determine how the metal budget of sulphide minerals may be released.

- In summary, sulphides must be accessible to partial melting (in terms of their petrographic setting) for their metal budget to reflect in the geochemistry of the magma generated. This important point is often overlooked in geological models discussing the 'fertility' of magmas.

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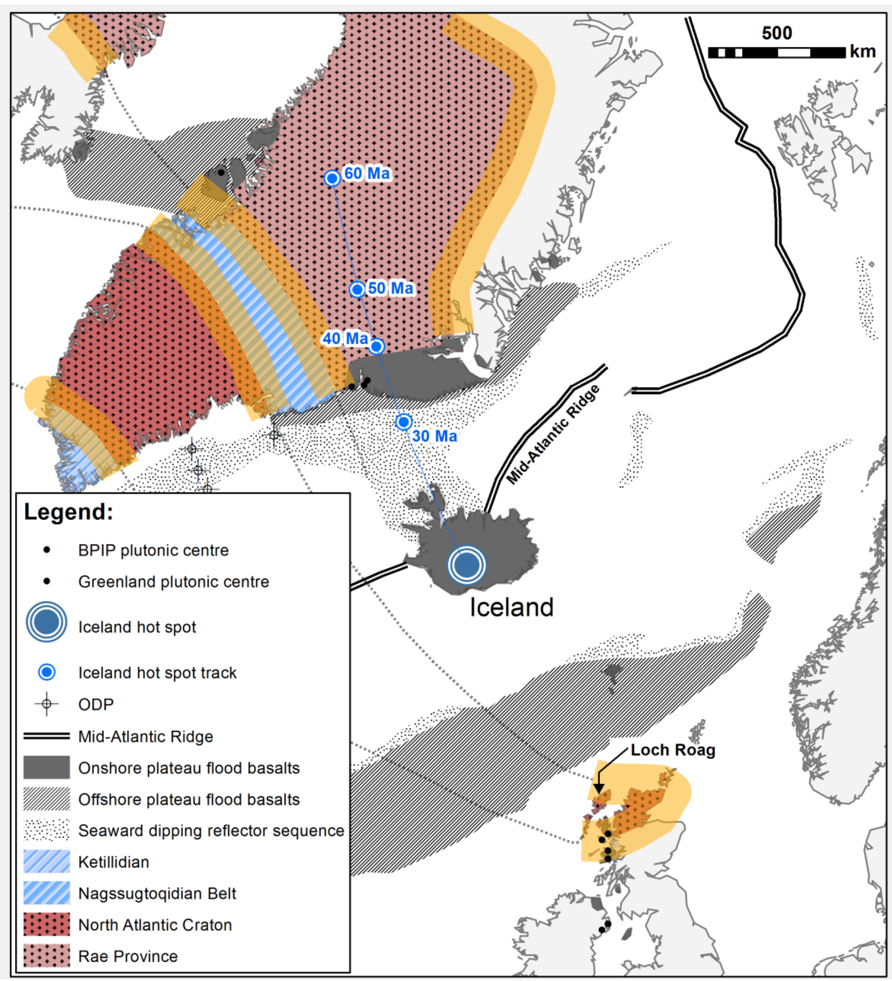
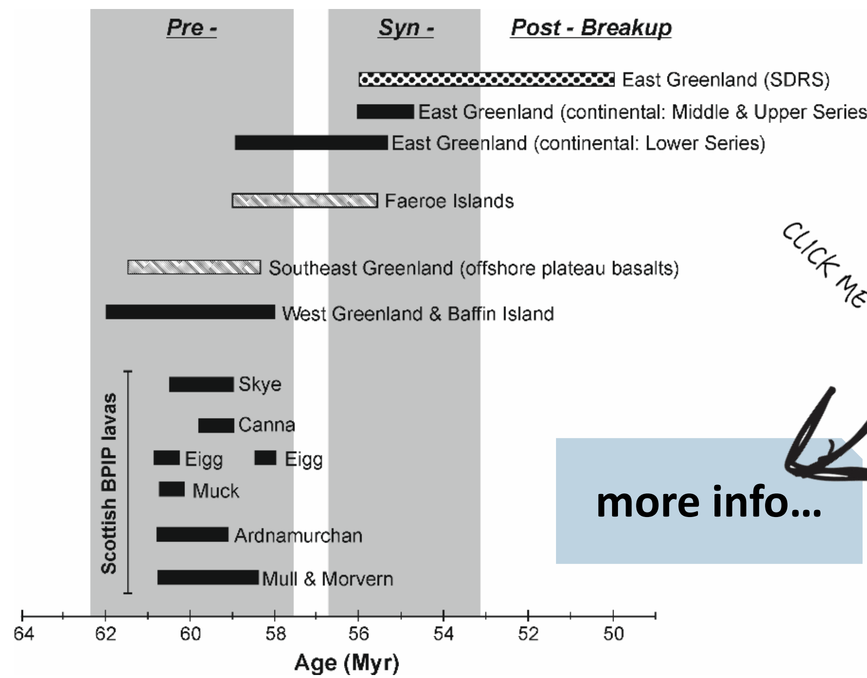
Back to partial melting info…

Diagram courtesy of Jens Andersen

Precious metal signatures of mantle melts The North Atlantic Igneous Province

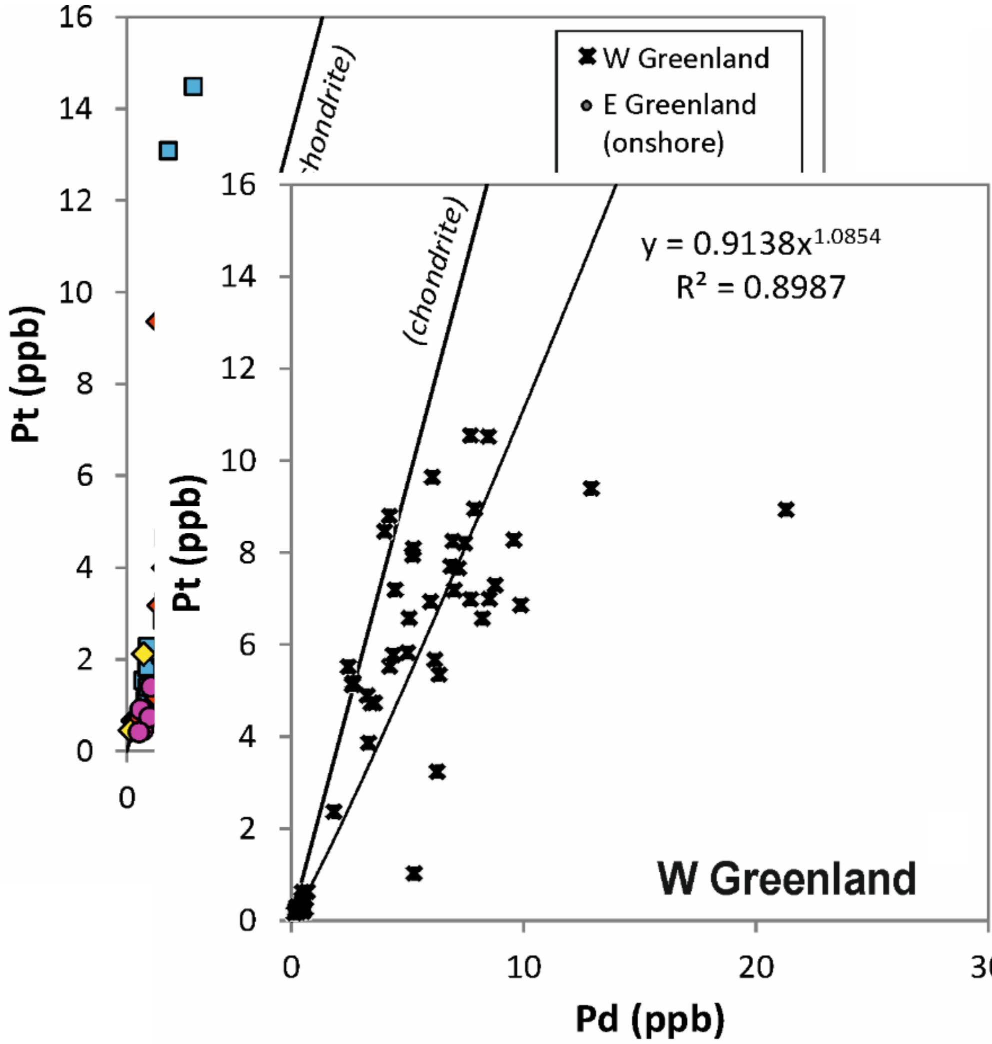


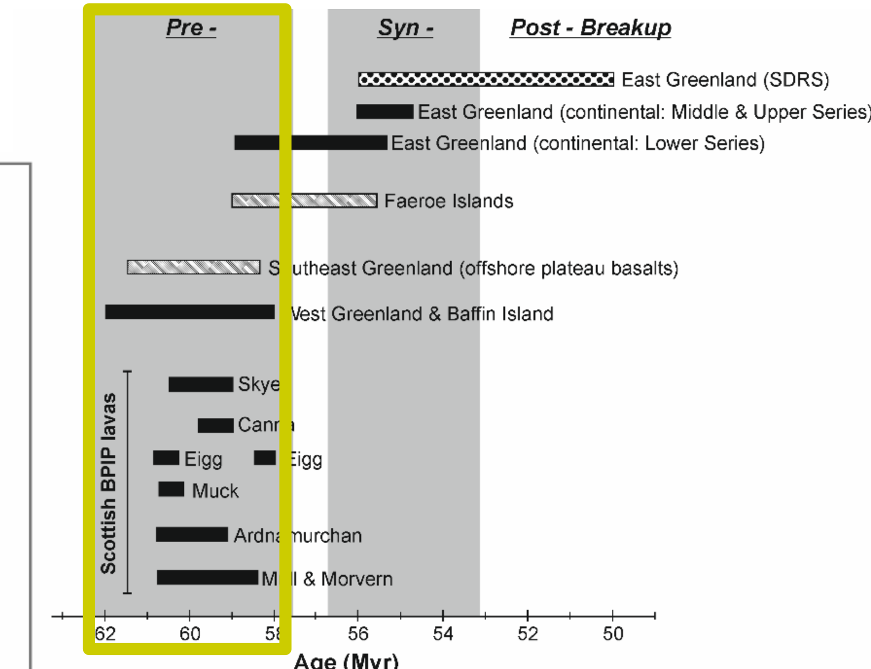


The ratio of precious metals, such as Pt/Pd, changes through time in the North Atlantic Igneous Province. This change corresponds with the changing geodynamic environment through which the Icelandic/proto-Icelandic plume-derived magmas were ascending – from a continental lithospheric lid (including cratonic) to an oceanic rifting environment.

Hughes et al. (2015)

Precious metal signatures of mantle melts The North Atlantic Igneous Province





We assessed the PGE geochemistry of basaltic lavas throughout the North Atlantic Igneous Province. *All data were screened to ensure no bias according to analytical technique, alteration, etc.*

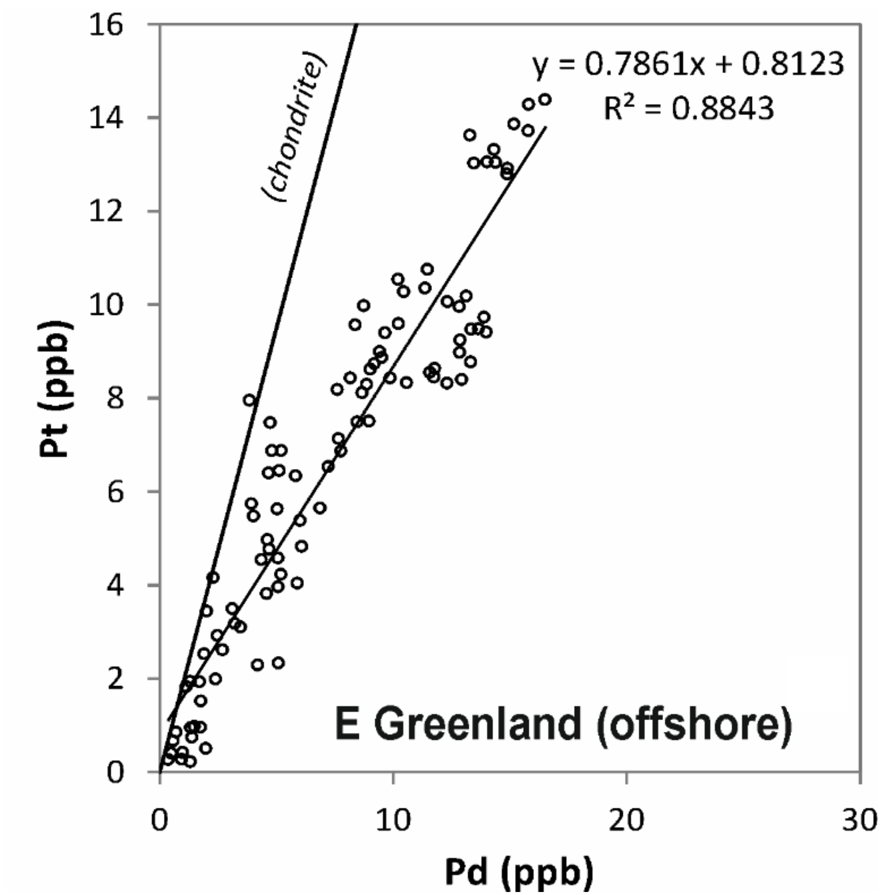
High Pt/Pd ratio in early lavas…

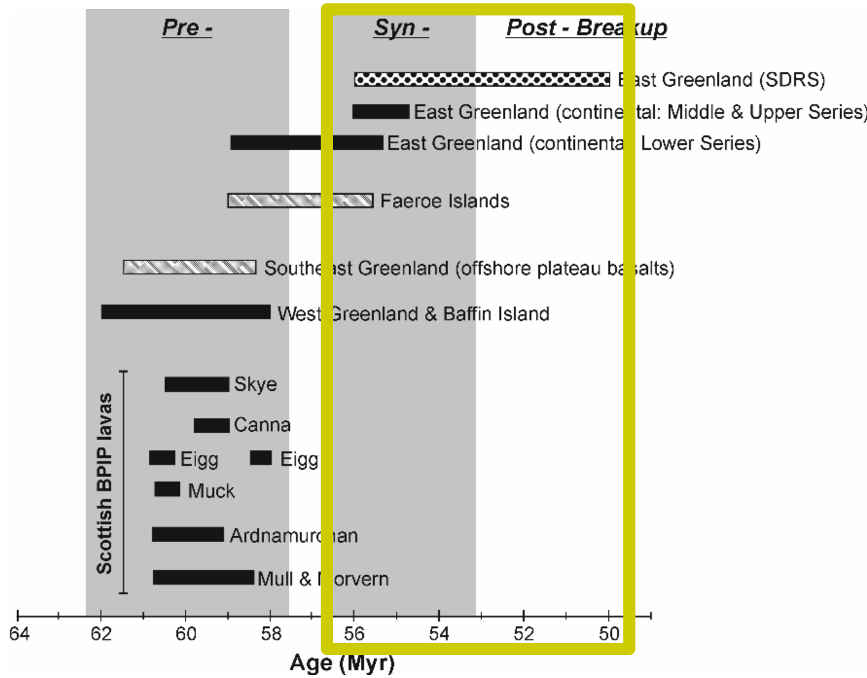
CLICK ME

more info…

Hughes et al. (2015)

Precious metal signatures of mantle melts The North Atlantic Igneous Province





… Decreasing Pt/Pd ratio in syn-rift lavas…

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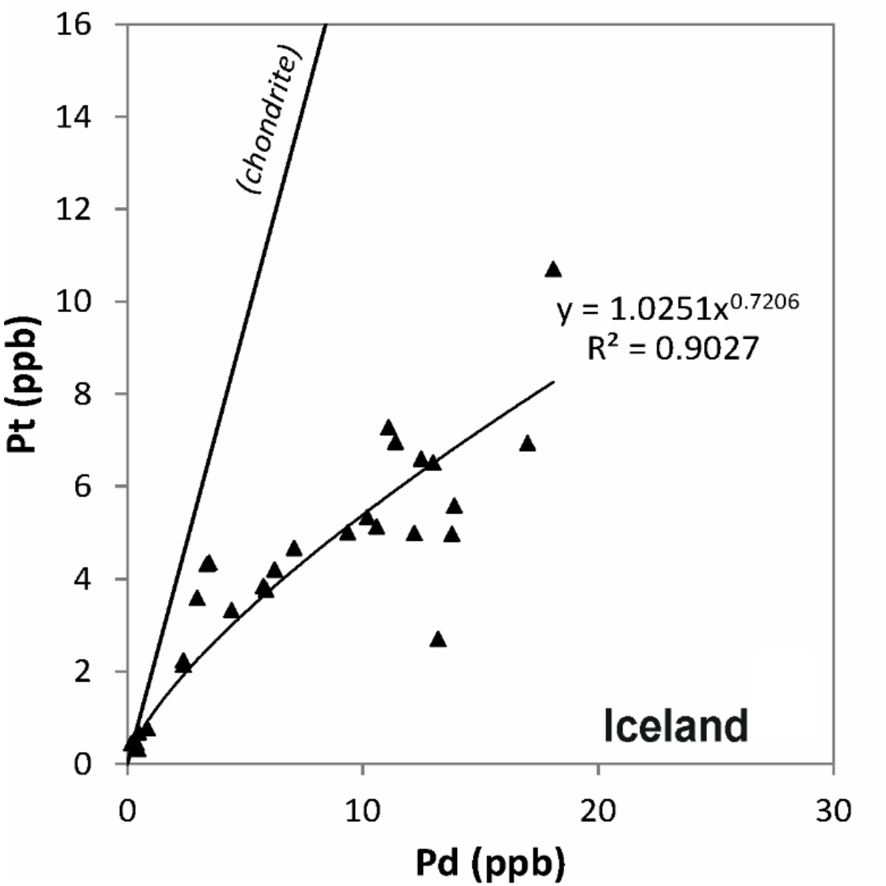
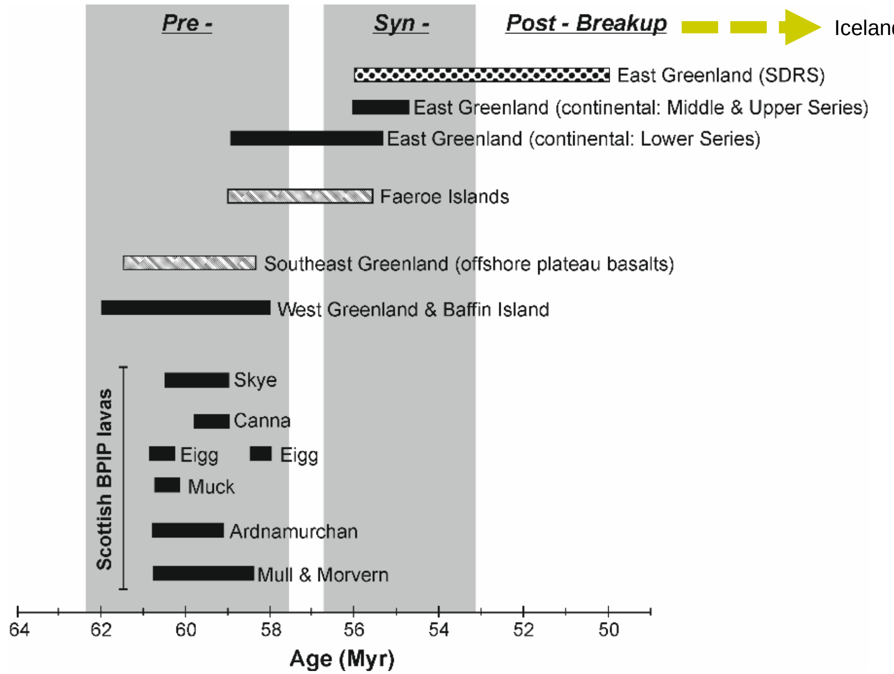
more info…

Hughes et al. (2015)

Precious metal signatures of mantle melts The North Atlantic Igneous Province





… Lowest Pt/Pd ratio in 'modern' Icelandic lavas

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Hughes et al. (2015)

Precious metal signatures of mantle melts The North Atlantic Igneous Province

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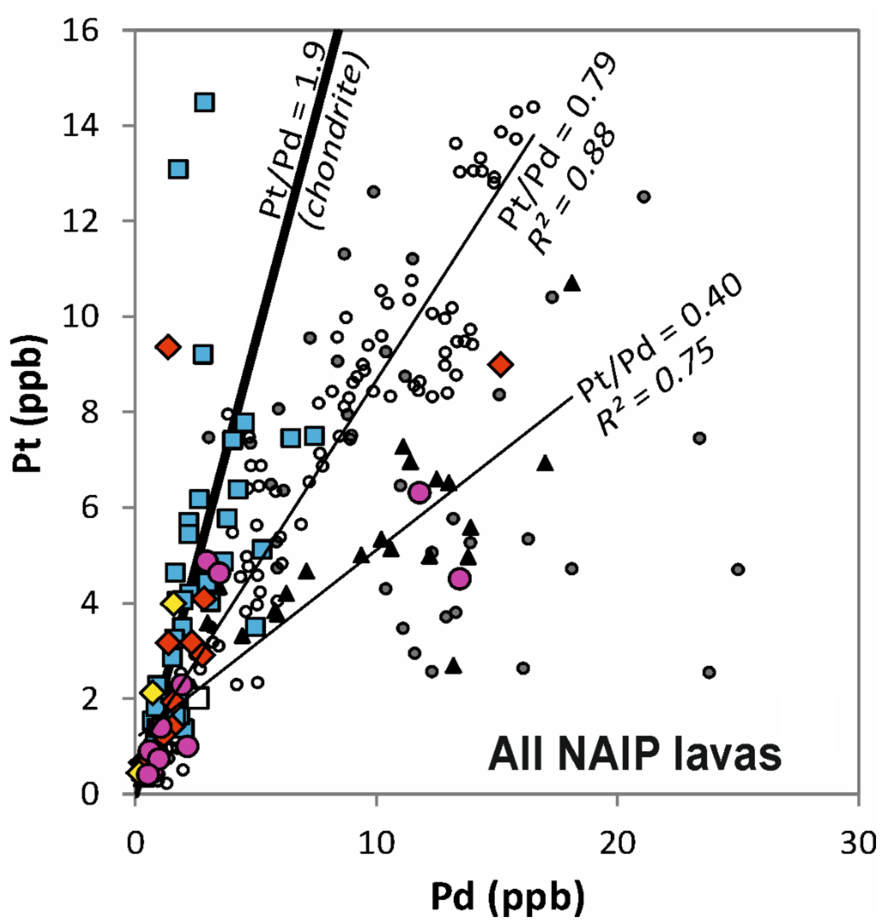
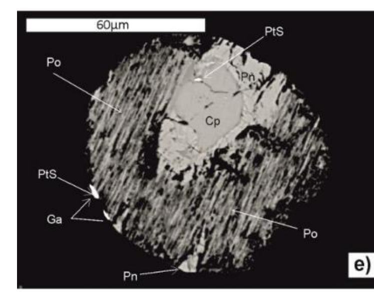


Hughes et al. (2015)

So why the shift in metal ratio?

