28th September 2023

Disruptive Strategies for Sourcing Energy Raw Materials

Yasur volcano (Vanuatu) – 2016

From Volcanoes to Green Mining

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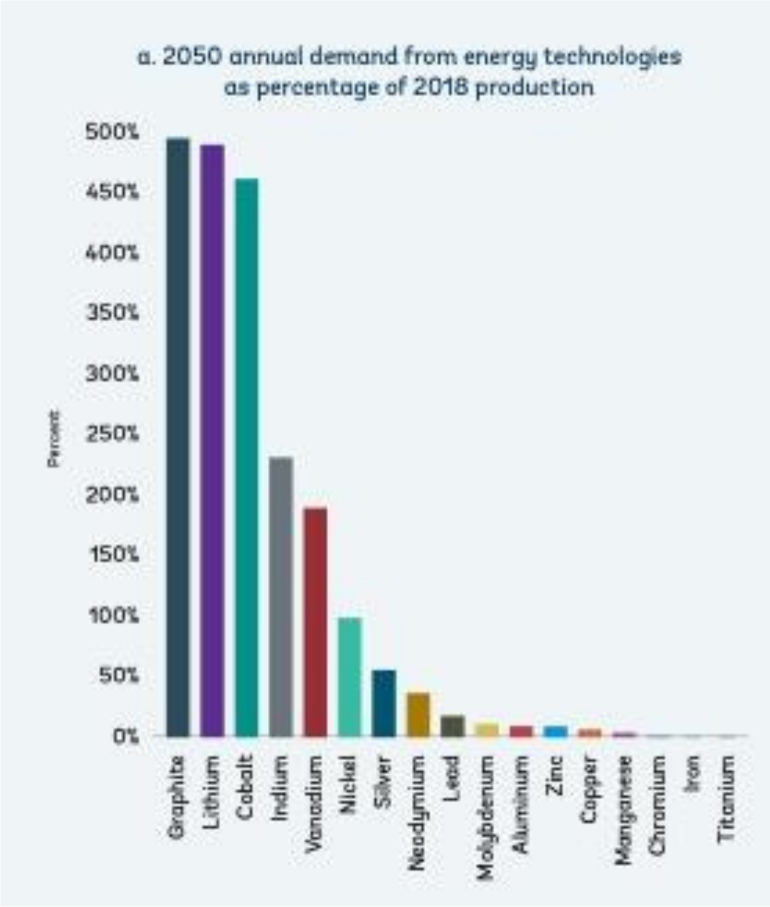
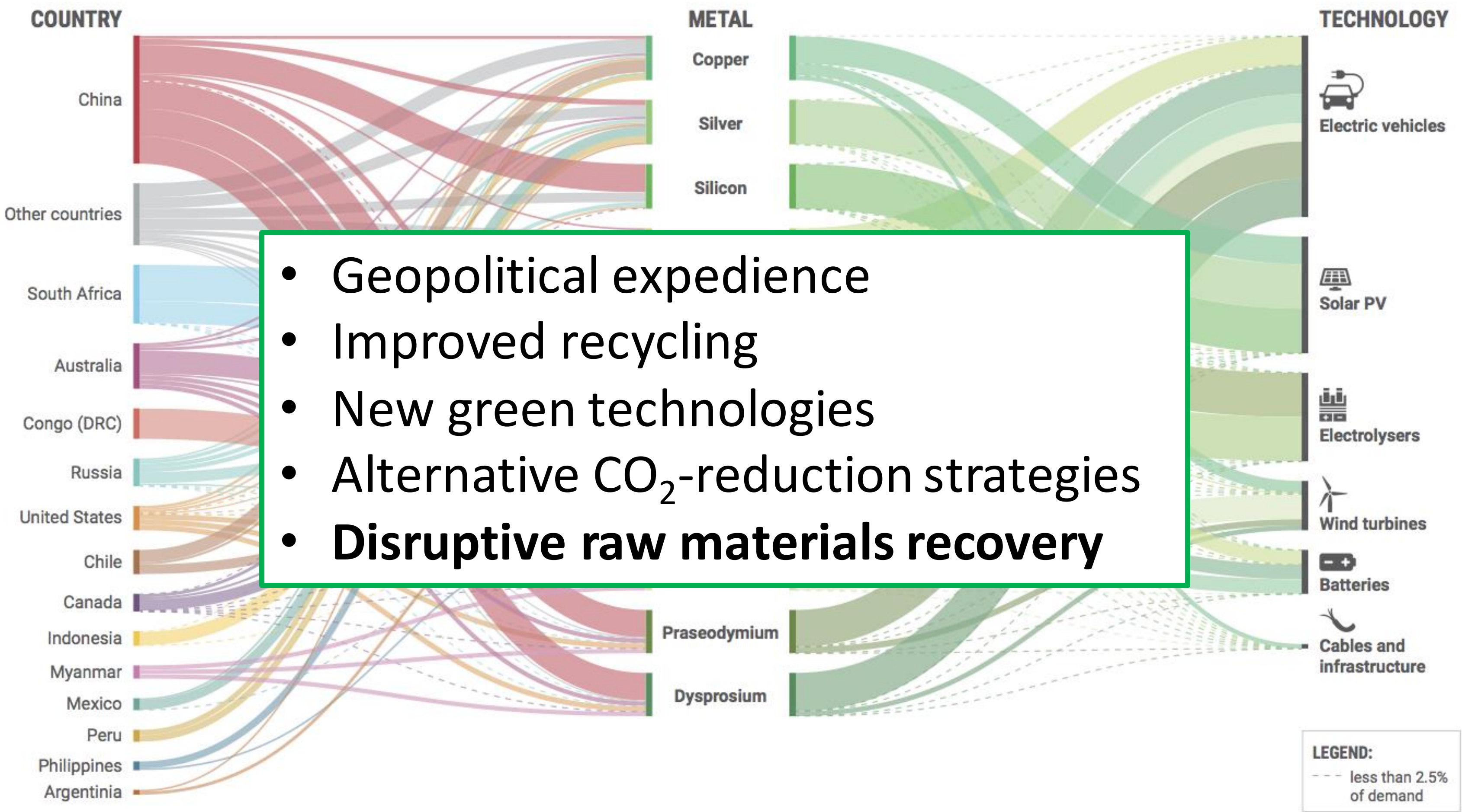
THE ROYAL SOCIETY