This could reflect a change in the mantle plume melting conditions (P, T) or a change in the plume melting source region (shallowing, deepening). This shift could also reflect the change in the ambient tectonic regime onto which the mantle plume impinged – i.e., from the presence to the absence of a (marginal) cratonic continental lithospheric lid during rifting and the opening of the North Atlantic.

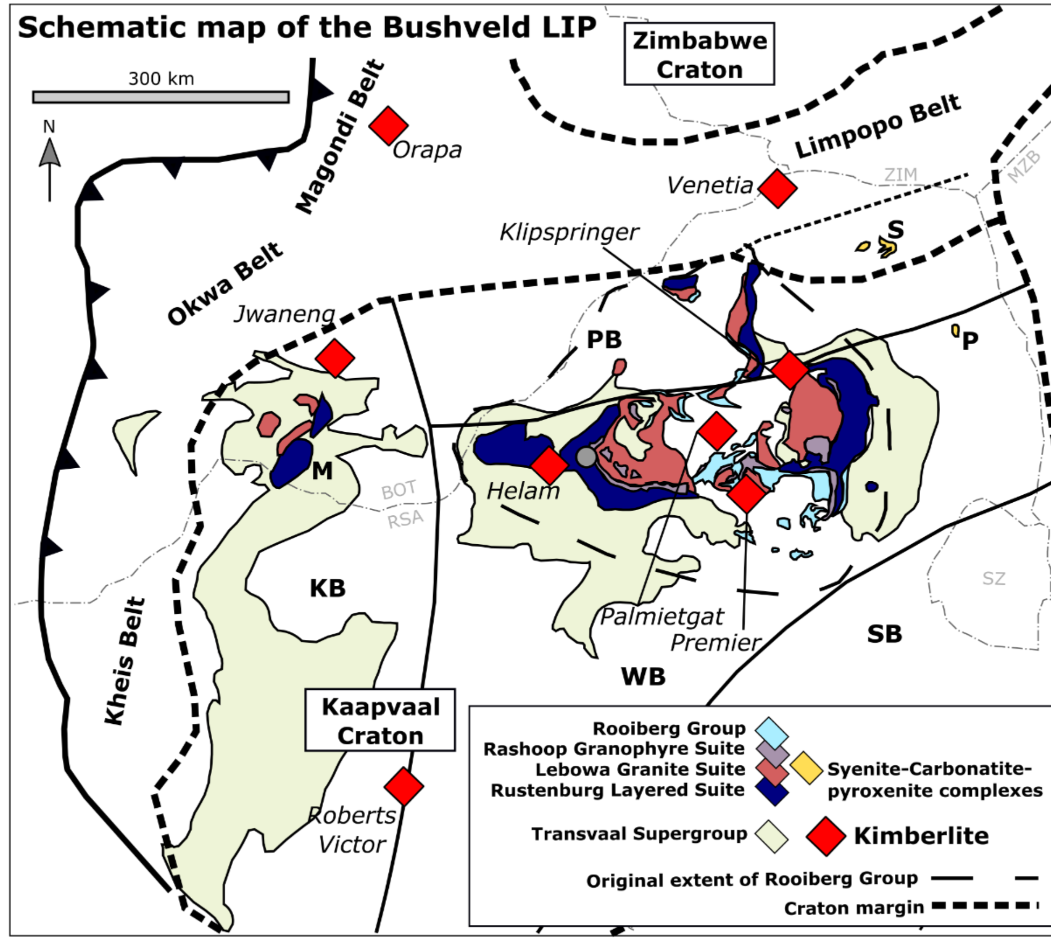


Research is ongoing as to how/if a change in plume melting conditions may affect the precious metal composition of magmas. Meanwhile we see evidence for a change in the precious metals available for 'contamination' by the subcontinental lithospheric mantle 'lid' of ascending asthenospheric magmas – e.g., cooperate (PtS) in marginal cratonic spinel lherzolite xenoliths from NW Scotland *(pictured above right).*

Magma sources of the Bushveld

Literature models for the origin of Bushveld magmas:

- deep mantle plume
- partial melting within the rigid subcontinental lithospheric mantle (SCLM)
- catastrophic melting in the asthenosphere under South Africa triggered by delamination of E-type SCLM
- subduction



Melting and emplacement of > 1 million km^3 magma

Bushve[redacted]

“The standard unit of area [redacted]
representing 0.0000207km[redacted]ales
(Wa) are, naturally, accepte[redacted]

Football pitch = 194[redacted]
Wales = 1,000,000,0[redacted]
Belgium = 1.47Wa
Democratic Republic [redacted]
Known universe (rolled [redacted]468502x1012x10256Wa”

Bushveld Complex = 4.51 Wa (95,000 km^2)
Rustenburg Layered Suite = 3.13 Wa (65,000 km^2)

theregister.co.uk (‘So, what’s the measure the velocity of a sheep in a vacuum?’)

Google Earth

Metal abundances in mantle sulphides

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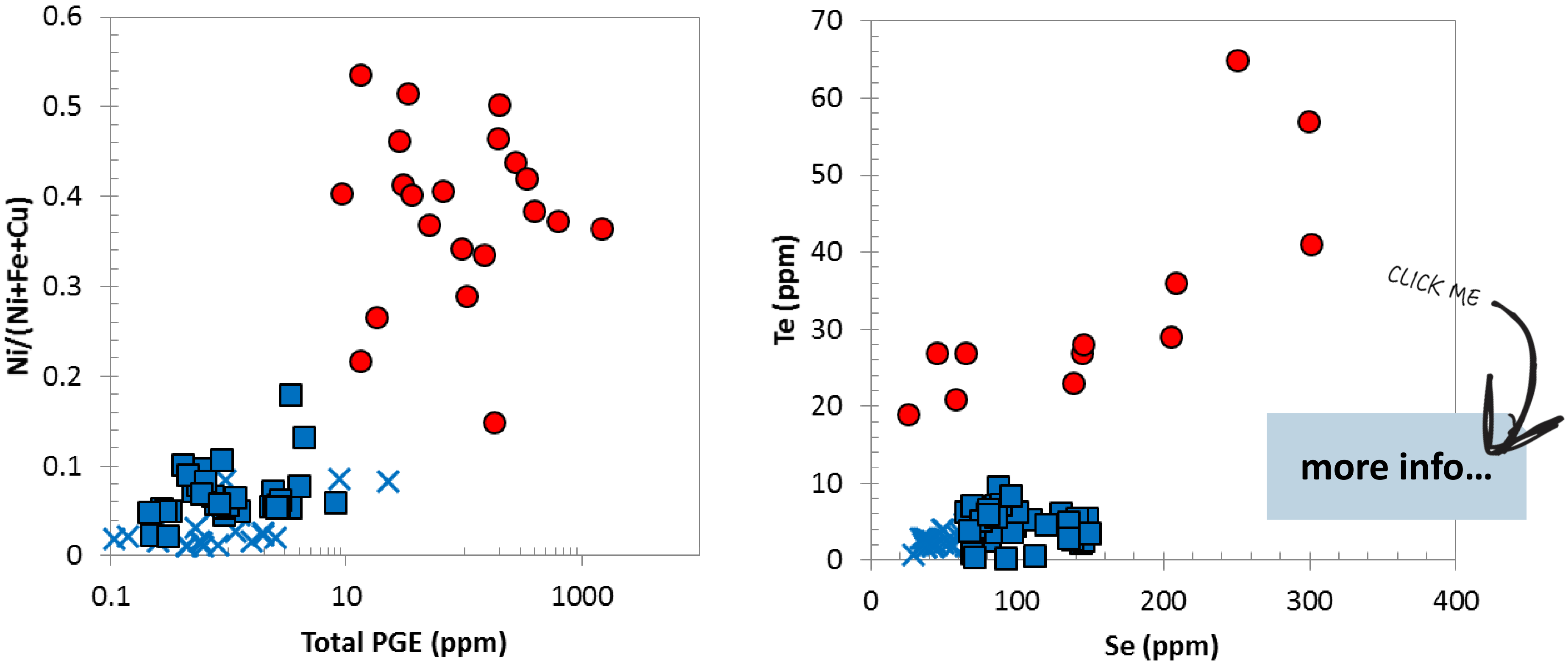
Close up view of sulphide inclusion within 1 carat Orapa diamond (3D volume rendered false colour image from µCT). Inclusion approx. 80µm long.

Clip available from McDonald et al. (2017)

Sulphide inclusions in diamond

Peridotite (P-type) vs Eclogite (E-type)

McDonald et al. (2017)



Diamonds may be P-type (derived from a peridotite) or E-type (derived from an eclogite). Both P- and E-type diamonds may have sulphide inclusions.

Appears to be a systematic difference in the metal budget of P- and E-type diamond sulphide inclusions.

- ● Bulanova et al 1996 - Yakutian P-type diamonds
- ✕ Aulbach et al 2012 - Diavik Mine (Slave Craton) E-type diamonds
- ■ McDonald et al. (2017) Orapa E-type diamonds

Sulphide inclusions in diamond

Peridotite (P-type) vs Eclogite (E-type)

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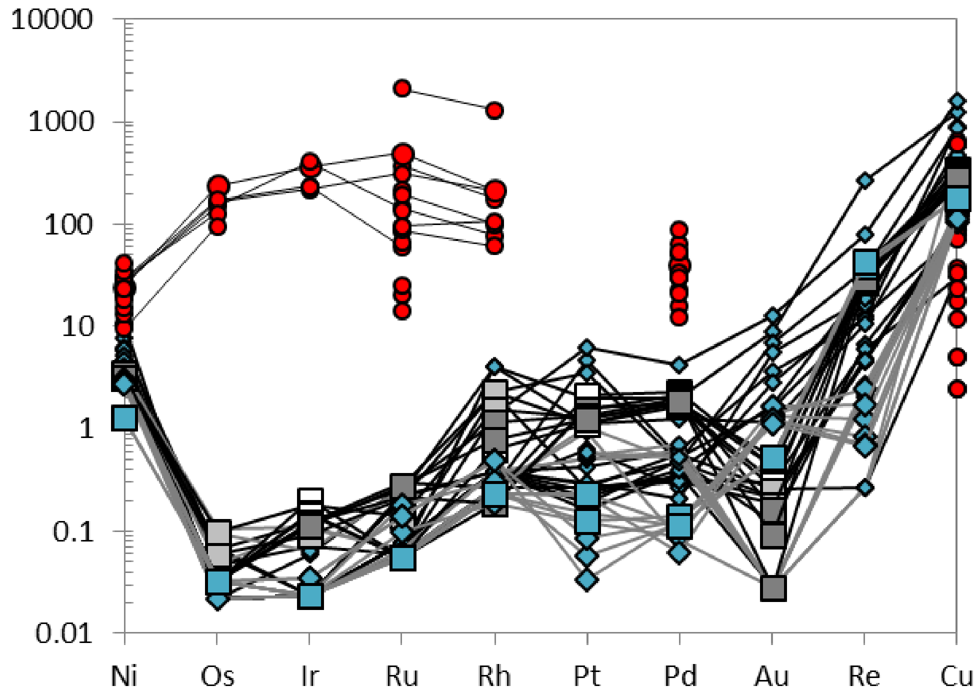


The characteristic features and PGE ratios of E- and P-type inclusions also appear to change:

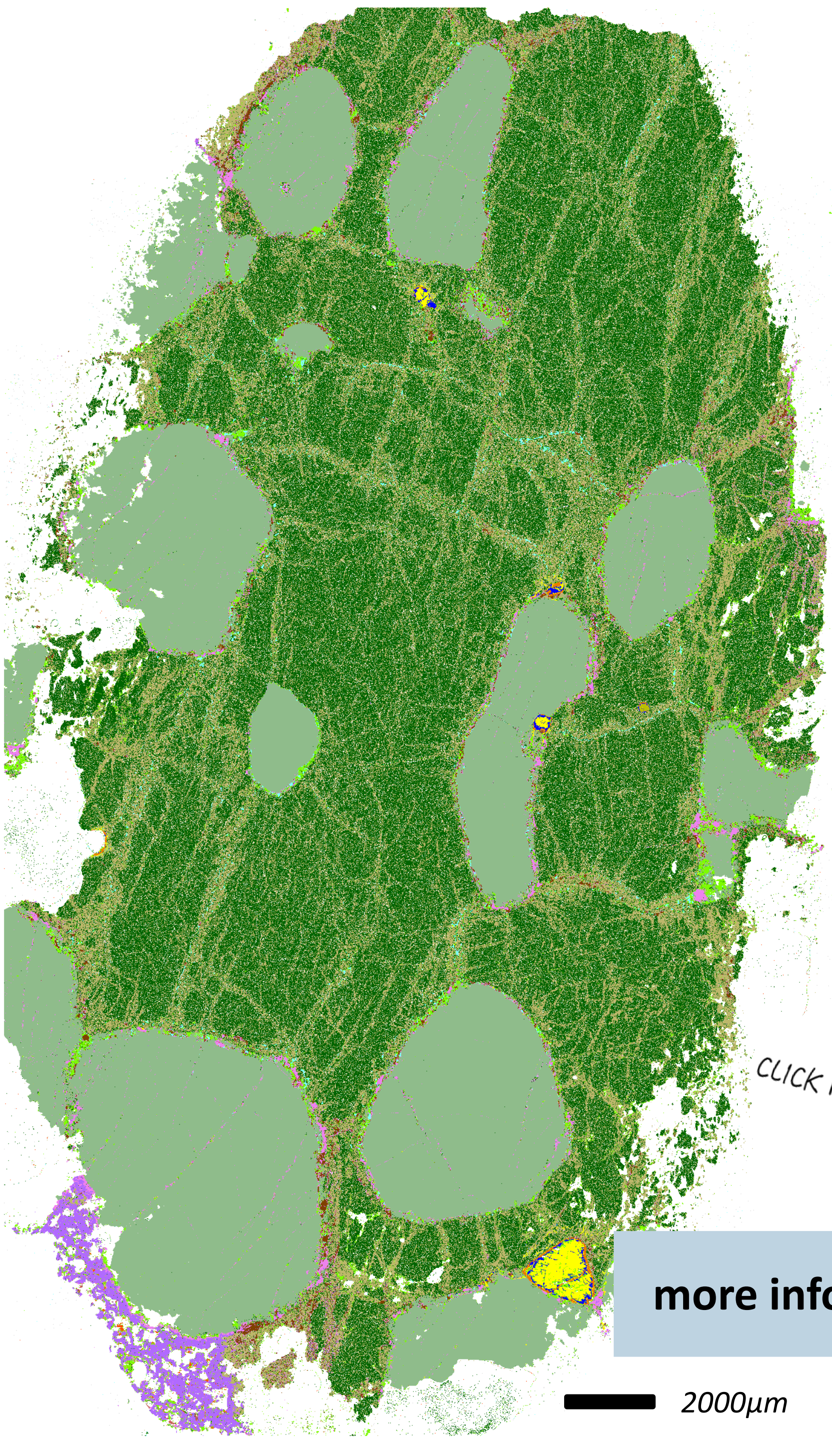
- Metasomatic sulphides (with low PGE abundance) are more common in E-type material.
- These metasomatic sulphides have lower IPGE concentrations than ‘primary’ sulphides typically in P-type material.

● Bulanova et al 1996 - Yakutian P-type diamonds

■ McDonald et al. (2017) Orapa E-type diamonds

McDonald et al. (2017)

Eclogite xenoliths



Mineral Name

- Background
- Garnet
- Clinopyroxene
- Diopside
- Albite
- K-Feldspar
- Biotite
- Phlogopite/Phengite
- Chlorite
- Talc
- Pyrite
- Pyrrhotite
- Chalcopyrite
- Pentlandite
- Sphalerite
- Calcite
- Apatite
- Others

Xenoliths are *open* systems – grain boundary pathways for fluid ingress/metasomatism, etc.

Heterogeneous: must account for Group-I or Group-II type material

QEMSCAN (and µCT) to map mineralogy and texture quantitatively and assess:

- ***Where are the sulphides situated within the xenoliths?***
- ***Interstitial vs. inclusion (in what)?***

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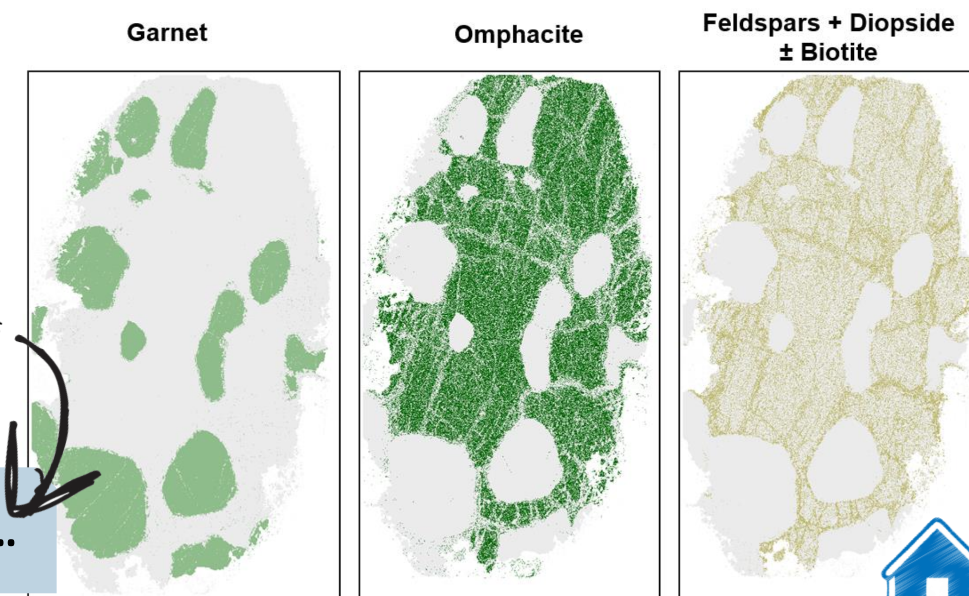