Critical metals –
increased demand and security of supply

World Bank (2DS)



The challenge

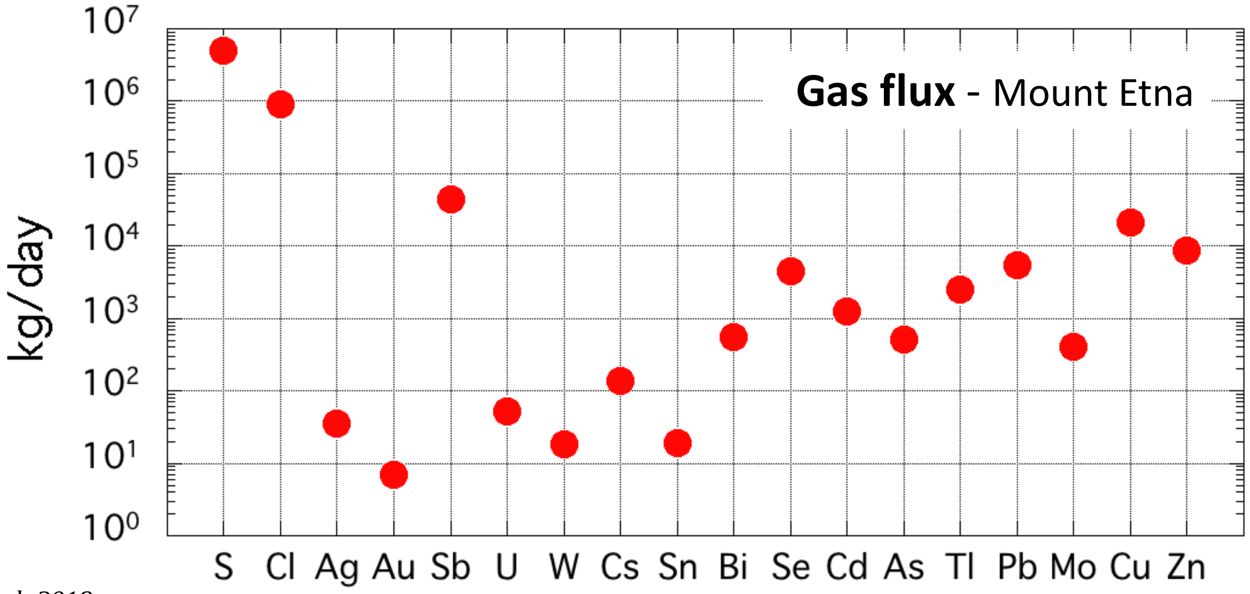


- Geopolitical expedience
- Improved recycling
- New green technologies
- Alternative CO_2-reduction strategies
- **Disruptive raw materials recovery**

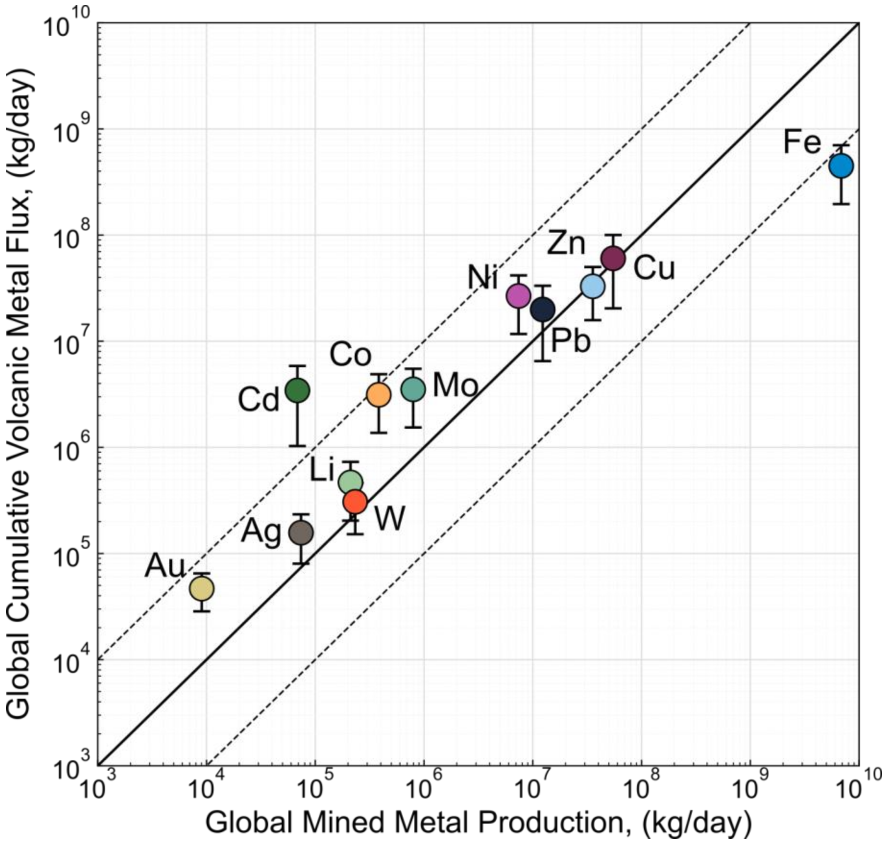
Netherlands Net Zero strategy

Magmatic systems and the energy transition

Volcanic fluids and metals



Edmonds et al, 2018

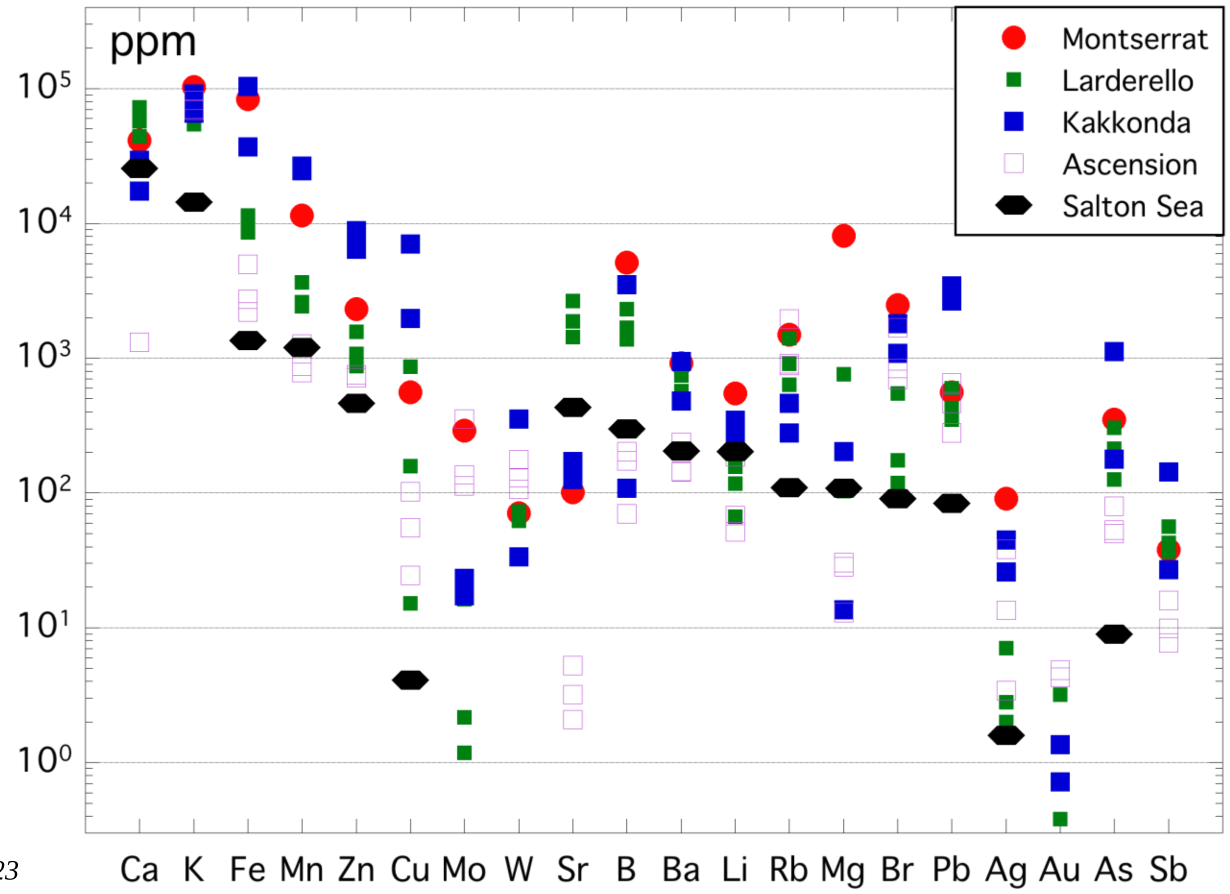


Hogg & Blundy, 2022

- Volcanic gases carry a **diverse portfolio** of metals and metalloids
- Approximately **2,000** degassing volcanoes worldwide
- Much more metal is dissolved in trapped, condensed liquids **underground**

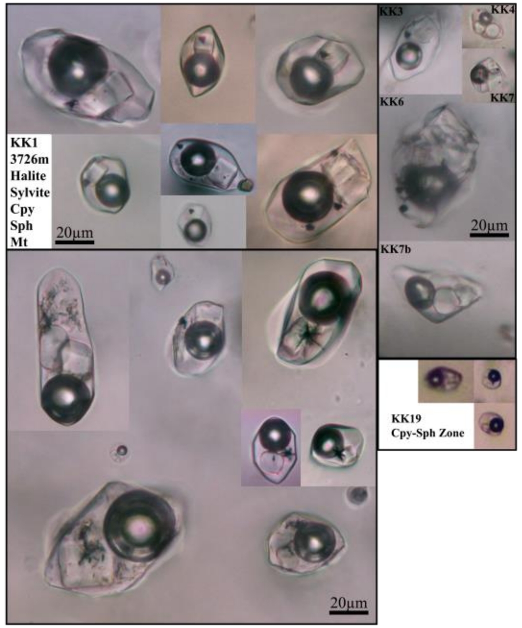
Magmatic brines – metal-rich hypersaline liquids