Sulphides in eclogite xenoliths

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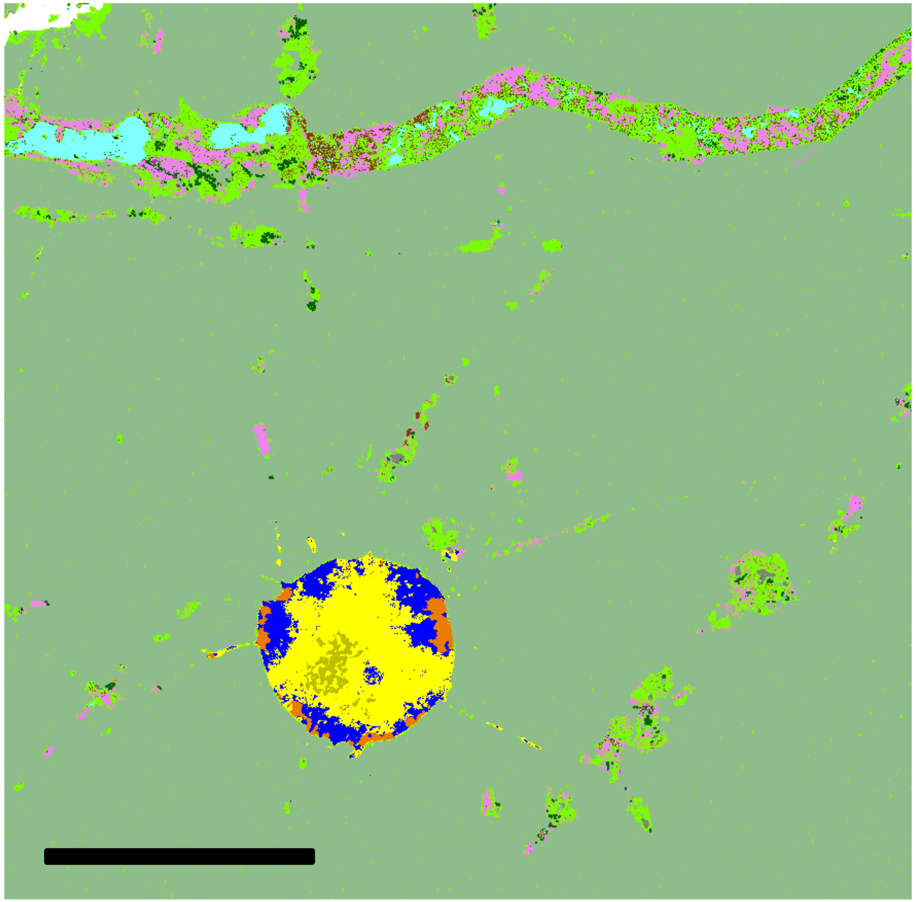
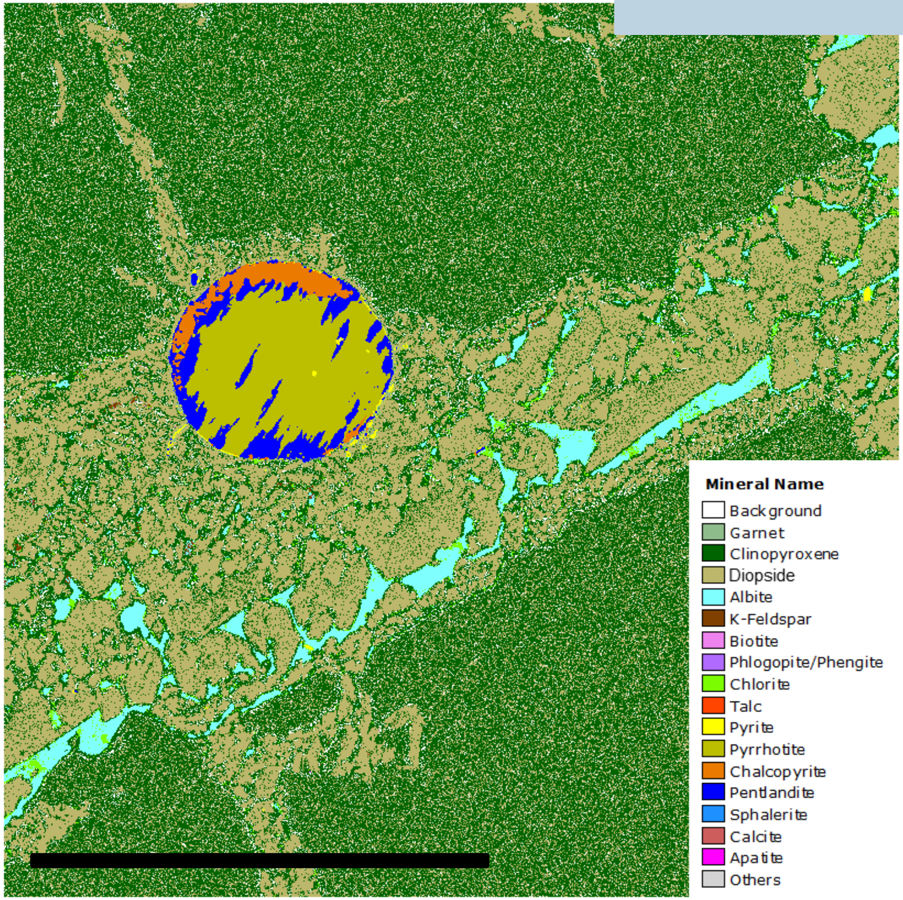
Inclusions in silicates (e.g., garnet)



Interstitial / 'melted channels'



Sulphide abundance in eclogite = 0.5-1 % (by area)

.... of the sulphides:
Py 10-65% Pn 25-55%
Cp 5-40% Po ~

Scale bars show 300μm

Peridotite xenolith mantle sulphides

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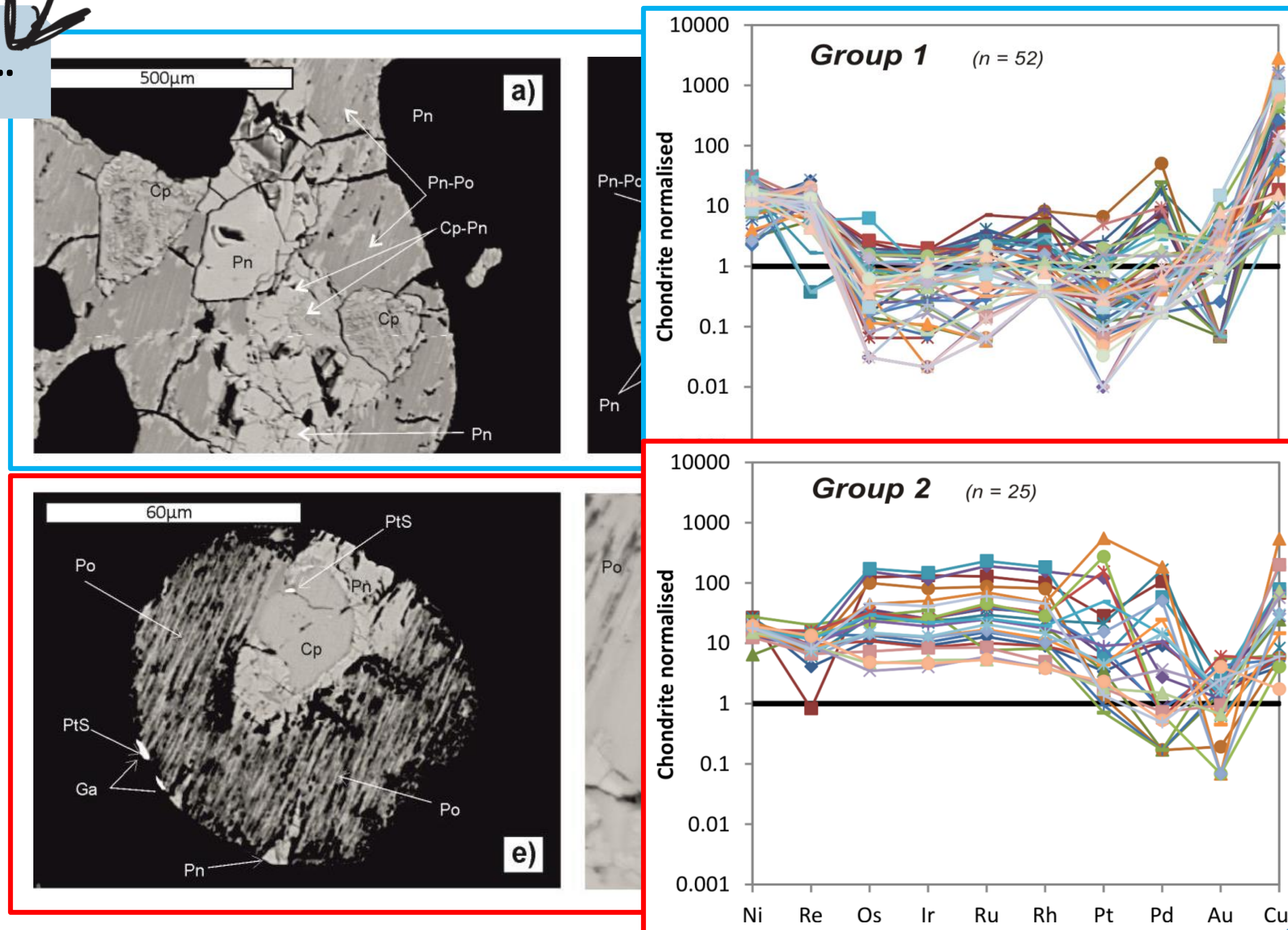

Hughes et al. (2016)

Back scattered electron images of sulphides within a fist-sized spinel lhzerolite xenolith from Loch Roag, NW Scotland

Scotland

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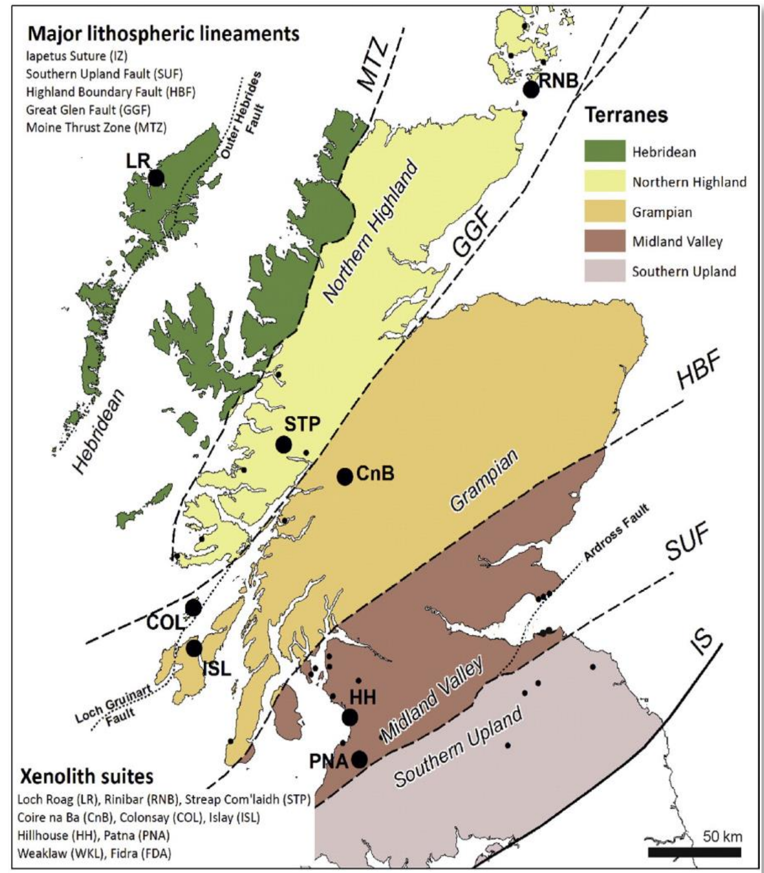
a testing ground for the lithospheric mantle metal record

- **Hebridean Terrane**
  Lewisian (North Atlantic Craton)
- **Northern Highland Terrane**
  Moine Supergroup + ‘Lewisianoid’ inliers
- **Grampian Terrane**
  Rhinnian basement + Dalradian

--- **Great Glen Fault:** major crustal lineament ---

- **Midland Valley Terrane**
  Transition between deeper Caledonian orogen (N) to subduction-related superficial deposits (S)
- **Southern Upland Terrane**
  Accetionary prism + Laurentia-Avalonia suture zone



Scotland has many terranes (both on the margin of the North Atlantic Craton and off-craton terranes linked to the Caledonian Orogeny), with many mantle xenolith localities in each terrane (xenoliths entrained in lamprophyre dykes). Together with it’s long magmatic history, this makes Scotland a good testing ground to assess how metal abundances change through time. We are now testing some of these ideas in other areas, including Scandinavia and Southern Africa.

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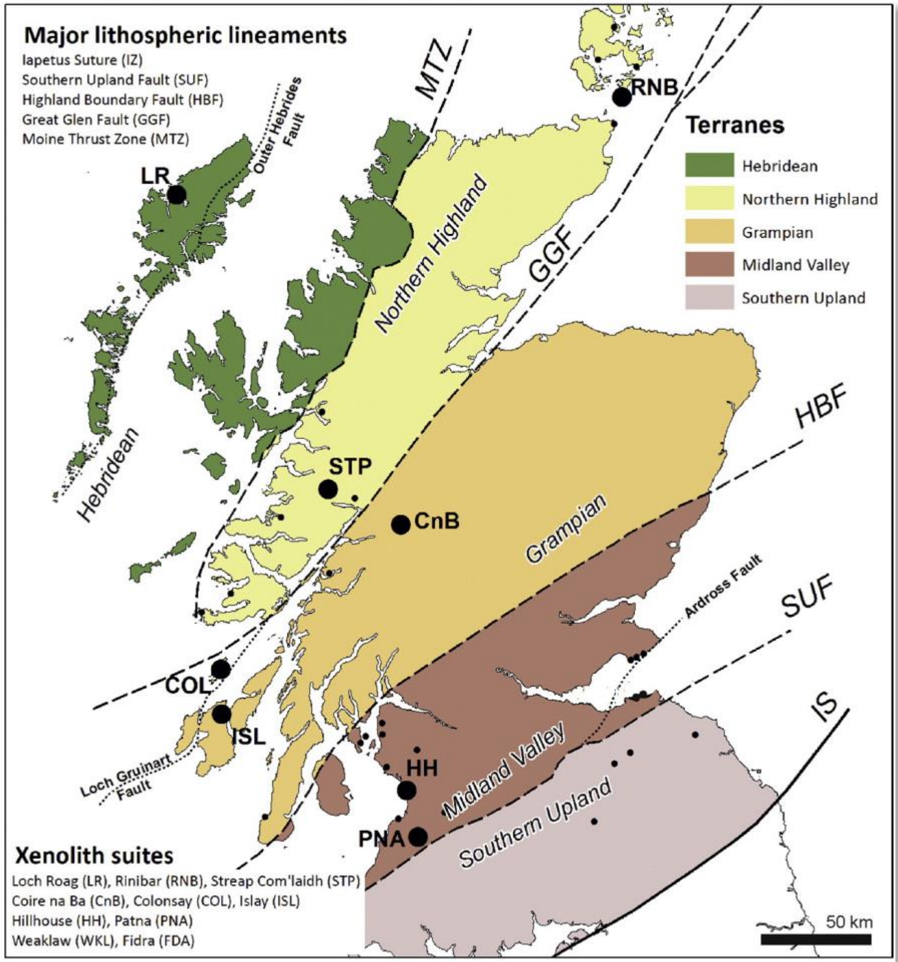
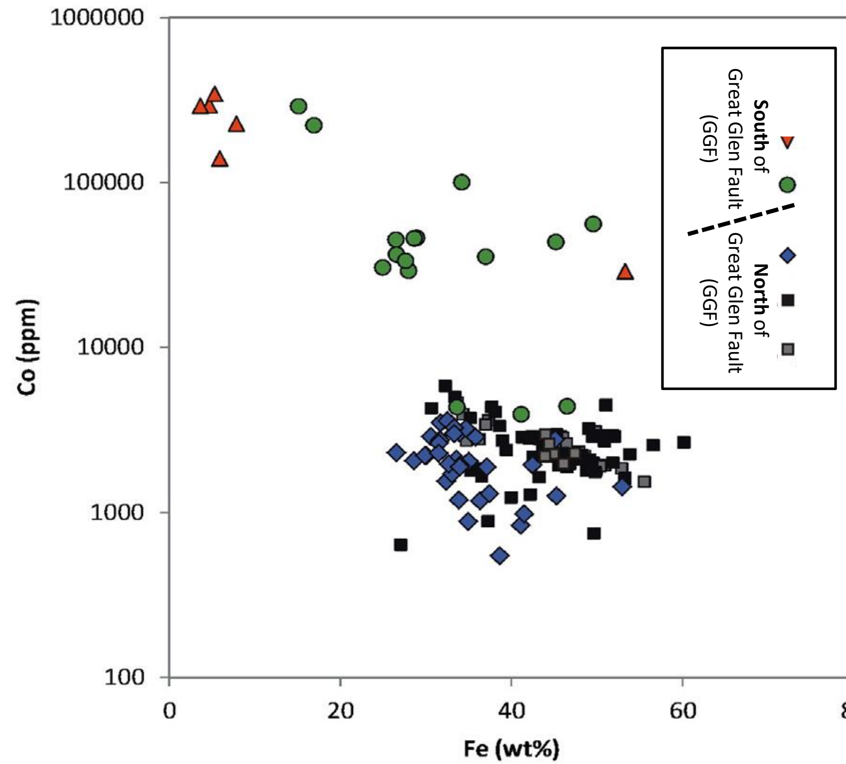
Cobalt terrane-scale trends in Scotland





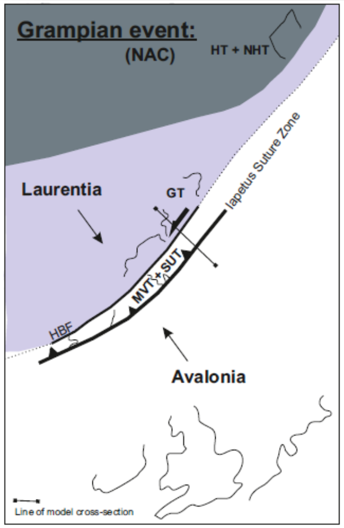
In situ analyses of sulphides from spinel lherzolite mantle xenoliths in Scotland show two trends:

- **North** of the Great Glen Fault (GGF*) have **ppm** levels of Co.
- **South** of the GGF have **wt.%** levels of Co.

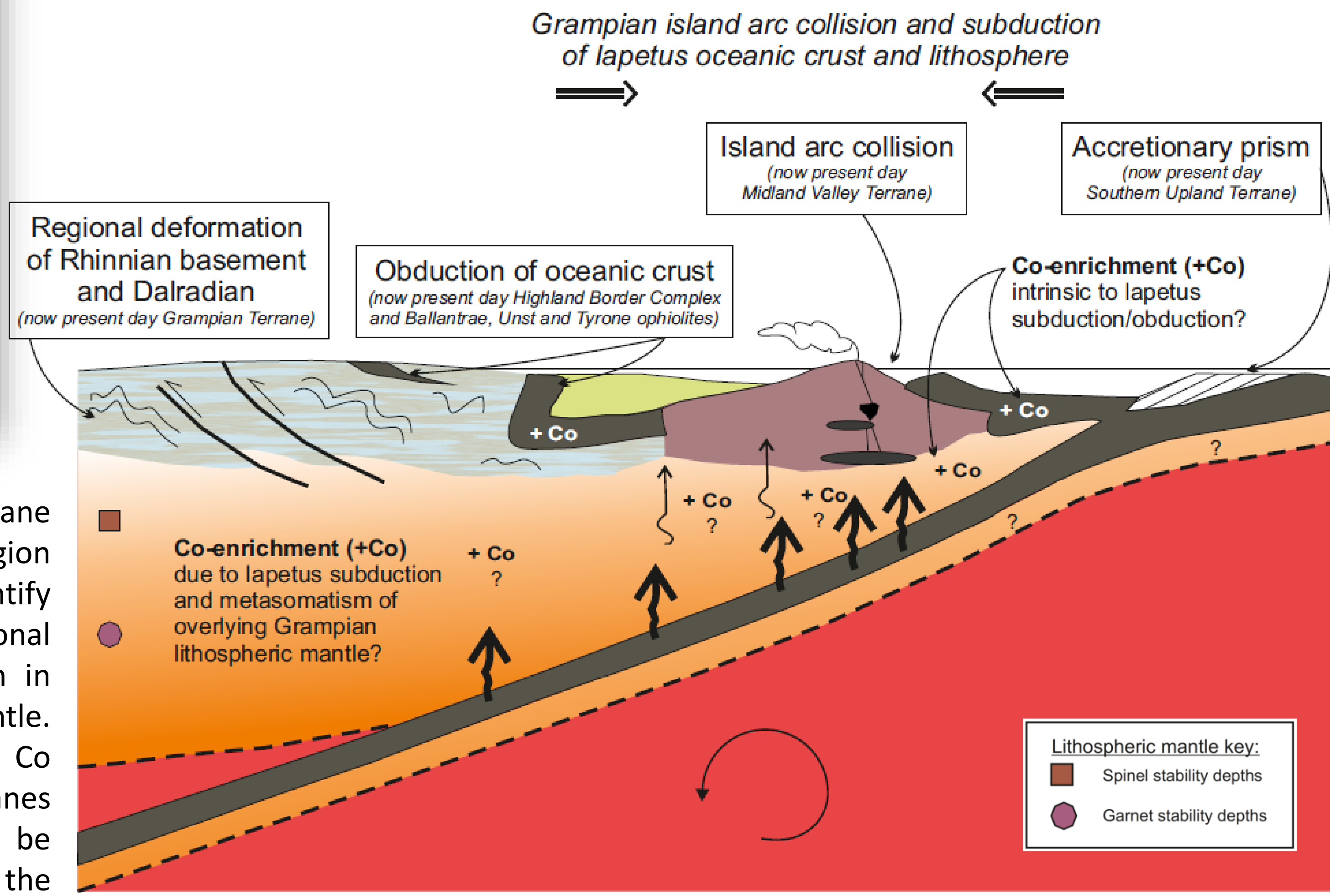
**The GGF is the crustal lineament dividing marginal cratonic terranes to the N from off-craton terranes to the S.*

Hughes et al (2016)

Cobalt terrane-scale trends in Scotland



By comparing the terrane histories of a region (Scotland) we may identify the causes for regional metal enrichment seen in the uppermost mantle. Accordingly, the Co enrichment of the terranes South of the GGF may be due to subduction of the Iapetus oceanic crust during the Caledonian.



Hughes (2015)

Sulphide inclusions in diamond

- Sulphide inclusions in diamonds provide a unique insight into the metal composition of the mantle.