CTR plant, Salton Sea (USA) $520M
50 MW, 25 tonnes LiOH (by 2025)



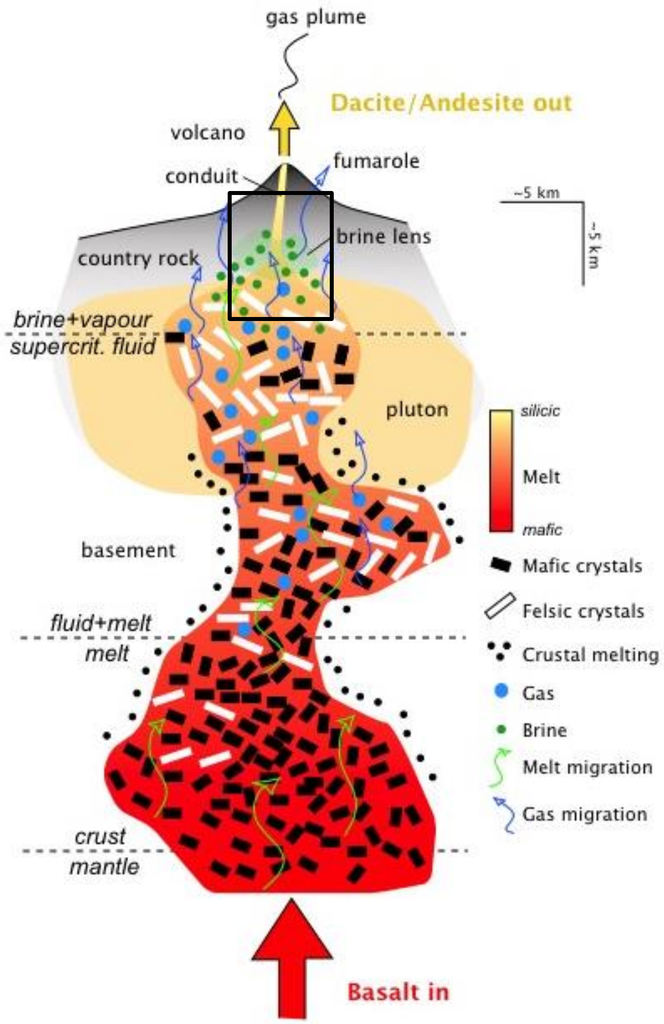
Tattitch et al, 2023

Fluid inclusions

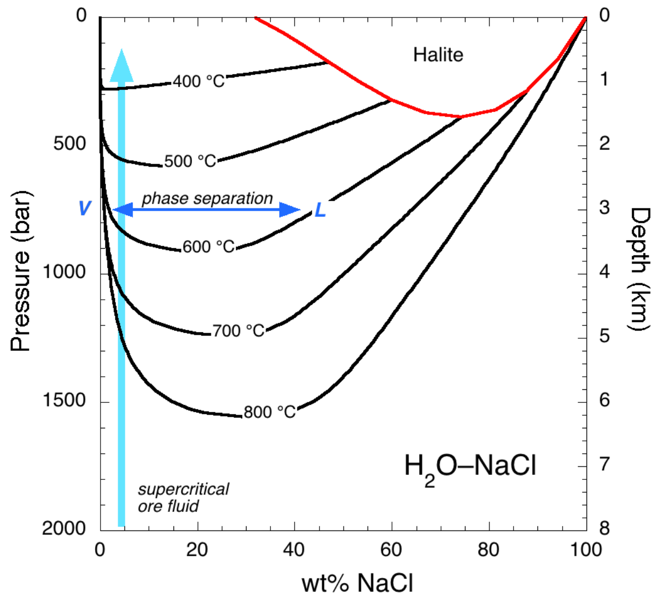


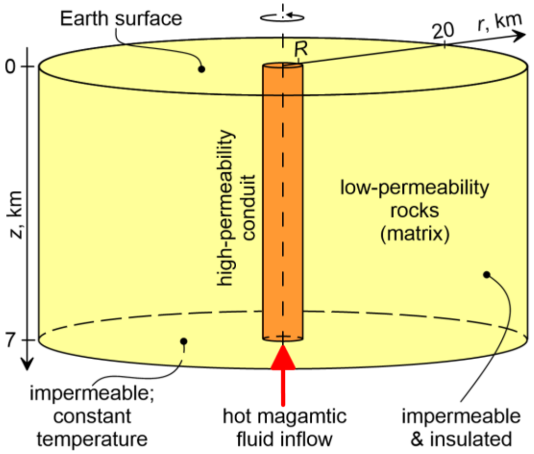
- Brine chemistry varies with magma type and tectonic setting
- Magmatic brines 'bleed' periodically into overlying geothermal systems
- Dilution by reservoir fluids
- Enrichment through fluid-rock reactions

Sub-volcanic brine lenses –
formed by low-pressure phase separation

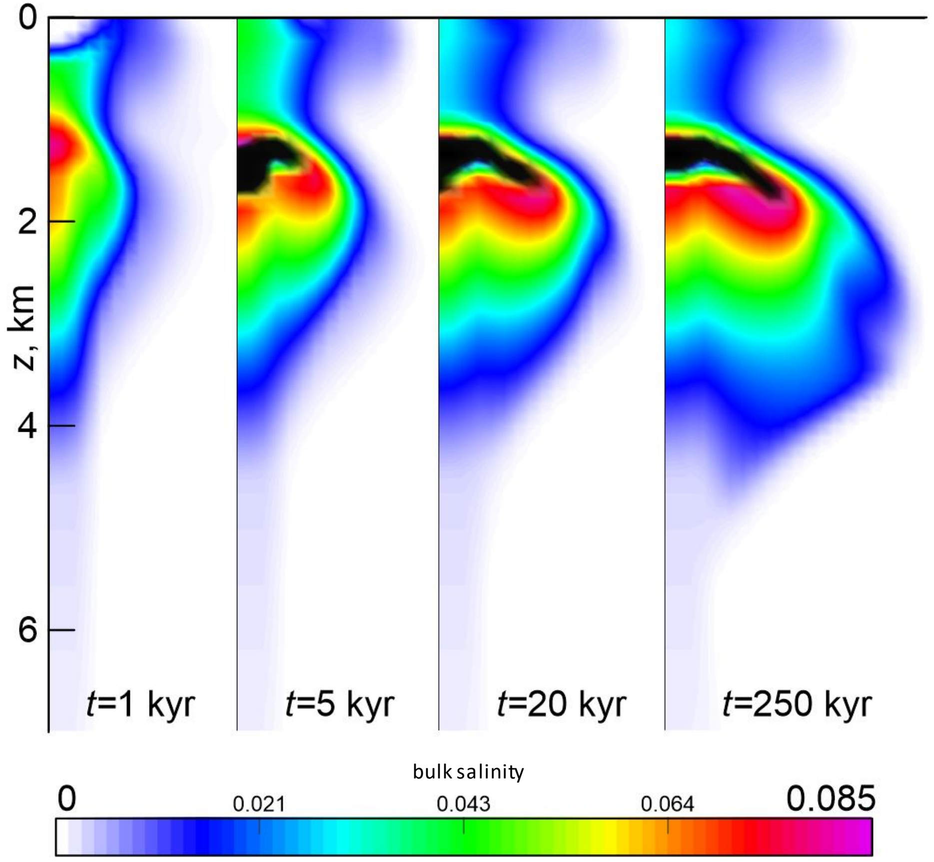


Transcrustal Magmatic System