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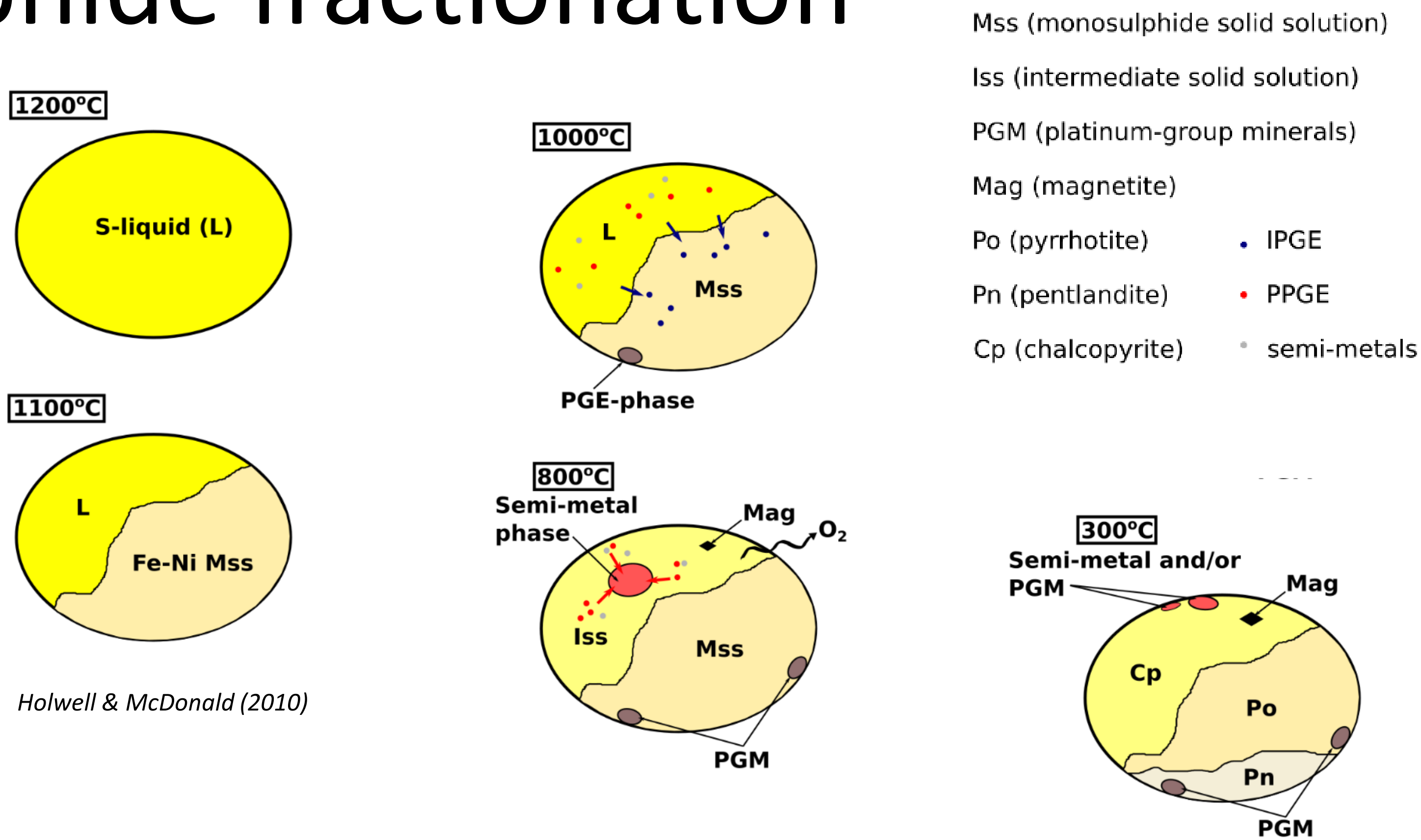
- We can assess:
  - the inclusion age (Re-Os isotopes) = diamond age?
  - where the sulphur came from (S-isotopes)
  - major element abundance (Fe, Ni, Cu)
  - minor and trace element abundance (Co, Pt, Pd, Au, etc)

Image of courtesy J.W. Harris

- ….But at temperatures < 1100°C sulphide inclusions undergo subsolidus re-equilibration from an original monosulphide solid solution (Mss), causing fractionation of the major and trace elements within the inclusions.

Sulphide fractionation



Holwell & McDonald (2010)

- T < 1100°C sulphide inclusions undergo subsolidus re-equilibration from an original monosulphide solid solution (Mss), causing fractionation of the major and trace elements within the inclusions.

- **To study sulphide inclusions, current techniques require the *entire* inclusion to be extracted for analyses.**

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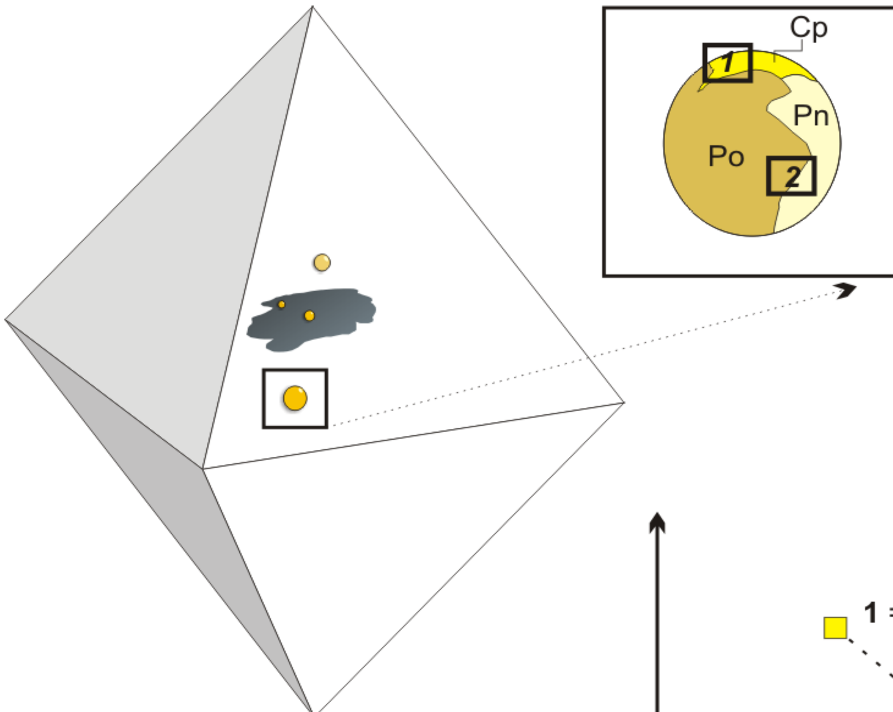
Sulphide fractionation

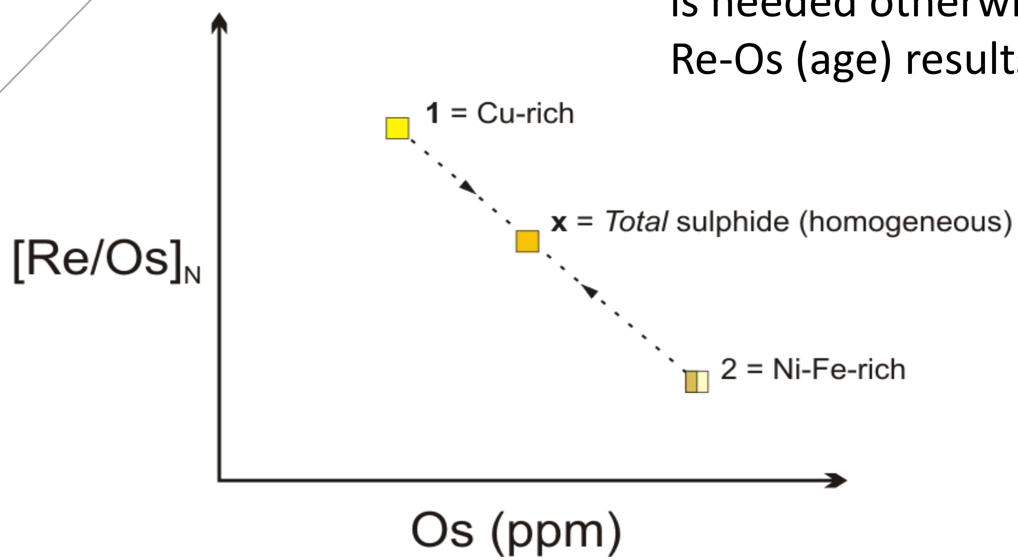


$^{187}Re \rightarrow {}^{187}Os$

$t_{1/2} = 4.16 \times 10^{10}$ yr

- Re ➔ Cu-rich sulphide
- Os ➔ Fe, Ni-rich sulphide

- Sampling of the *entire* inclusion is needed otherwise a bias in the Re-Os (age) results may be introduced.



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McDonald et al. (2017)

Method Homogenisation of inclusions in diamond

McDonald et al. (2017)

- Homogenisation of sulphide inclusions *prior* to break-out from the host stone
- Diamonds are heated to 1100°C under a reduced atmosphere, then quenched:
  - Vertical tube 1 atmosphere furnace
  - connected to H_2 and CO_2 gas supplies to establish a defined fO_2
  - gas mix of 14% H_2 and 86% CO_2 ➔ calculated oxygen fugacity (controlled atmosphere to prevent combustion of diamond)

For further details, see McDonald et al. (2017)

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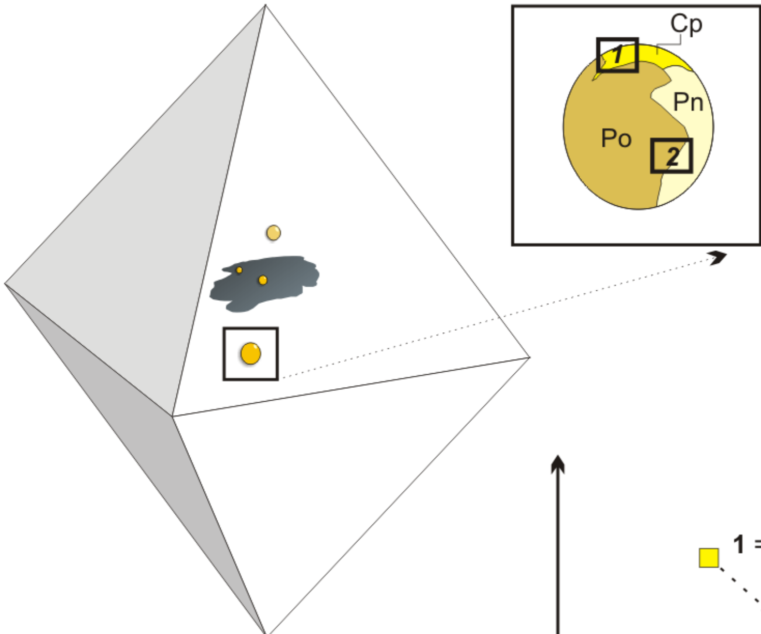
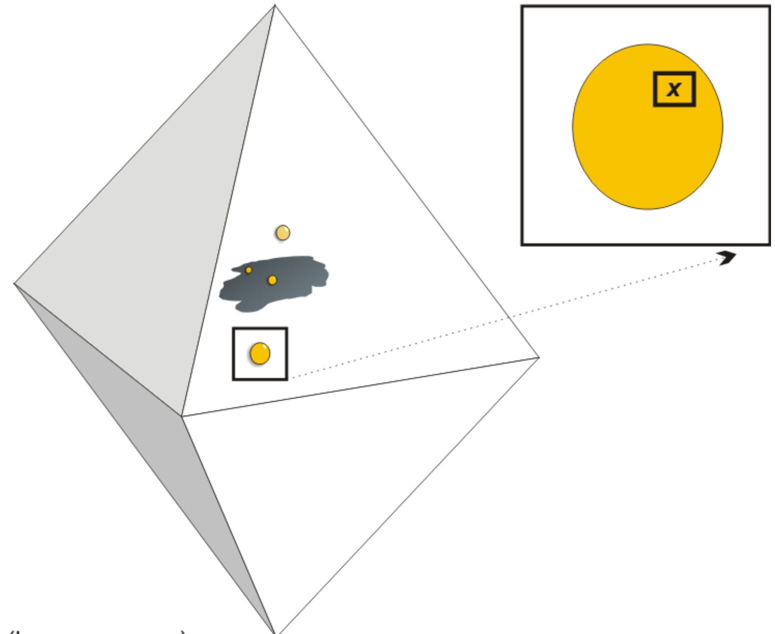
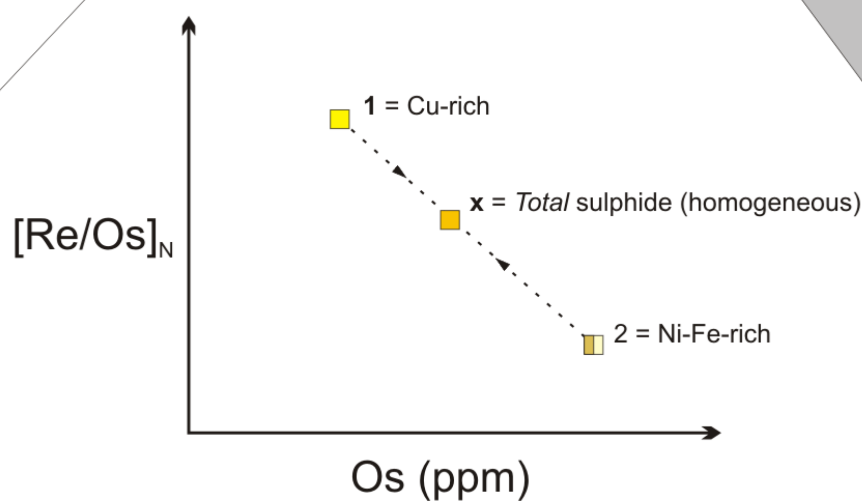
Sulphide fractionation

Unhomogenised



Homogenised





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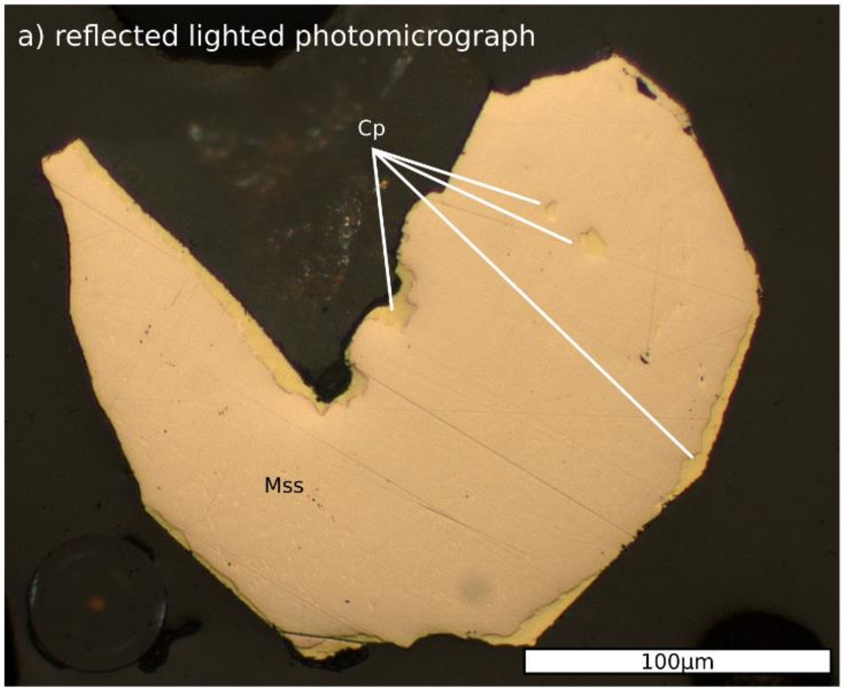
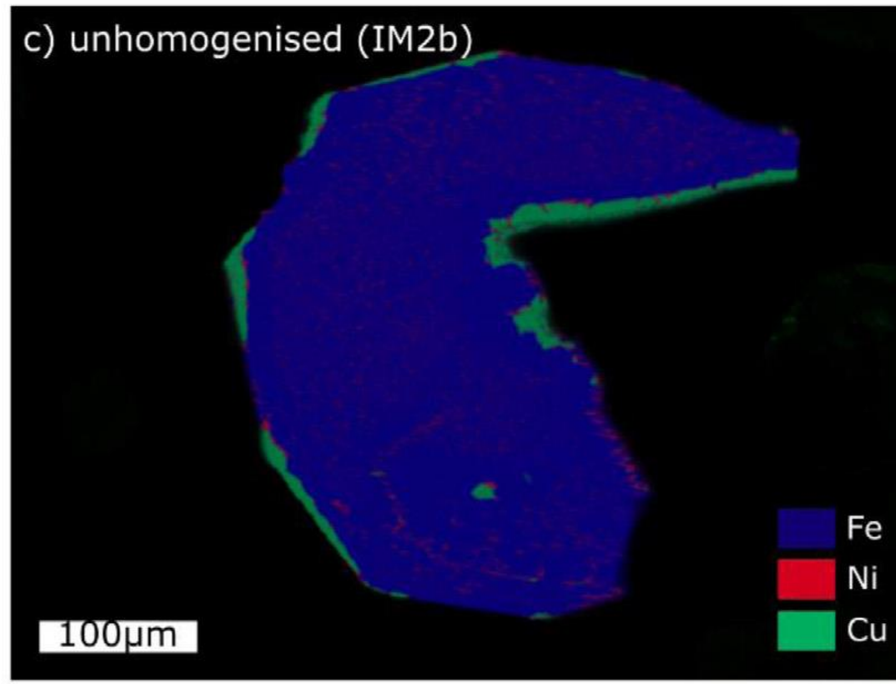
McDonald et al. (2017)

Unhomogenised sulphide





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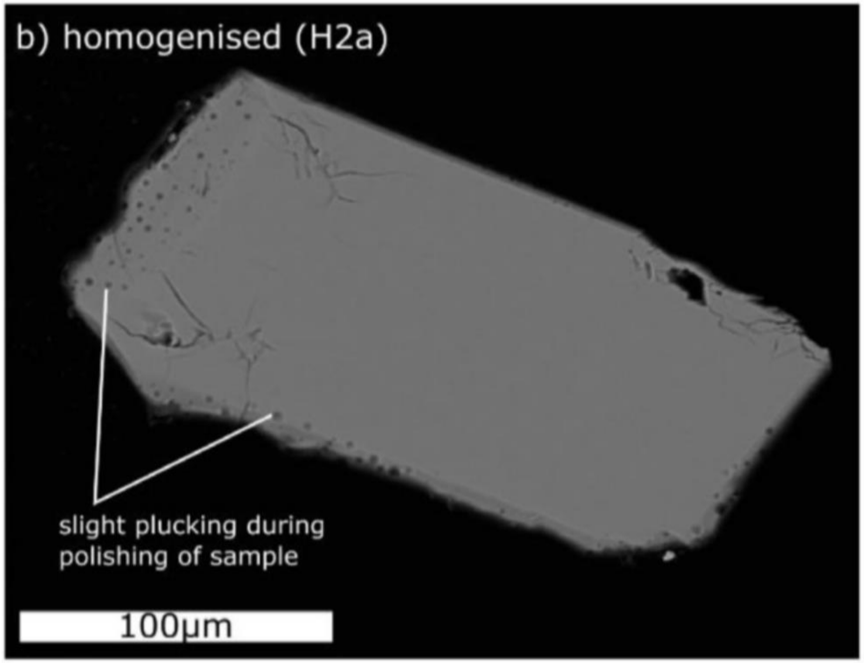
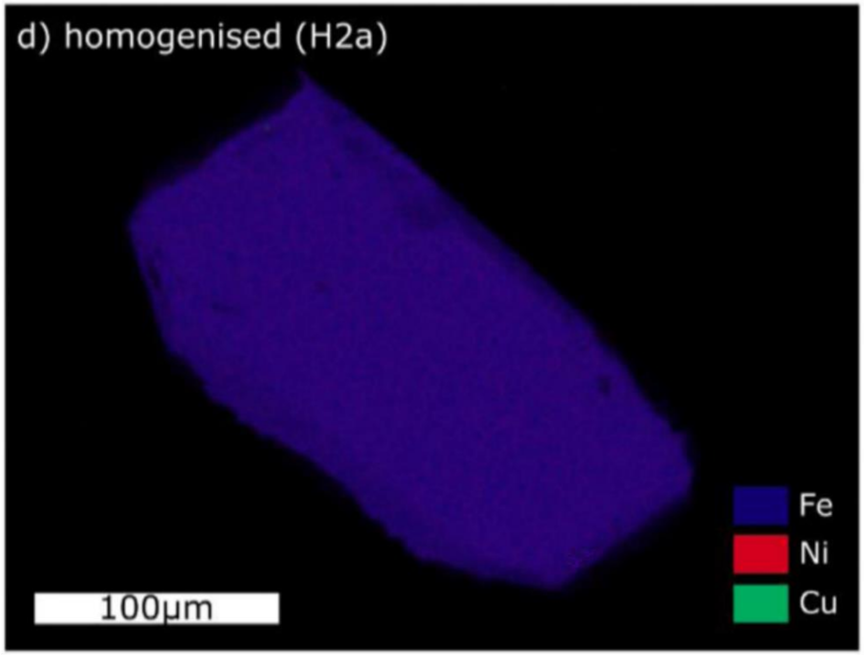
Homogenised sulphide





Compositions of typical igneous rocks

Major elements: Listed in weight percent of oxide components in general order of decreasing cation valency.

Magma type	Basalt	Rhyolite
	I-23	I-2
SiO_2	50.44	72.82
TiO_2	1.00	0.28
Cr_2O_3	0.15	-
Al_2O_3	16.28	13.27
Fe_2O_3	2.21	1.48
FeO	7.39	1.11
MnO	0.14	0.06
MgO	8.73	0.39
CaO	9.41	1.14
Na_2O	2.26	3.55
K_2O	0.70	4.30
P_2O_5	0.15	0.07
H_2O^+	0.84	1.10
H_2O^-	0.13	0.31
Total	99.83	99.88

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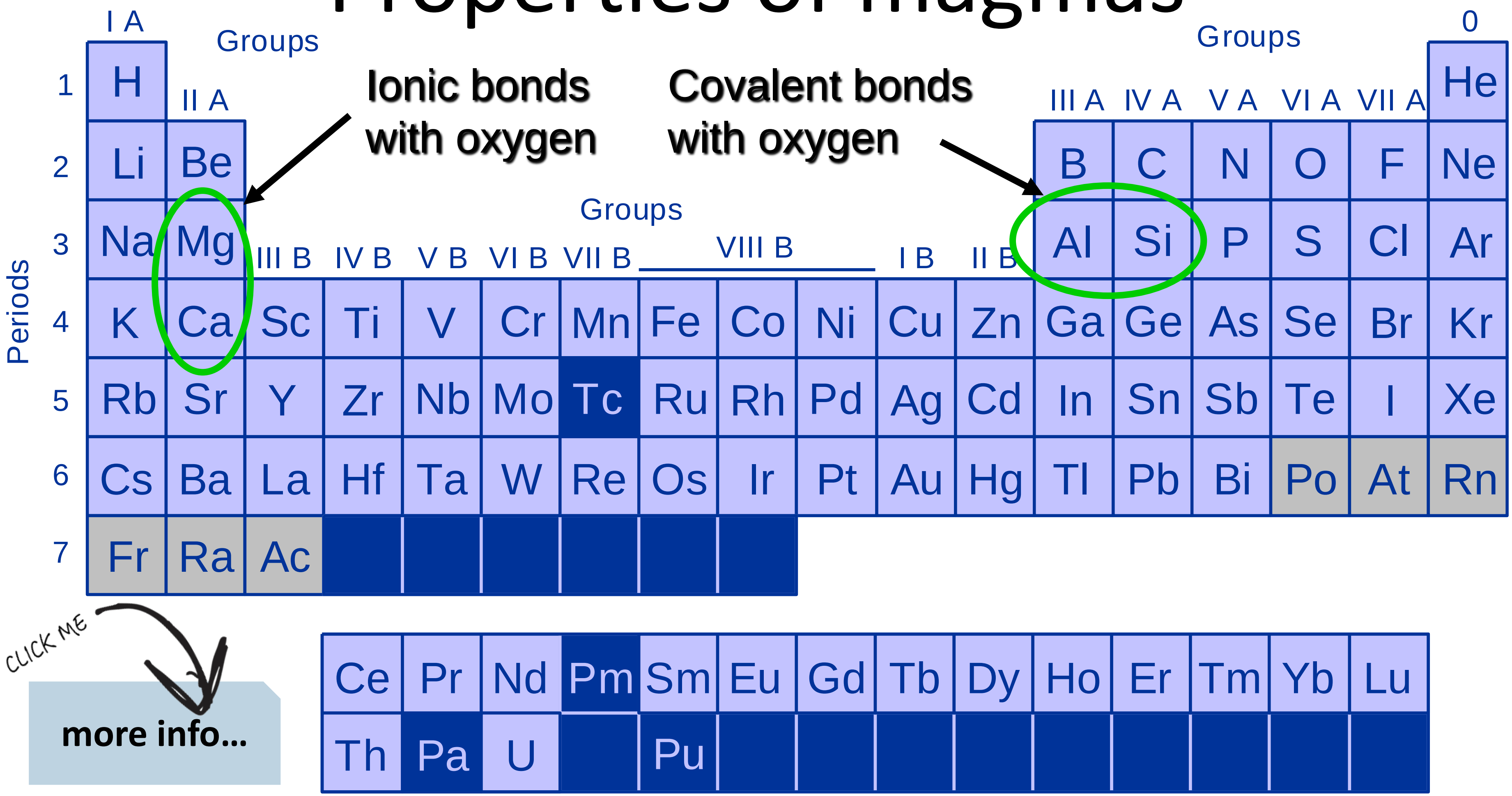
Properties of magmas



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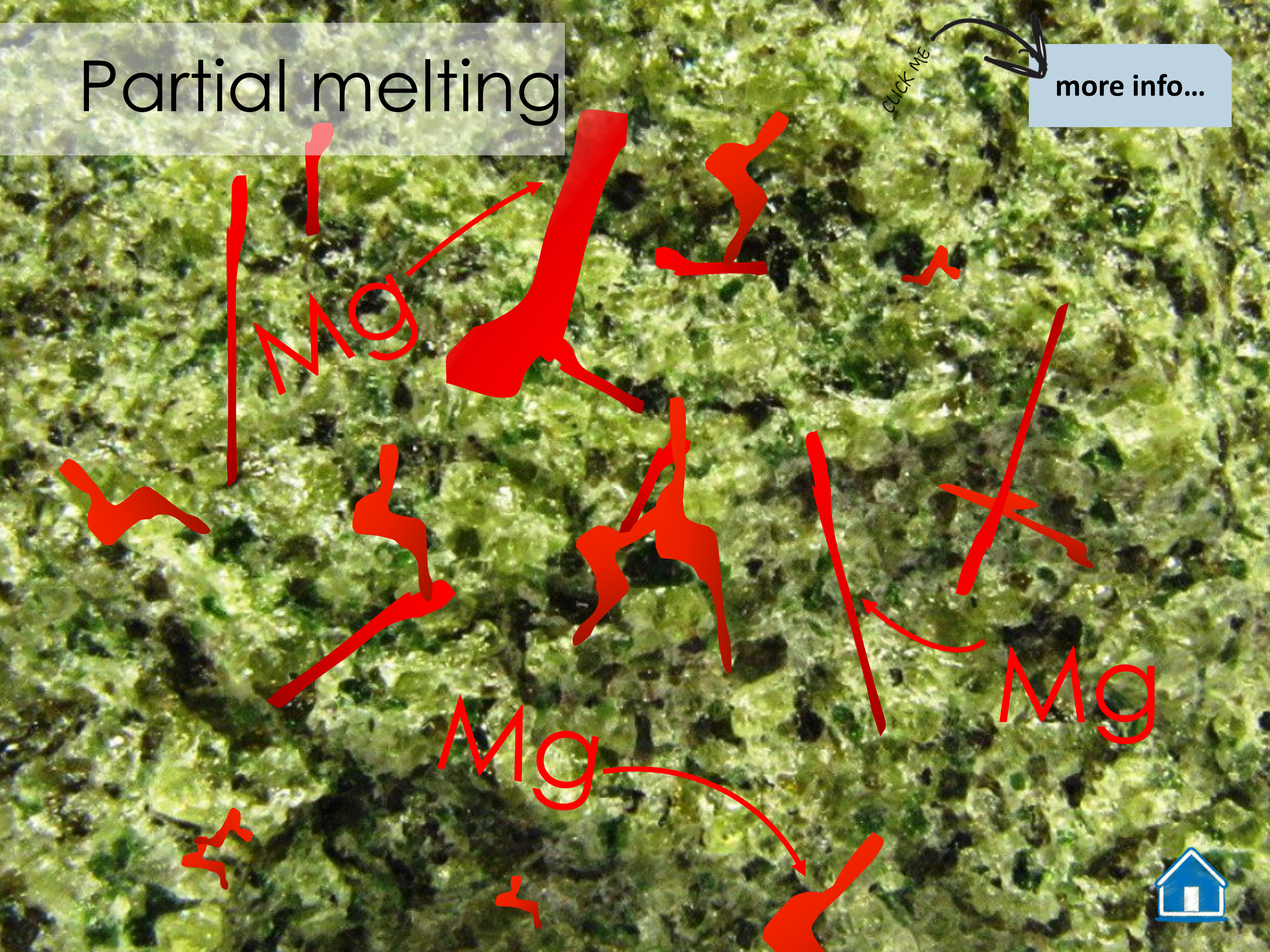
Not occurring in nature

Metastable decay products of Th and U


Partial melting
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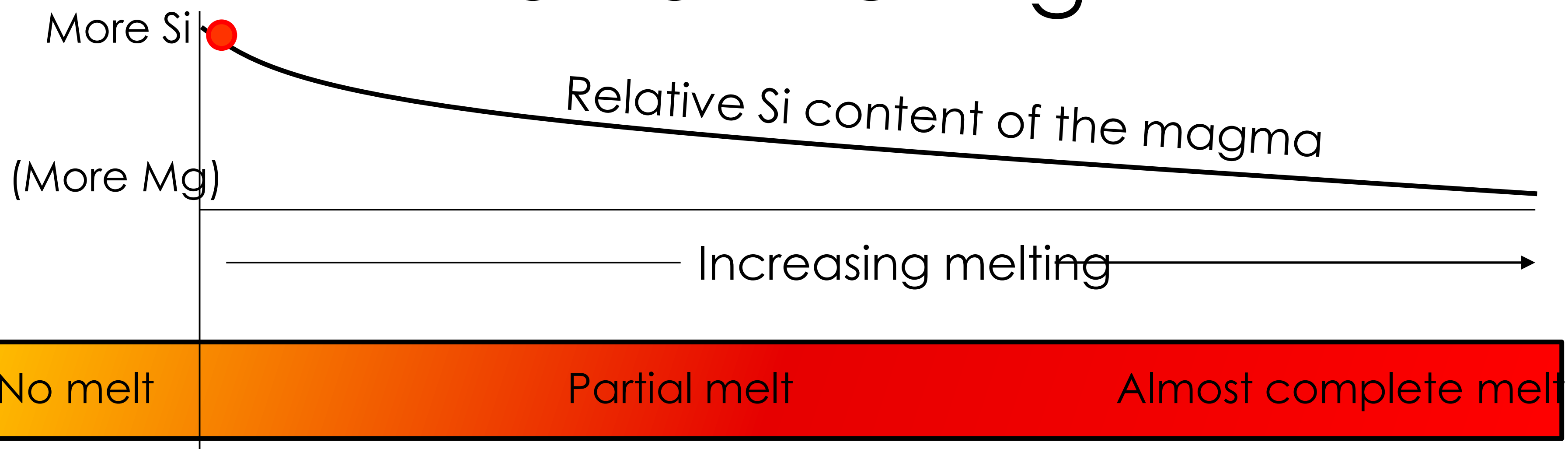
Mg
Mg
Mg

Partial melting



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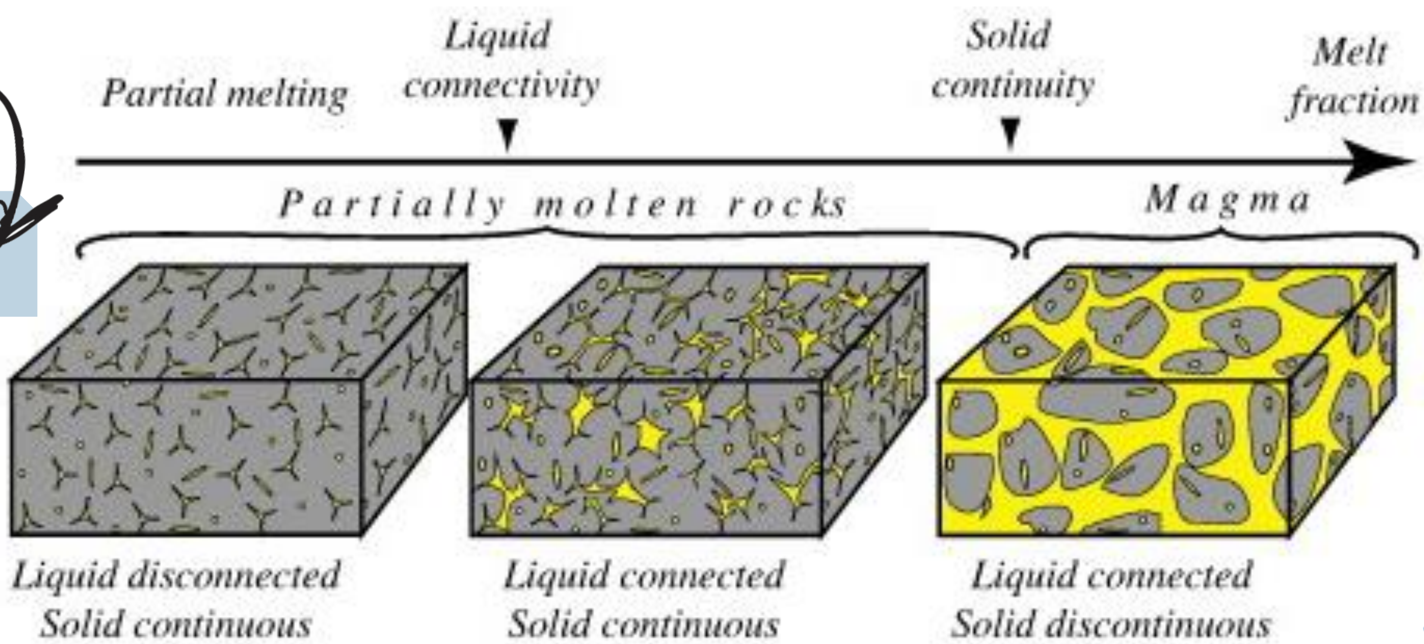
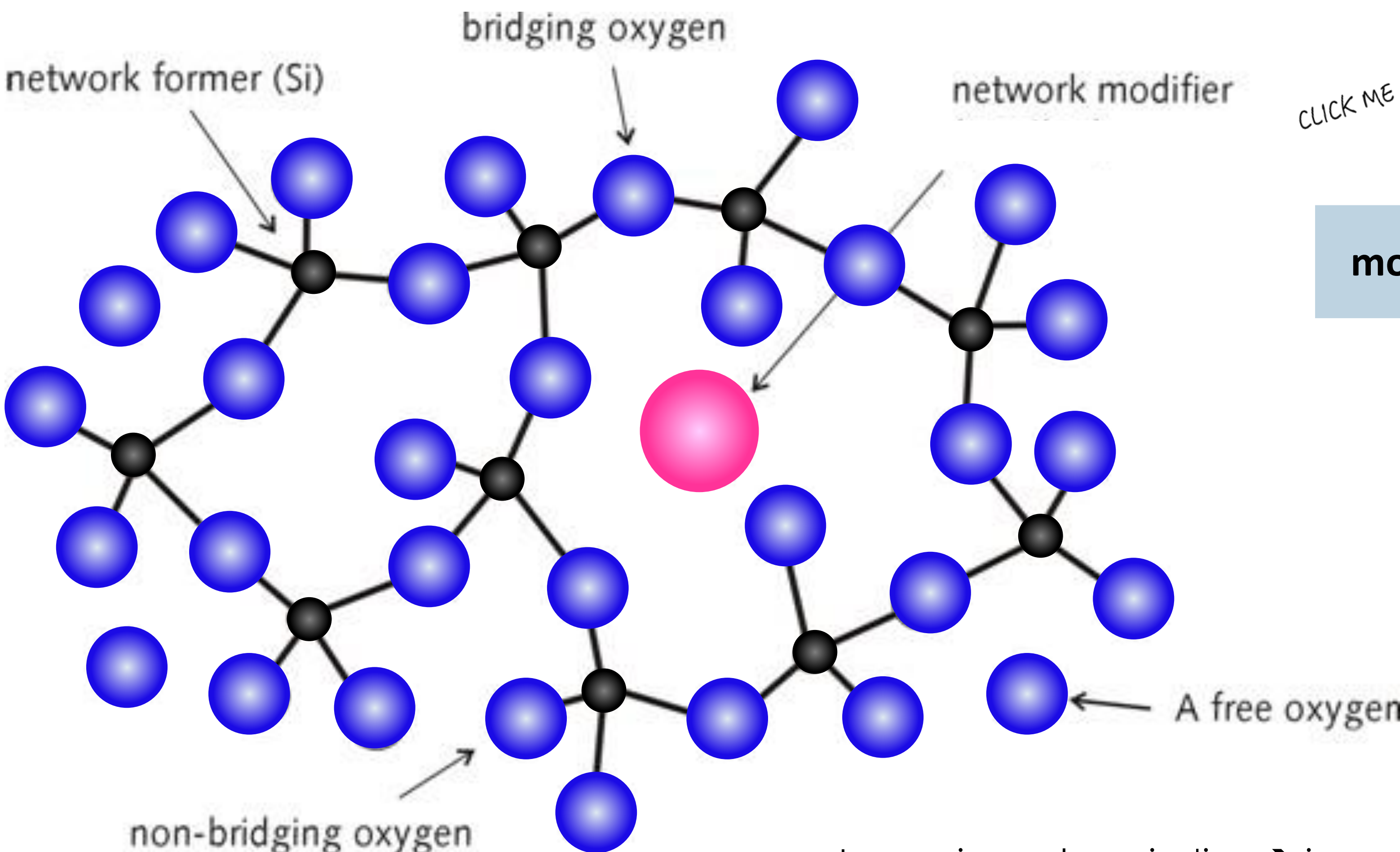


Lower figure: Vanderhaeghe (2009)

Polymerisation

$SiO_4^{4-} + SiO_4^{4-} = Si_2O_7^{6-} + O^{2-}$



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Increasing polymerisation ➔ increasing viscosity

Adding metal cations (e.g., Mg and Ca), H_2O or CO_2 ➔ depolymerisation ➔ decreases viscosity

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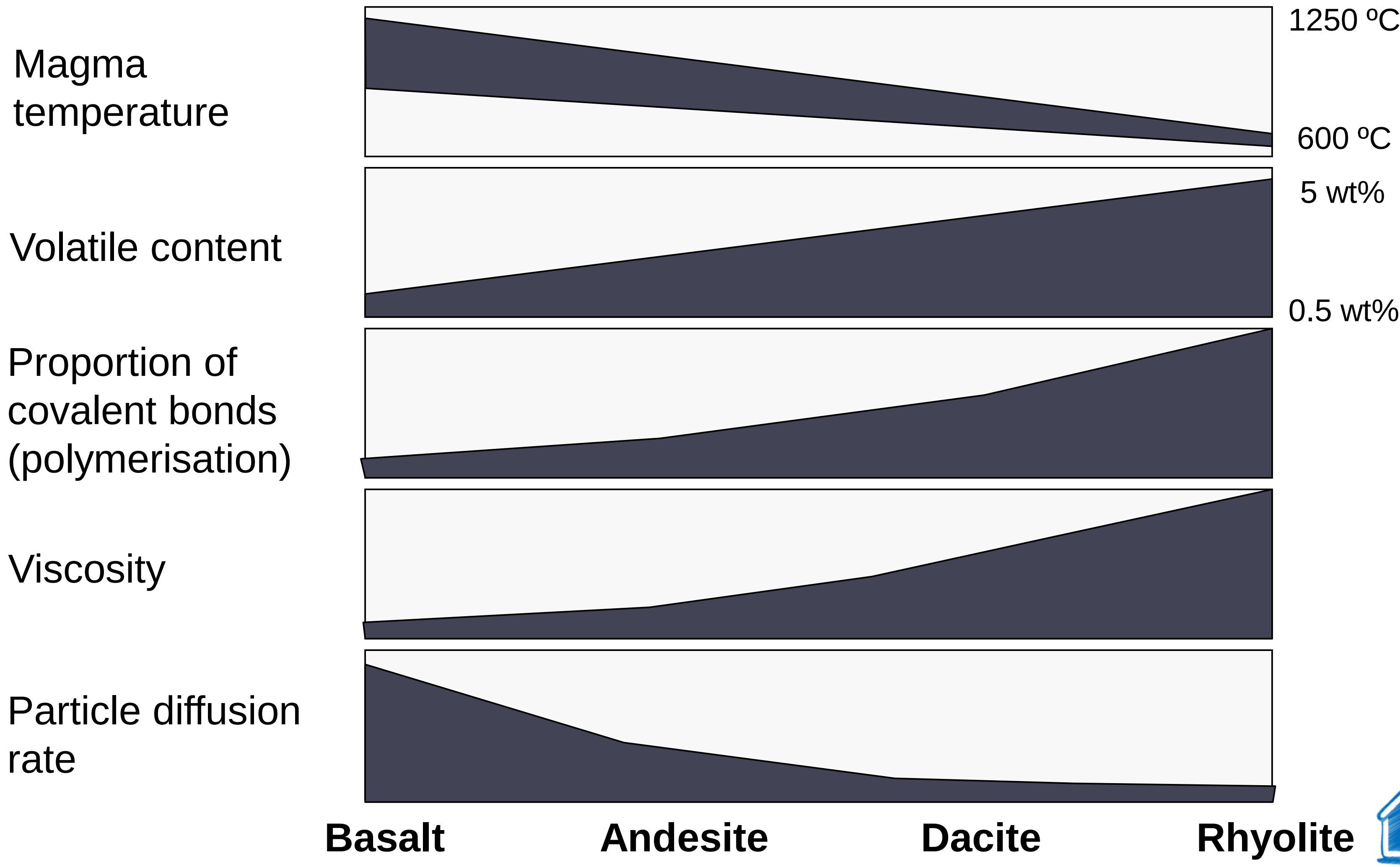
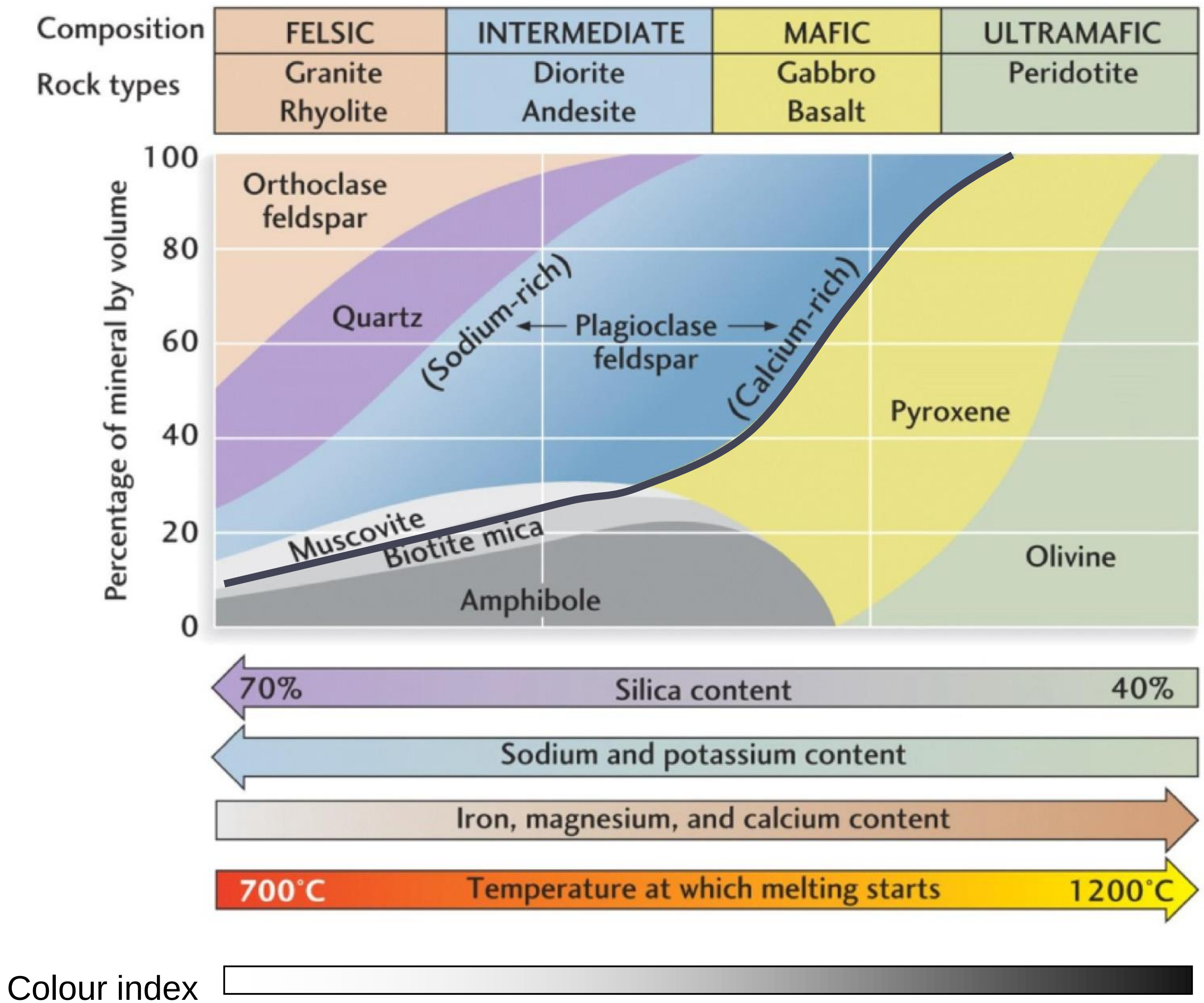
Properties of magmas