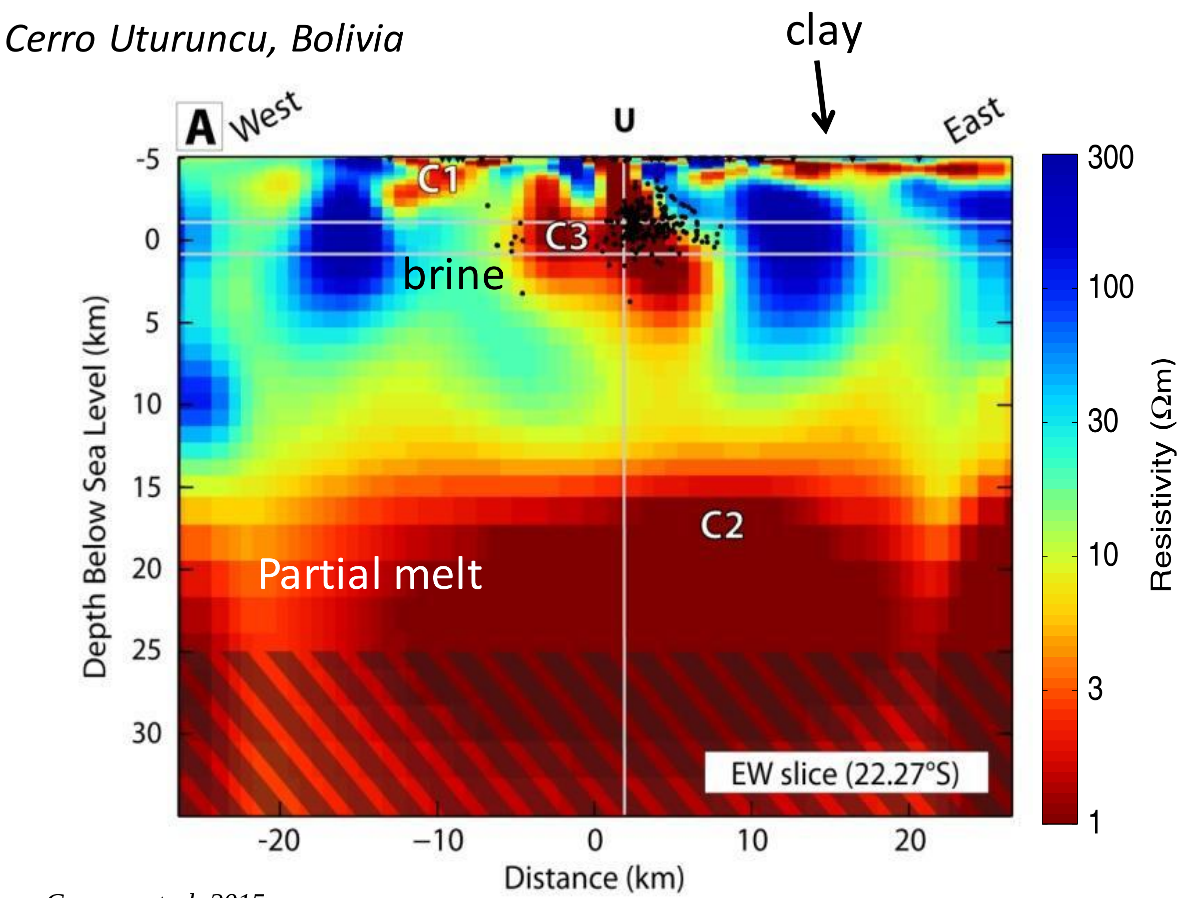


Hydrodynamic modelling

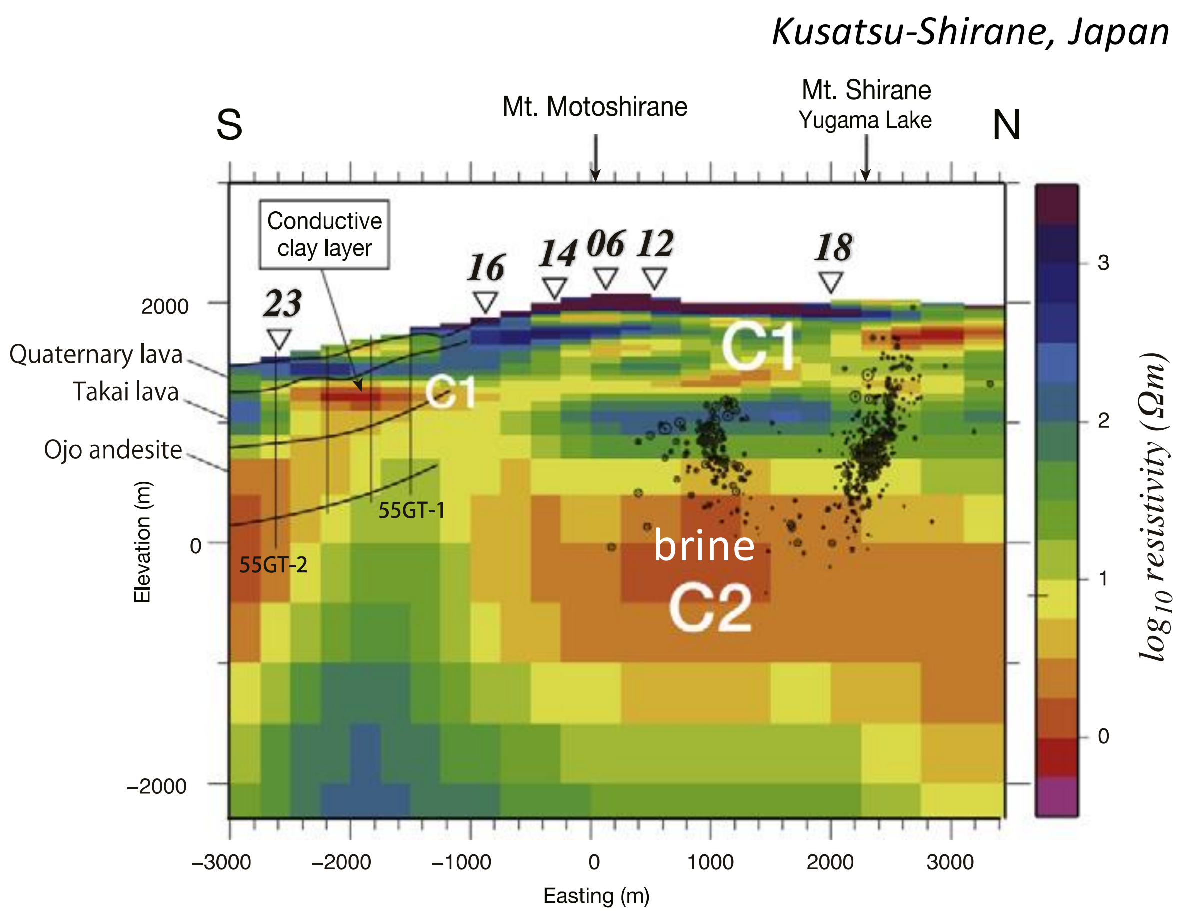


Afanasyev et al (018)