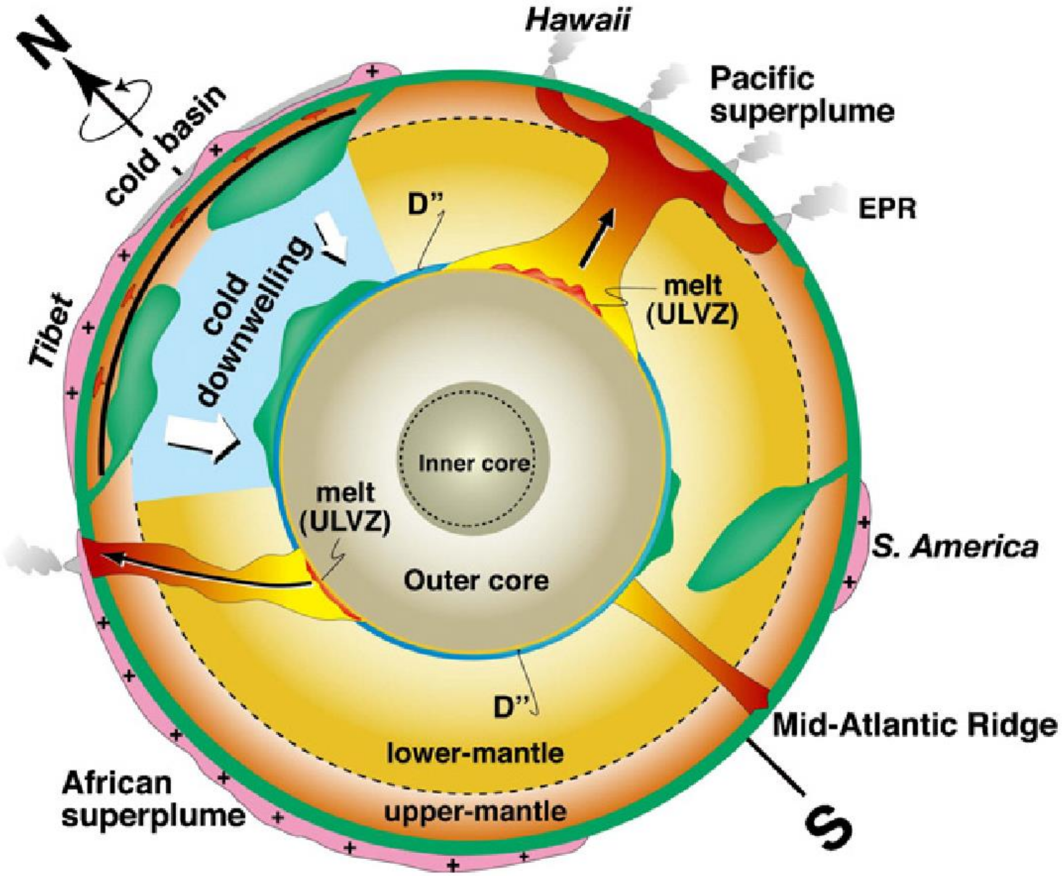
Types of igneous rocks:

Field mineralogical classification ("box diagram")



Geodynamics: Internal structure of the Earth

- Crust
  - Continental
  - Oceanic
- Mantle
  - Lithosphere
  - Upper mantle
  - Lower mantle
- Core
  - Outer core
    - Liquid metal
  - Inner core
    - Solid metal



Maruyama et al., 2007, Gondwana Research 11, 7–37

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Geodynamics: Magmatic activity in tectonic environments

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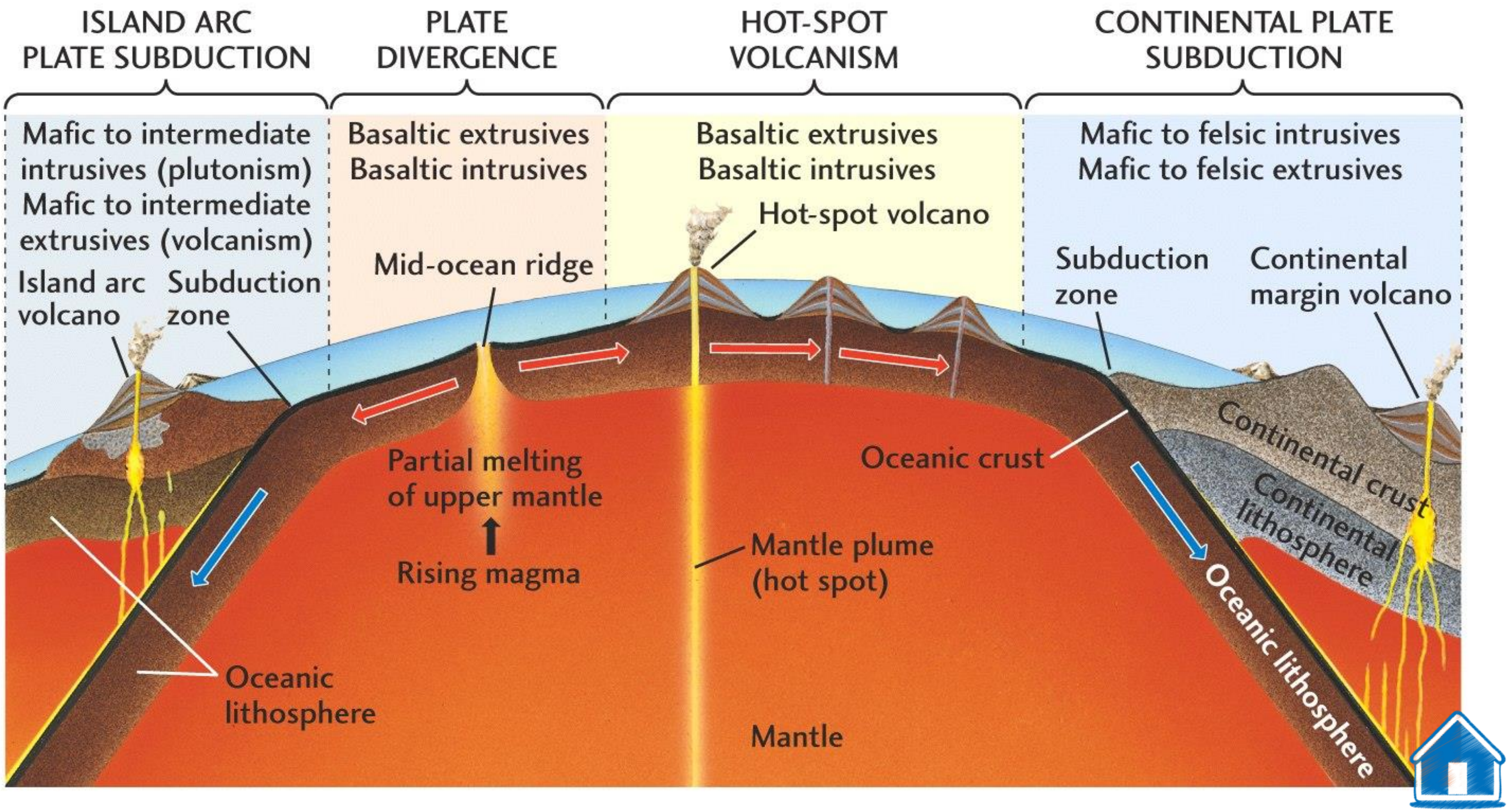

Examples of ore forming environments in collisional settings

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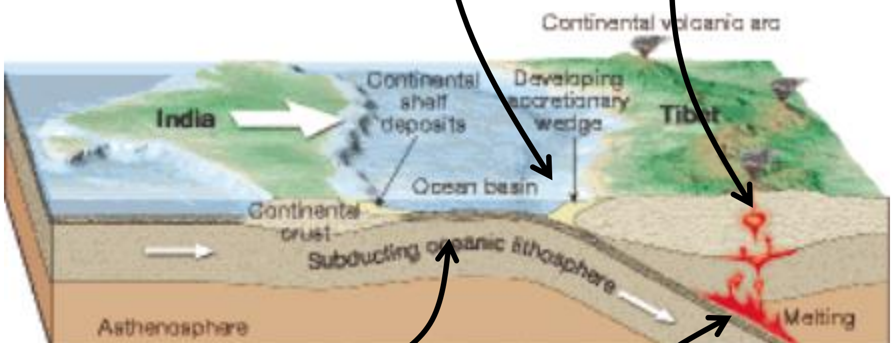
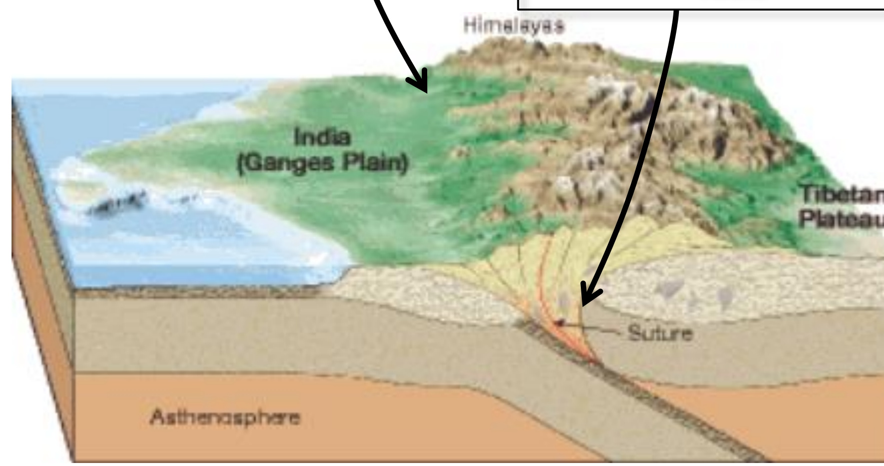
Deep faults allow for circulating fluids to transport metals into hydrothermal mineral deposits

Volatiles exsolve from hydrous magmas and transport metals into porphyry (Cu, Mo) and epithermal (Au, Ag, Sn) mineral deposits

Uplift leads to increased erosion, unroofing of plutons and placer formation

Crustal thickening leads to heating, metamorphism, dehydration and possibly partial melting of crustal rocks





Collision/orogenesis leads to ophiolite obduction (Cr, PGE)

Hydrous partial melting leads to formation of "wet" magmas that may include basalt (Cr, PGE) as well as produce significant Cl-rich brine (magmatic-hydrothermal) during ascent and crystallisation

Block diagrams from the PB Works Website: http://cosscience1.pbworks.com/w/page/8286031/Lesson%2010-5%20Convergent%20and%20Transform%20Boundaries

Porphyry deposits: Mineral deposit type with strong geodynamic control

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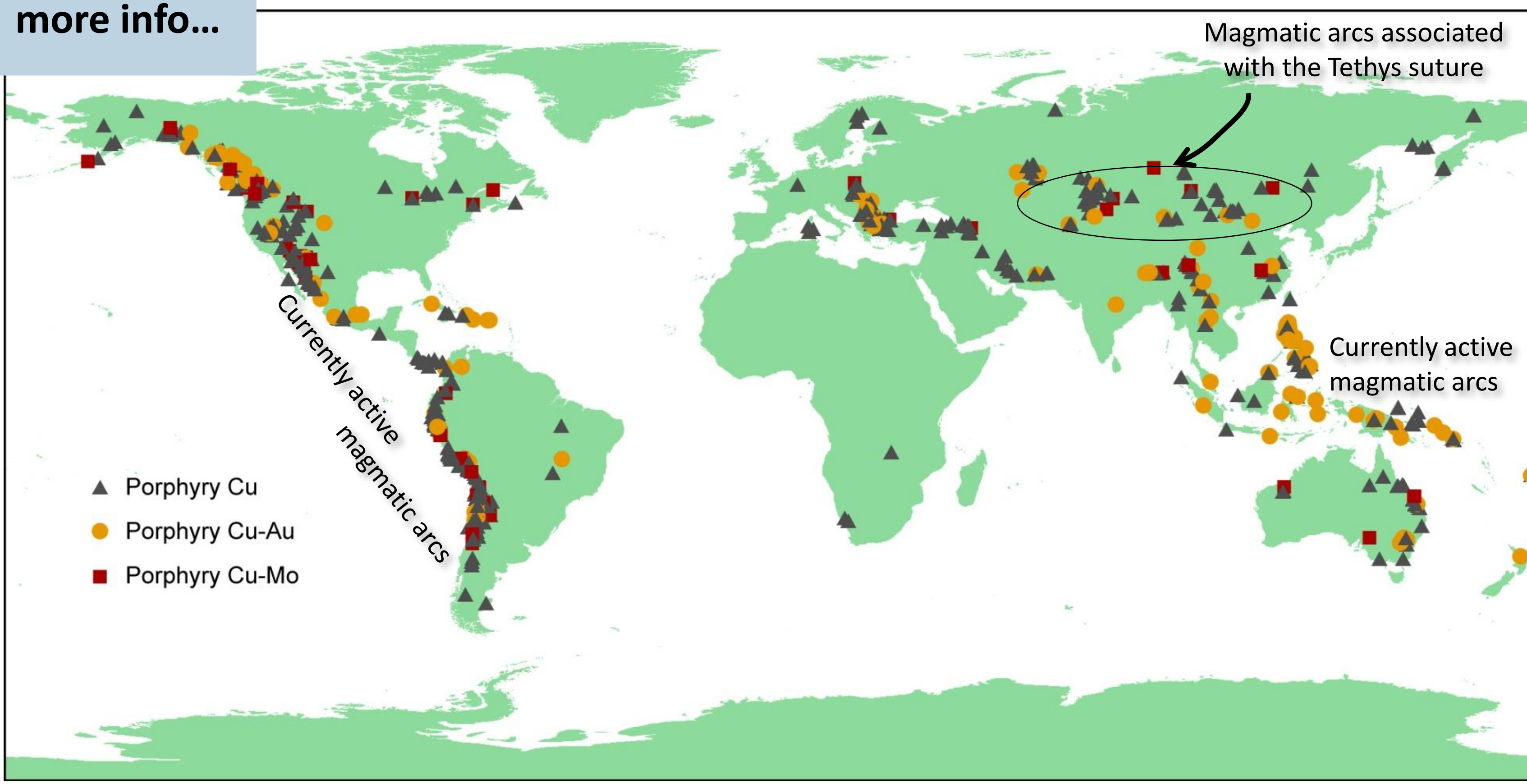
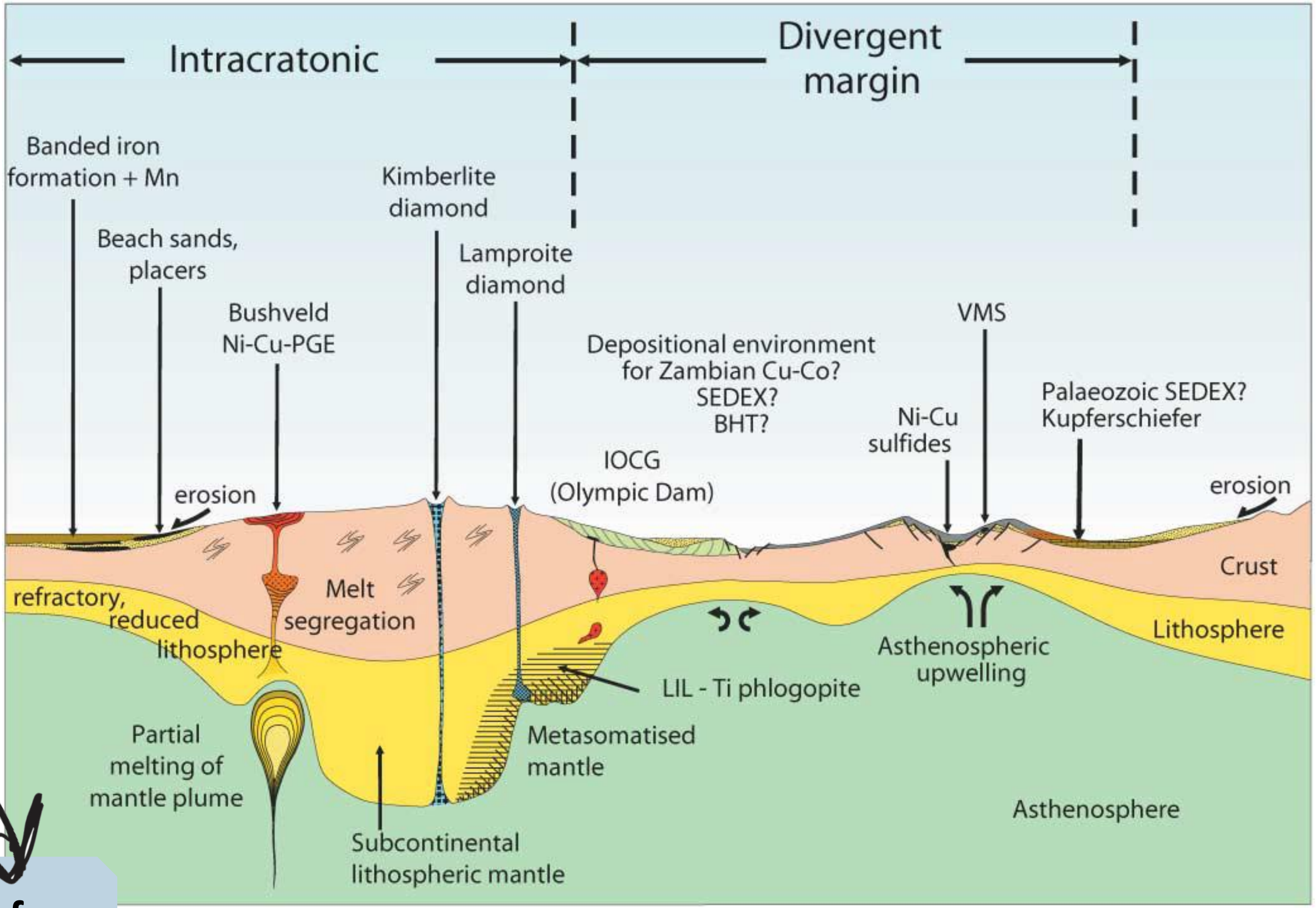


Porphyry deposits are closely linked to subduction magmatism. They form at shallow depths in orogenic crust and tend to get rapidly eroded. They are consequently rarely preserved in ancient geological terranes.