Volcano geophysics – electrical conductivity



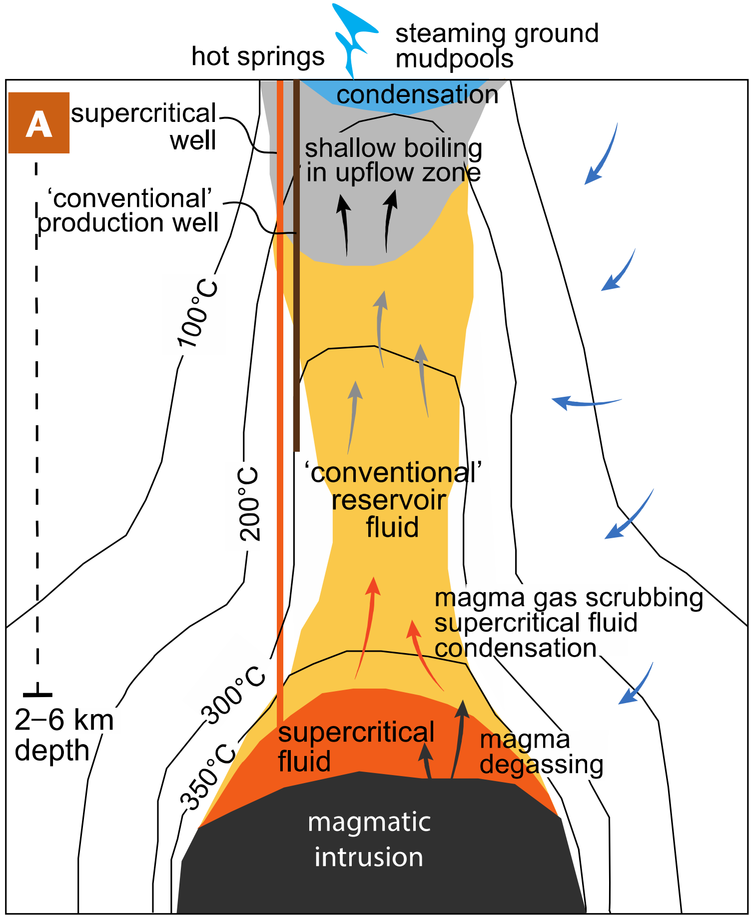
Comeau et al, 2015



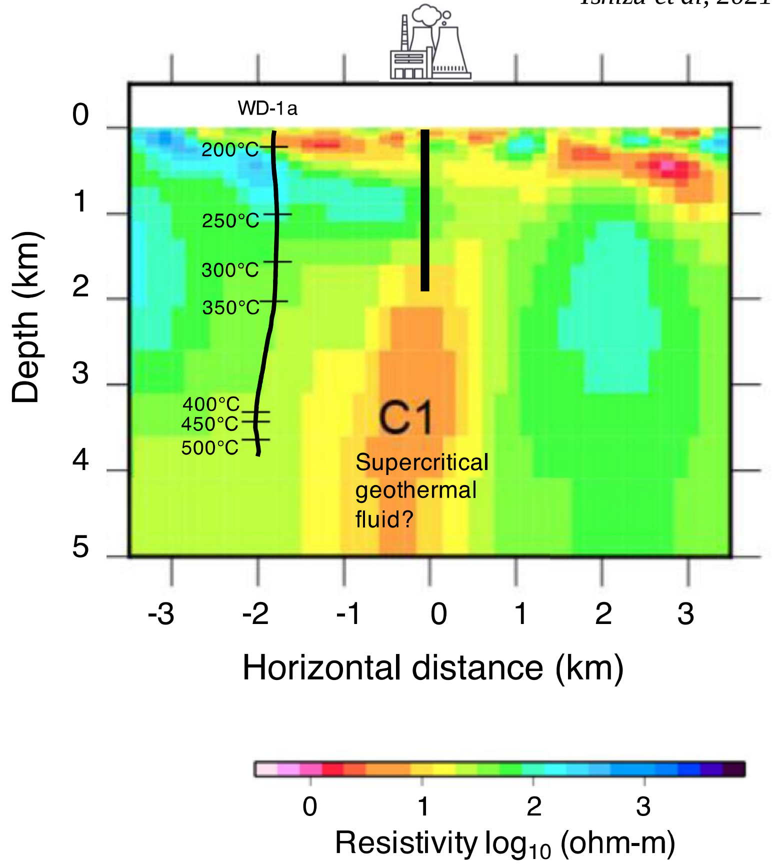
Nurhasan et al, 2006

- ≤1 S/m conductors present at 2–4 km depth beneath **all** surveyed volcanoes
- Located below the convecting hydrothermal system and its clay cap
- Lenses of hot, electrically-conductive, metal-rich brines

Geothermal energy



Ishizu et al, 2021

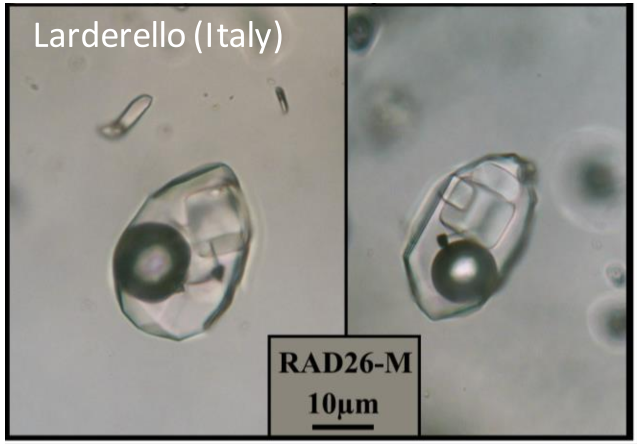


Kakkonda power plant, Japan (50 MW)
89,000 yr-old granite heat source
Potential supercritical geothermal site (100 MW)