Cratons and rifting



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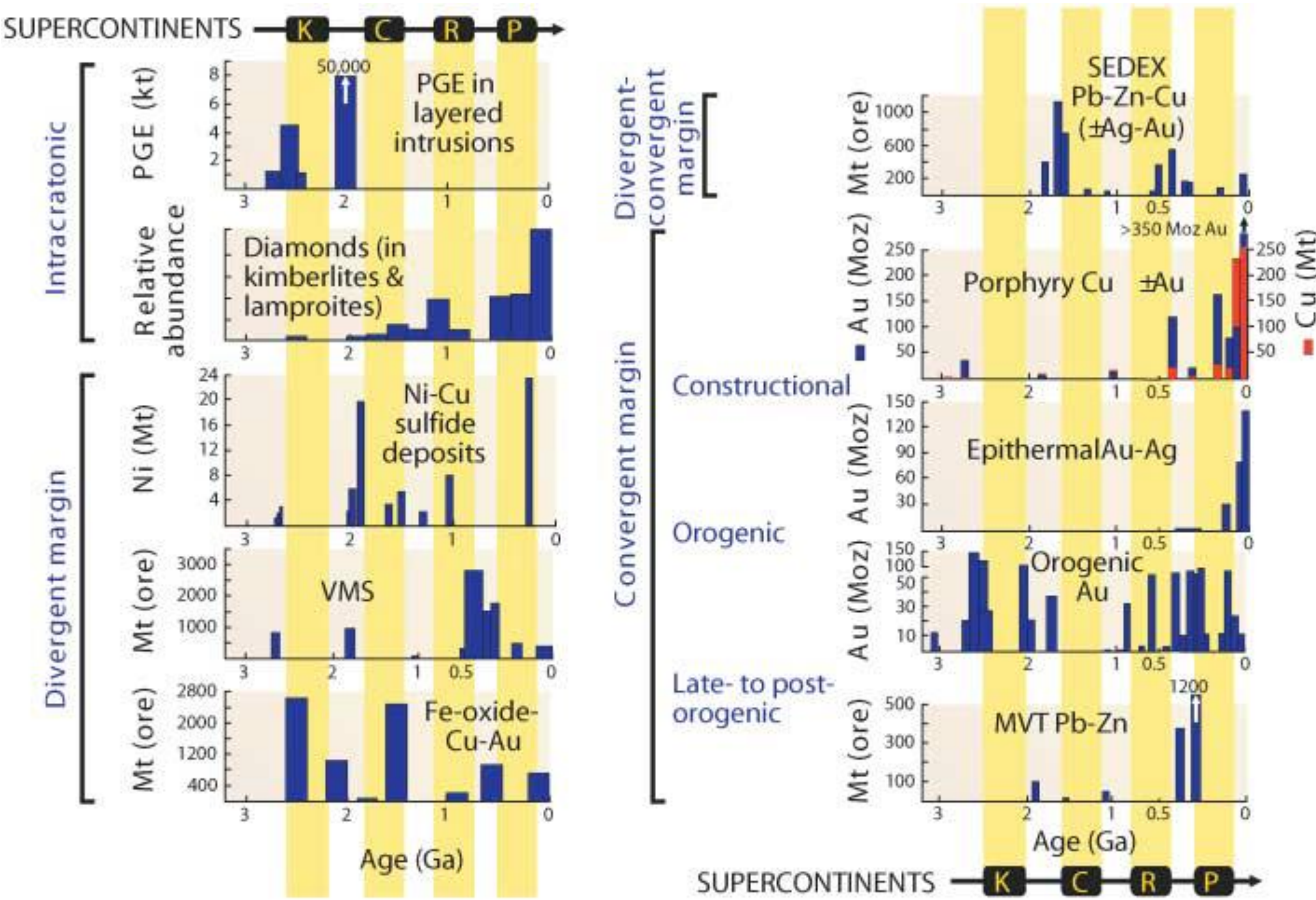
Source: Groves & Bierlein (2007)

Spatial and temporal patterns in mineral deposits



Source: Groves & Bierlein (2007)
K, Kenorland; C, Columbia; R, Rodinia; P. Pangaea

Ore provinces are related to the global tectonic cycles

- Ore formation
    - Orogenesis
    - Crustal thinning and spreading
- Ore preservation
    - Depth of formation
    - Rate and depth of erosion

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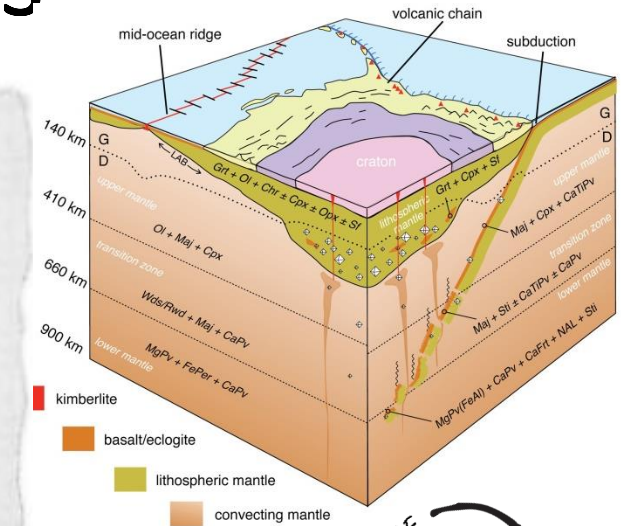
‘Metallogenesis’

“The **temporal distribution of the mineral deposit** types also assists in understanding of the **progressive changes in tectonic processes** related to a cooling Earth…. Excellent preservation of giant **orogenic gold**…. provinces in **Archaean** and **Palaeoproterozoic** terranes (e.g. Goldfarb et al. 2001), yet their essential absence in **Mesoproterozoic** terranes…. points to a change in tectonic process at this time.”



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“….in combination with evidence from **crustal growth rates** (e.g. Condie 2000), the temporal distribution of **mantle plume events** (e.g. Abbott & Isley 2002), and progressive **change in density and thickness of SCLM** (e.g. Griffin et al. 2003), Groves et al. (2005a, b) and Kerrich et al. (2005), among others, have argued that the Mesoproterozoic represents the transition from mantle-plume influenced (or dominated) plate tectonics to modern-style plate tectonics.”

Source: Groves & Bierlein (2007)

Spatial and temporal patterns in mineral deposits

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Supercontinent cycles and the distribution of metal

Miner Depo
DOI 10.100

ARTICL

Temp
PGE

Journal of the Geo

Bicenten

Temporal relations between mineral deposits and global tectonic cycles

PETER A. CAWOOD[1,2]* & CHRIS J. HAWKESWORTH[1]

[1]*Department of Earth Sciences, University of St Andrews, Irvine Building, North Street, St Andrews, Fife KY16 9AL, UK*

[2]*Centre for Exploration Targeting, School of Earth and Environment, The University of Western Australia, Crawley, WA 6009, Australia*

**Corresponding author (e-mail: peter.cawood@st-andrews.ac.uk)*

Abstract: Mineral deposits are heterogeneously distributed in both space and time, with variations reflecting tectonic setting, evolving environmental conditions, as in the atmosphere and hydrosphere, and secular changes in the Earth's thermal history. The distribution of deposit types whose settings are tied to plate margin processes (e.g. orogenic gold, volcanic-hosted massive sulphide, Mississippi valley type Pb–Zn deposits) correlates well with the supercontinent cycle, whereas deposits related to intra-cratonic settings and mantle-driven igneous events, such as Ni–Cu–PGE deposits, lack a clear association. The episodic distribution of deposits tied to the supercontinent cycle is accentuated by selective preservation and biasing of rock units and events during supercontinent assembly, a process that encases the deposit within the assembled supercontinent and isolates it from subsequent removal and recycling at plate margins.

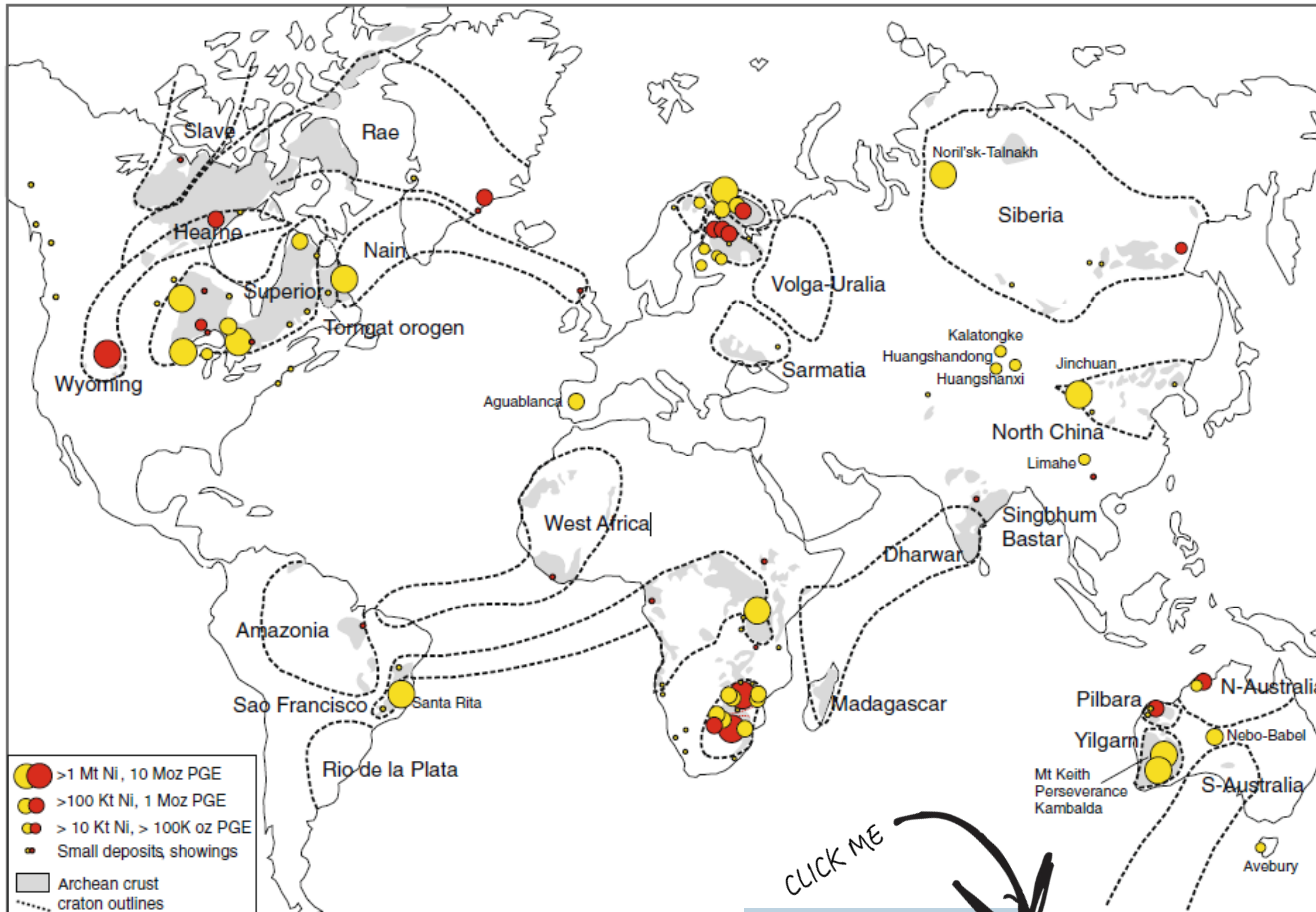
DAVID I. GROVES & FRANK P. BIERLEIN

Centre for Exploration Targeting and Tectonics Special Research Centre, School of Earth and Geographical Sciences, The University of Western Australia, Crawley, W.A. 6009, Australia (email: dgroves@cyllene.uwa.edu.au)

Spatial patterns for Ni-Cu-PGE and precious metal deposits

- ✓ Association with **Archaean crust/ cratons**
  - Ni-Cu-PGE deposits preferentially located near craton margins
- ✓ Association with **mantle plumes**

Is this a biased preservation potential of Archaean/ Palaeoproterozoic large layered intrusion deposits **(in a stabilized cratonic setting)?**
… or chemical/physical interaction between the plume and craton?



Source: Maier & Groves 2011

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Lithospheric mantle architecture

Contrasting views on the lithosphere's role in melting, Large Igneous Provinces, and Ni-Cu-PGE mineralisation

Economic Geology, v. 105, pp. 1057–1070

Lithospheric, Cratonic, and Geodynamic Setting of Ni-Cu-PGE Sulfide Deposits

Graham C. Begg,[1,2,†] Jon A.M. Hronsky,[3,4] Nicholas T. Arndt,[5] William L. Griffin,[1]
Suzanne Y. O'Reilly,[1] and Nick Hayward[6]

[1]*GEMOC, Department of Earth and Planetary Sciences, Macquarie University, NSW 2109, Australia*
[2]*Minerals Targeting International PL, Suite 26, 17 Prowse St. West Perth, WA 6005, Australia*
[3]*Western Mining Services PL, Suite 26, 17 Prowse St. West Perth, WA 6005, Australia*
[4]*Centre for Exploration Targeting, School of Earth and Environment, The University of Western Australia, Crawley, WA 6009, Australia*
[5]*LGCA, UMR 5025 CNRS, Université de Grenoble, 1381 rue de la Piscine, 38401 Grenoble, France*
[6]*Teck Australia PL, Level 2, 35 Ventnor Avenue, West Perth, WA 6005, Australia*

Abstract

The location of magmatic Ni-Cu-PGE sulfide deposits is related to lithospheric architecture, particularly that of the subcontinental lithospheric mantle (SCLM). At crustal levels, this relationship is manifest by a close proximity to craton and paleocraton margins. Deposits are associated with mafic-ultramafic rocks and many show a close spatial relationship with a coeval large igneous province (LIP). Metal quantities and tenors observed in deposits require segregation of a magmatic sulfide melt from a large volume of parental ultramafic melt. Generation of these parental melts requires melting of upwelling mantle rising to depths of 100 km or less. The timing and tectonic setting of deposits indicates that this most likely occurs when mantle plumes impact on the base of the SCLM and are channeled laterally to areas of thinnest SCLM, where they undergo decompression melting. Alternatively, the setting of some smaller deposits suggests that upwelling may be induced by syn- to post-collisional lithospheric delamination.

Economic Geology, v. 108, pp. 1953–1970

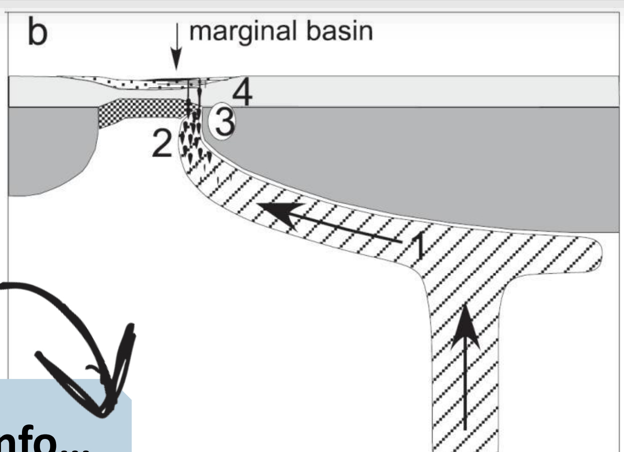
The Lithospheric Mantle Plays No Active Role in the Formation of Orthomagmatic Ore Deposits

Nicholas Arndt†

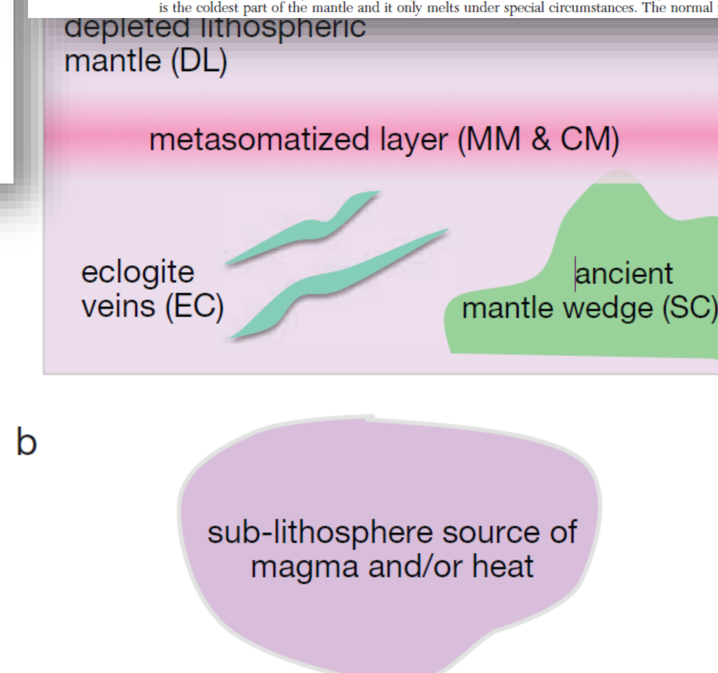
ISTerre UMR 5275 CNRS, Université Grenoble Alpes, BP 53, 38041 Grenoble cedex 9, France

Abstract

The hypothesis that the metals in certain orthomagmatic ore deposits come from a source in the subcontinental lithospheric mantle is evaluated in this paper. According to this hypothesis, parts of the mantle beneath the continents are metasomatically enriched in metals like Ni, Cu, and the platinum group elements (PGE). It is proposed that under some circumstances, these metals are transported into the crust where they become concentrated in orebodies. An examination of the compositions of xenoliths from the lithospheric mantle reveals little evidence, however, of components that could represent the source of metal-enriched magmas. In addition, the mechanism whereby metals are brought from the source to the surface is very unclear. The lithosphere is the coldest part of the mantle and it only melts under special circumstances. The normal product is a low-



Source: Begg et al. (2010)



Source: Arndt (2013)

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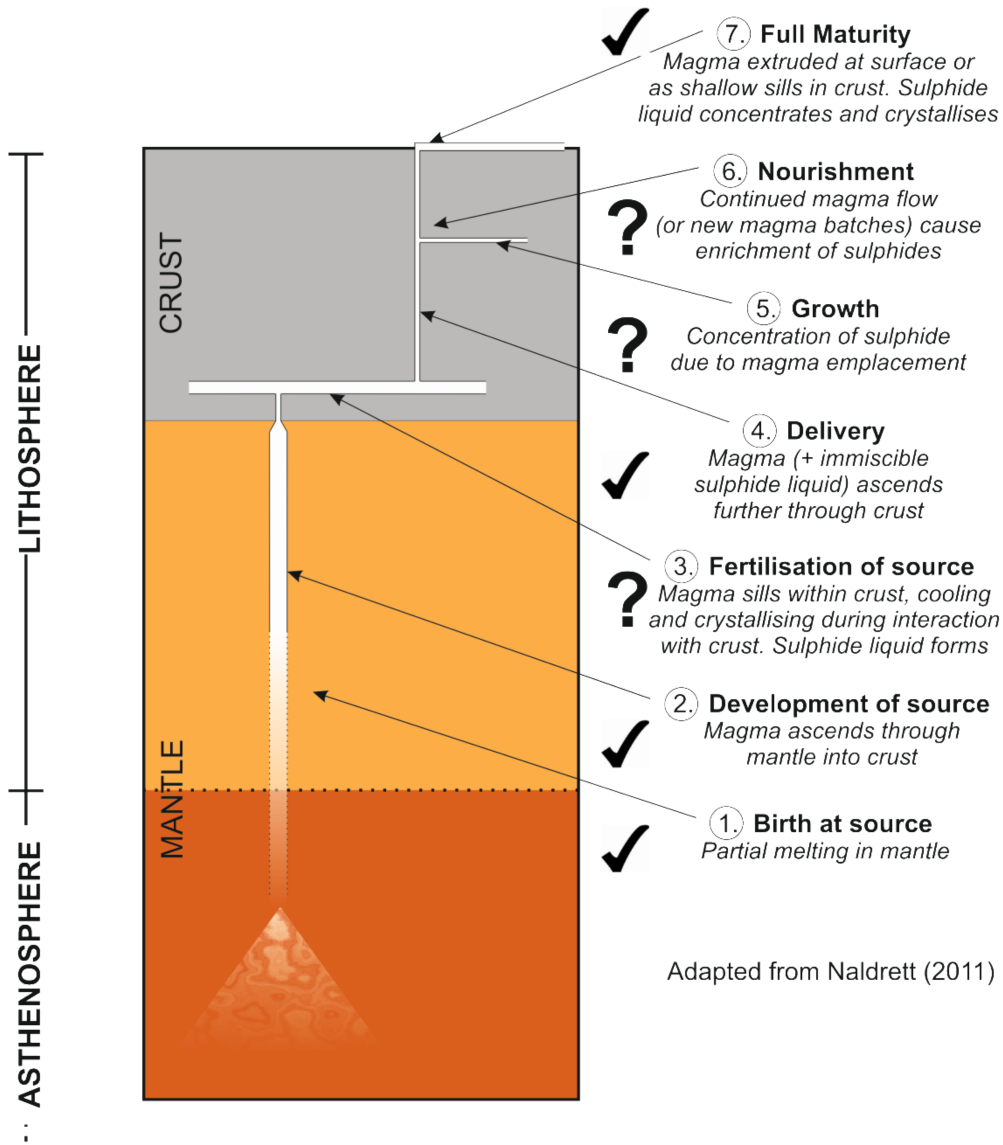
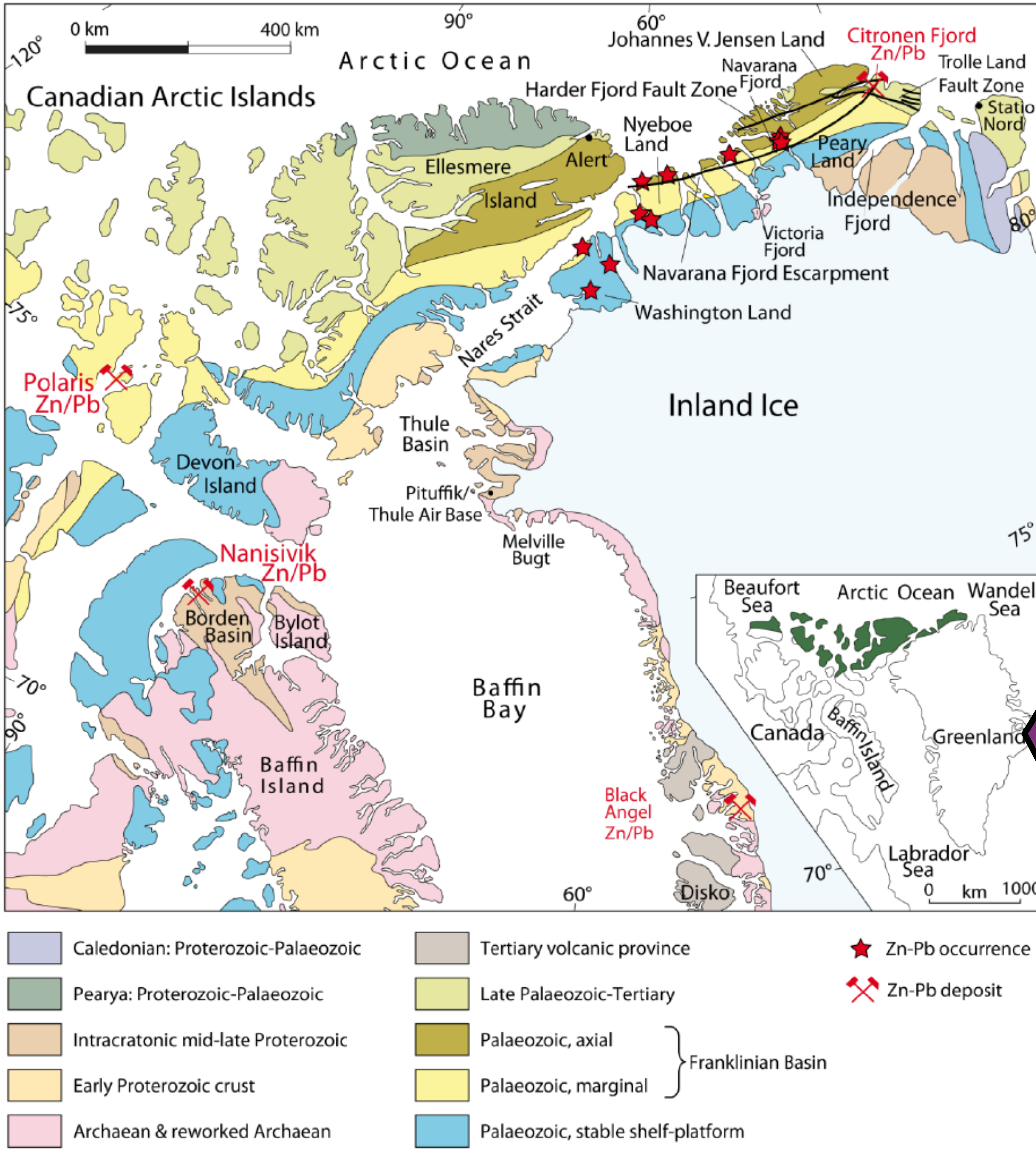
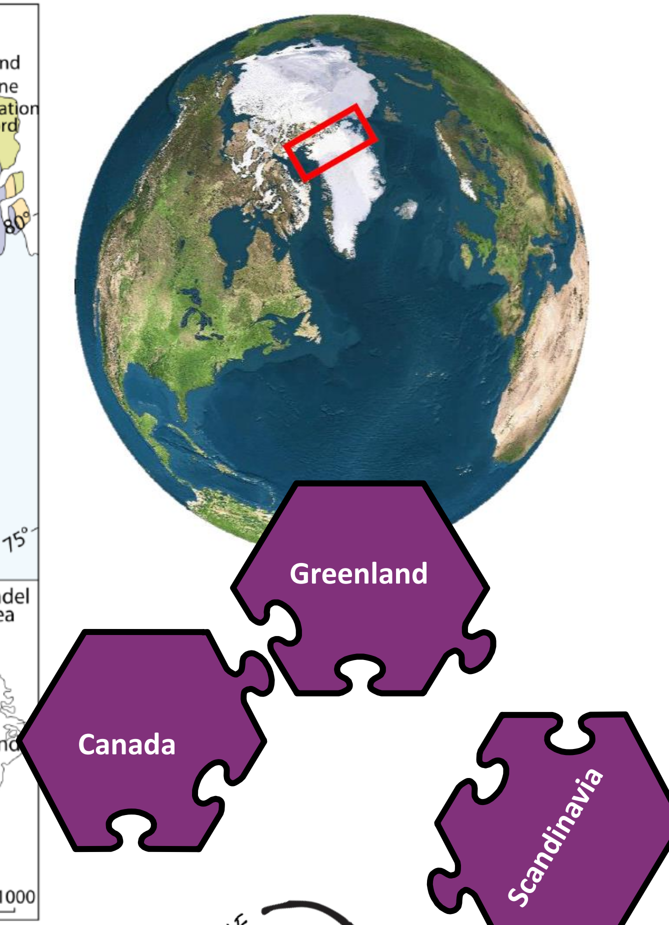
Requirements for Ni-Cu-PGE mineralisation



Geology without borders?

....Craton-specific exploration





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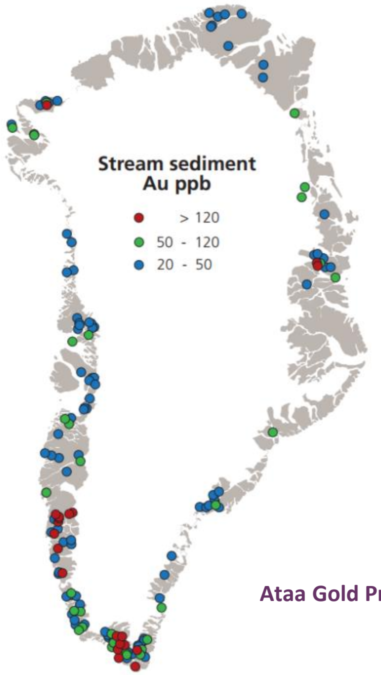
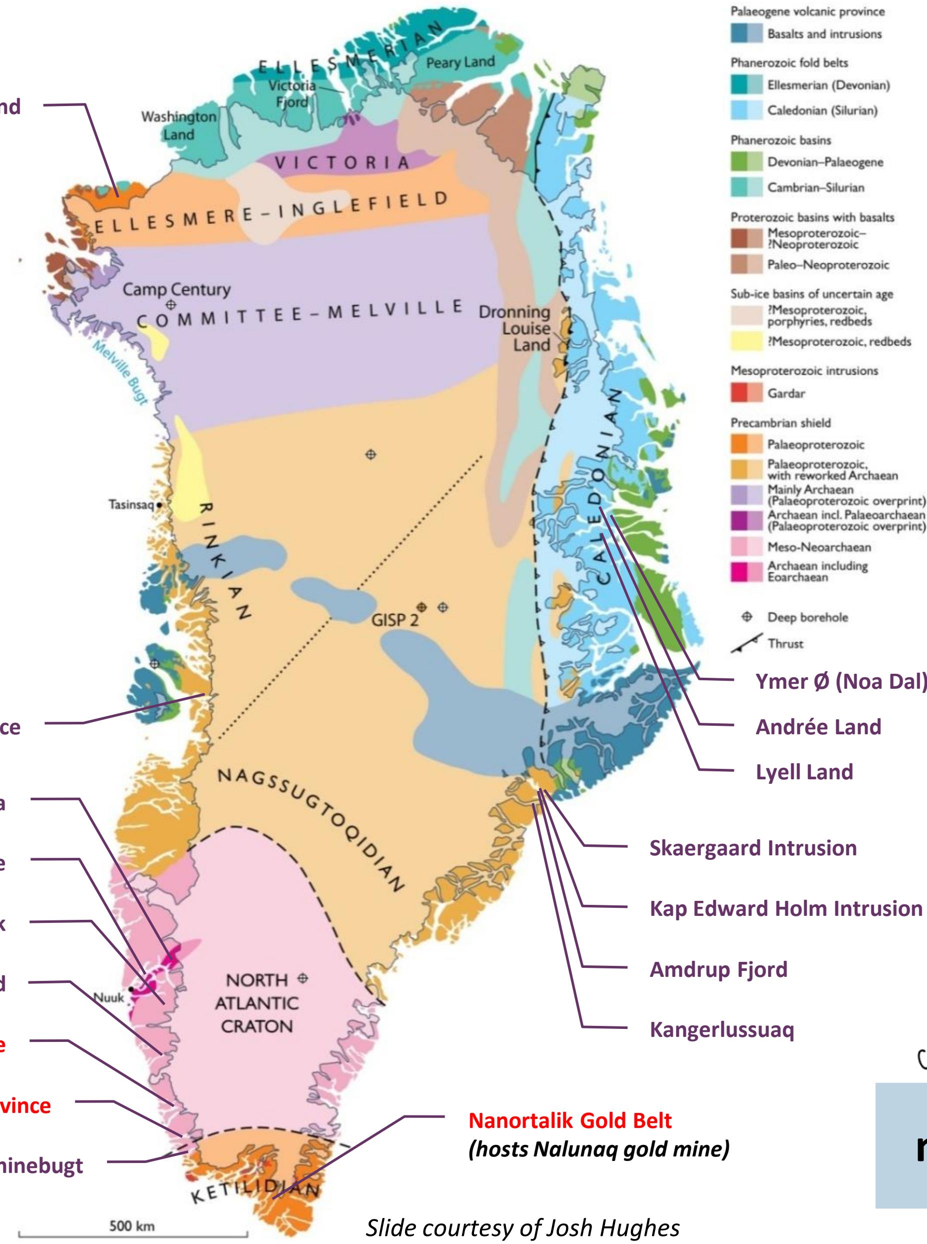
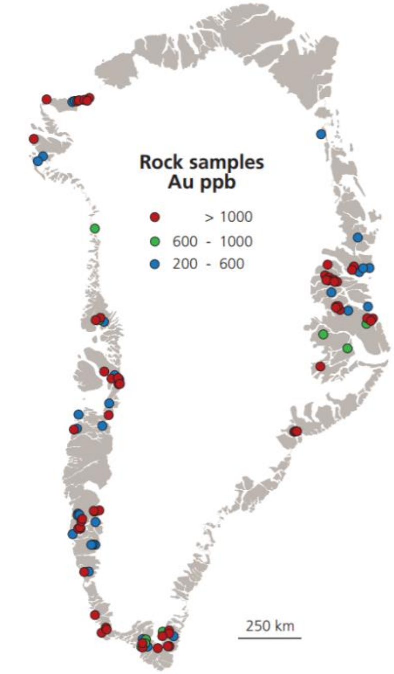
Gold in Greenland







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Figures adapted from: Dawes (2008), Kolb (2015)

Slide courtesy of Josh Hughes

Collective thinking:

GEUS-MMR "Mineral Resource Assessment Workshop on the Orogenic gold potential in Greenland"

NAALAKKERSUISUT
GOVERNMENT OF GREENLAND

G E U S

Held annually. Previous workshops on: **Cu, Zn, REE, Ni, W, V, Ti, Ni, U, Au and graphite**

"3-part undiscovered mineral resource estimation methodology" developed by the **USGS Global Mineral Resource Estimation Program**

International **Expert Panel** comprised of academics and industry geologists with specific knowledge on aspects of Greenlandic geology and/or expertise in the deposit type.

- Historic exploration (company reports, presentations)
- Academic literature
- Geological maps
- Global grade-tonnage models
- Geochemistry
- Geophysics
- Geochronology

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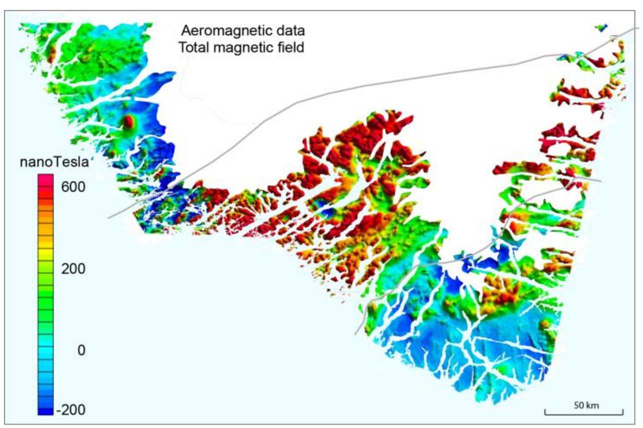
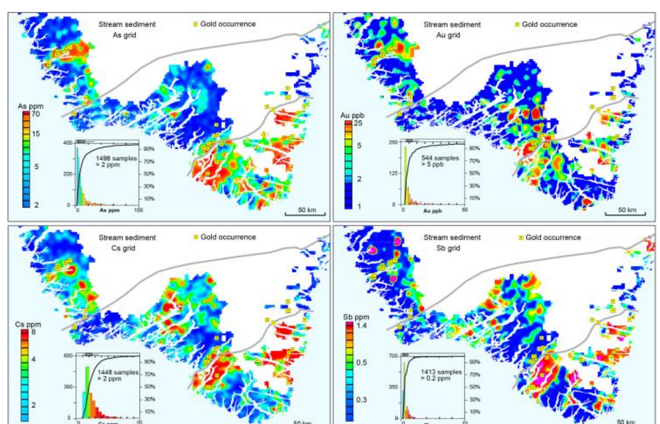
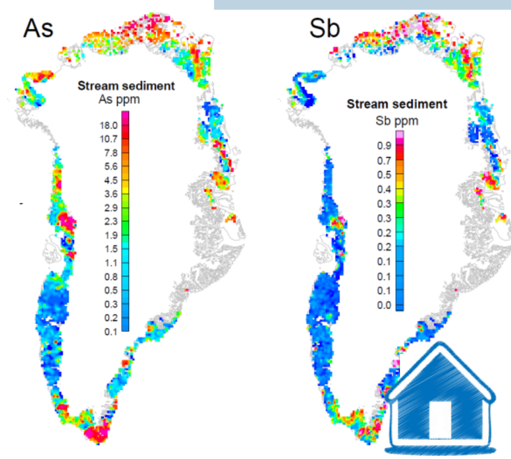






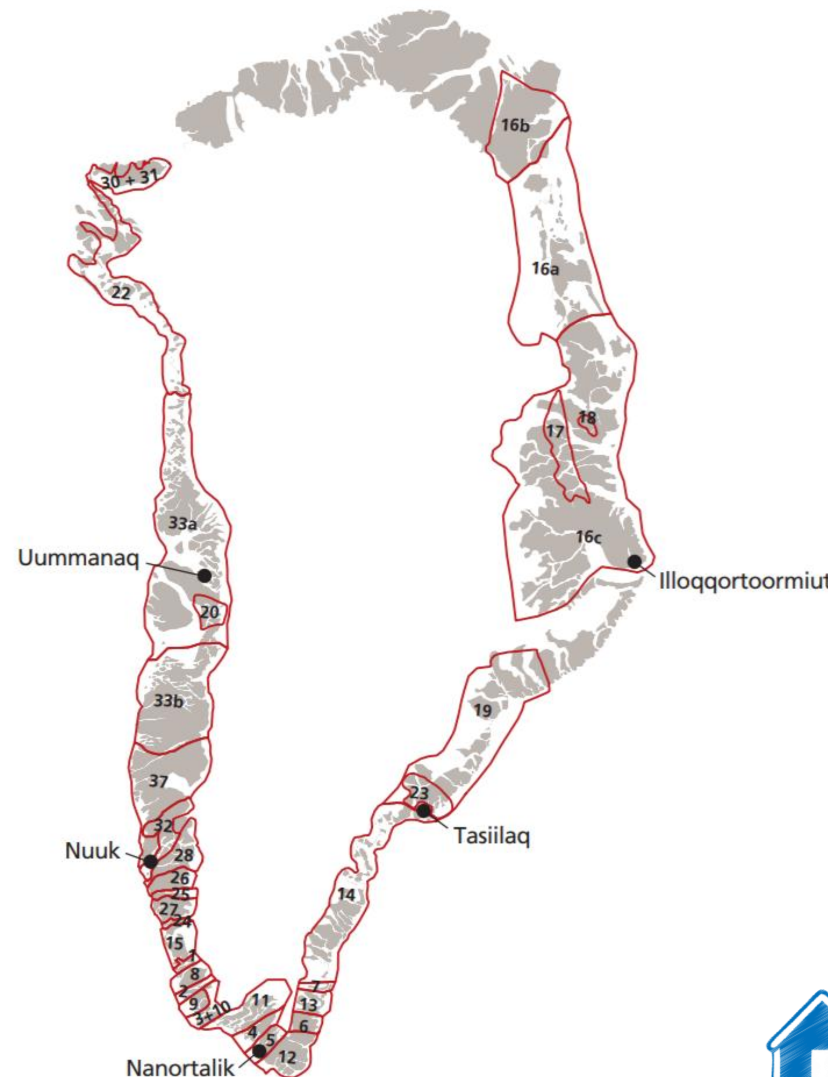
Slide courtesy of Josh Hughes

Collective thinking:
GEUS-MMR "Mineral Resource Assessment Workshop on the Orogenic gold potential in Greenland"

Figures from: Kolb (2015)

Tract name	Tract Area (km2)	Consensus bid on the number of undiscovered orogenic gold deposits at different confidence levels					Summary statistics		
		N90	N50	N10	N05	N01	Number of unknown deposits	Deposit density	Mean estimate of undiscovered orogenic gold (metric tons)
1	702	1	2	4	7	10	3	3.6	44
2	866	2	5	7	11	13	5	5.7	87
3+10	1,543	0	1	2	4	6	1	0.8	22
4	1,961	0	0	2	3	5	1	0.4	14
5	2,078	4	6	10	16	23	6	3.5	110
6	787	0	2	3	4	5	2	2.3	32
7	205	0	0	0	1	3	0	0.7	3
8+9+15+26+27	12,277	0	0	2	5	7	1	0.1	15
11	4,367	0	0	1	2	3	0	0.1	7
12	4,402	1	2	4	6	8	2	0.5	41
13	635	0	0	0	1	3	0	0.2	2
14	7,967	0	0	2	4	6	1	0.1	15
16a	19,297	0	2	10	20	50	6	0.3	96
16b	14,985	1	2	3	5	10	2	0.2	40
16c	65,921	1	3	8	16	36	5	0.1	91
17+18	7,715	2	4	8	12	20	5	0.7	92
19	8,728	0	1	2	4	6	1	0.1	23
20	2,344	2	4	5	8	10	4	1.6	67
22	5,733	0	1	2	5	7	1	0.2	24
23	3,238	0	0	2	4	6	1	0.3	13
24	543	0	0	2	3	5	1	1.4	13
25	751	0	0	2	2	4	1	0.9	12
28	5,191	0	0	2	3	6	1	0.1	14
30+31	5,206	0	1	3	6	9	2	0.3	29
32	5,211	4	7	11	20	33	8	1.6	150
33a	29,440	0	2	6	11	15	3	0.1	55
33b	25,338	0	0	2	3	5	1	0.1	12
37	16,892	0	1	3	5	7	2	0.1	28

N90, N50, N10, N05, N01 = Confidence levels; a measure of how reliable a statistical result is, expressed as a percentage that indicates the probability of the result being correct. A confidence level of 10% (N10) means that there is a probability of 10% that the result is reliable. Deposit density = The total number of deposits per 1000 km^2.



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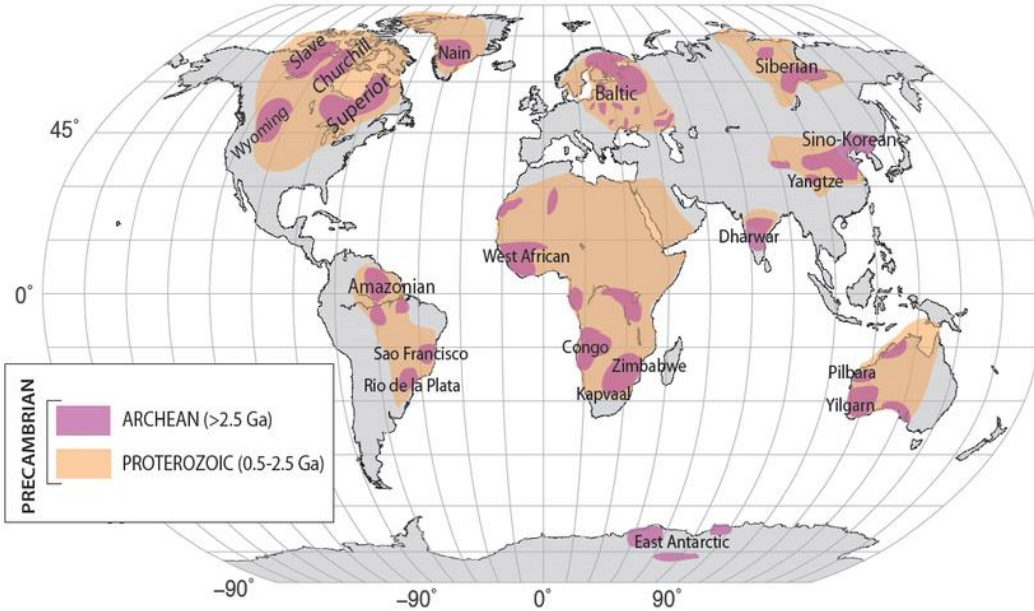
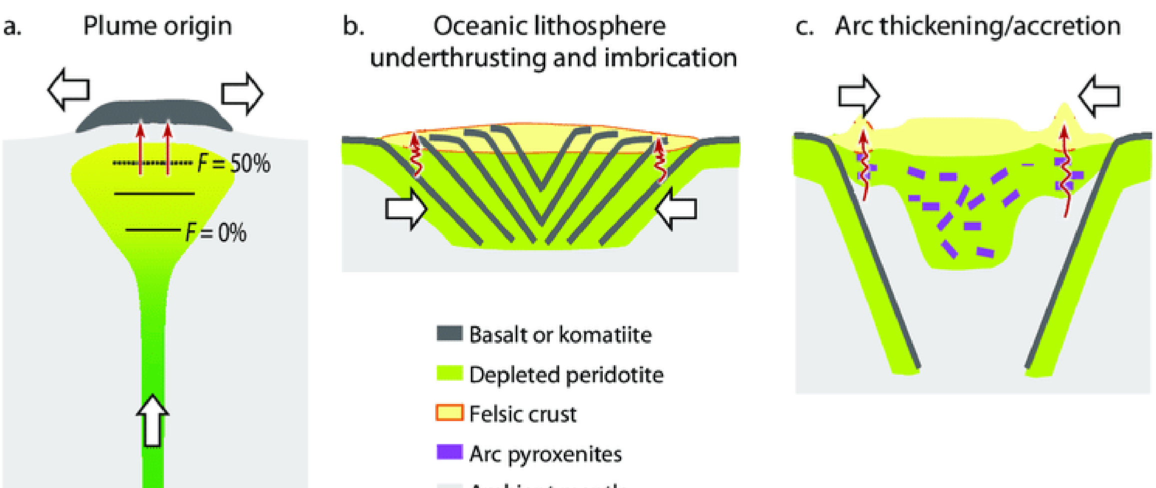
What is a craton?



Cratons are stable portions of the Earth's continental crust typically composed of ancient crystalline basement rocks. The margins may be deformed, but the interior of cratons have a stable density, thermal and compositional profile. [nice summary info here]

Debated how they form:

1. Mantle plume
2. Successive subduction
3. Accretion of island arcs & continental fragments
4. Sagduction …



Figures from Petrescu (2017)