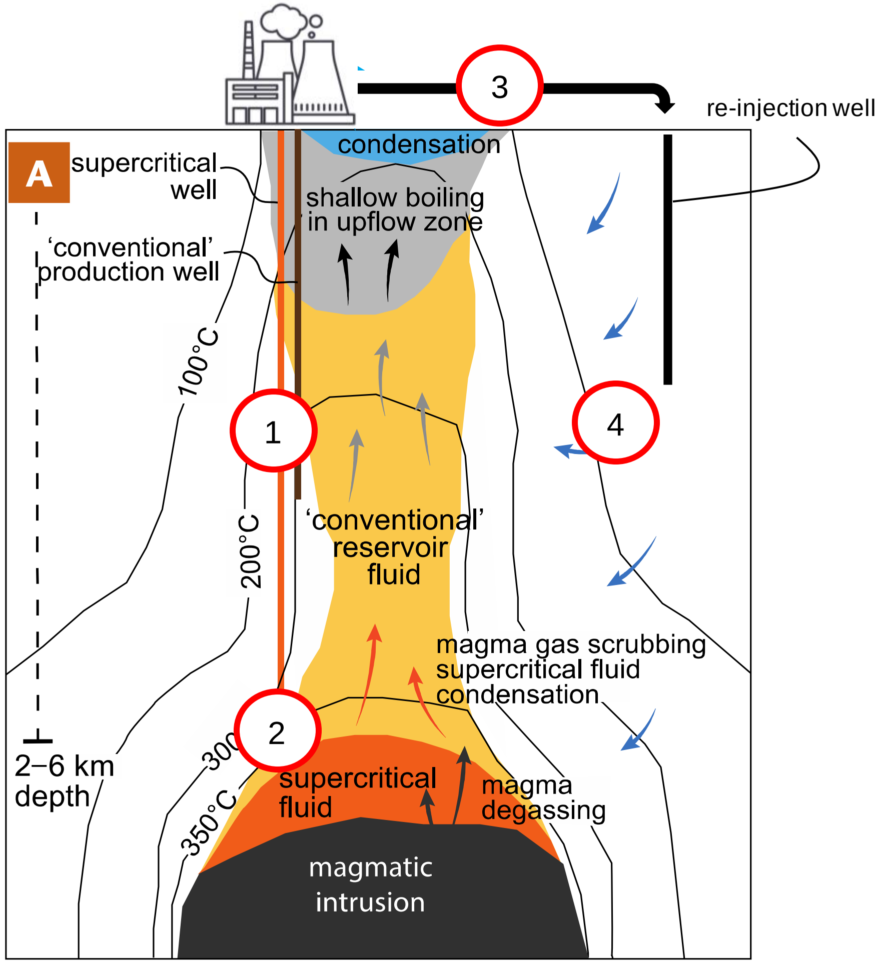
- **Baseload renewable** energy; high capital costs
- Major **electricity** source in Iceland, New Zealand, Philippines, Indonesia, Kenya…
- Does not require active or dormant volcanoes (Tuscany, Salton Sea, Kakkonda)
- **Supercritical** Geothermal System ≤10 times more joules per kg of fluid
- Can energy and metals be co-recovered economically?

Disruptive strategies for metals recovery

1. Mechanical extraction of mineral scales



2. Down-hole metals capture from fluids

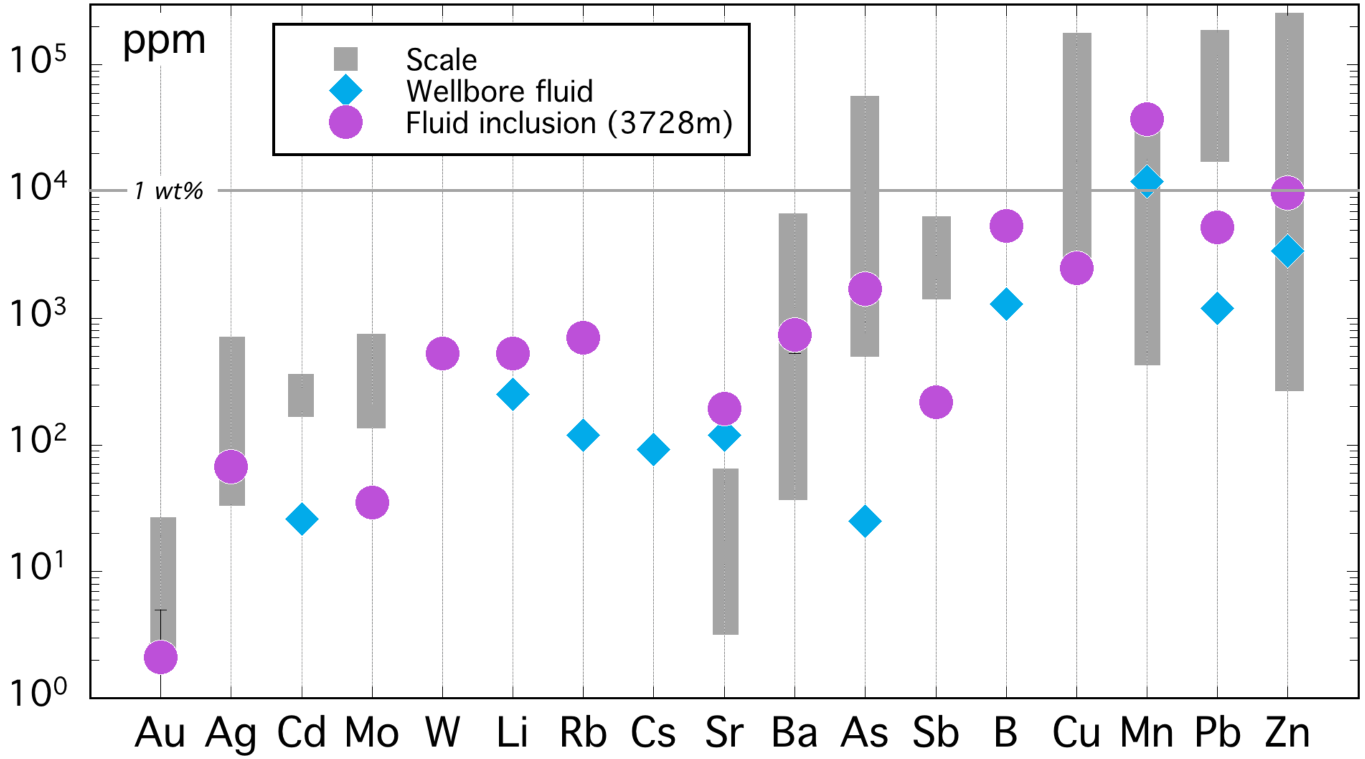


3. Processing of spent geothermal fluid

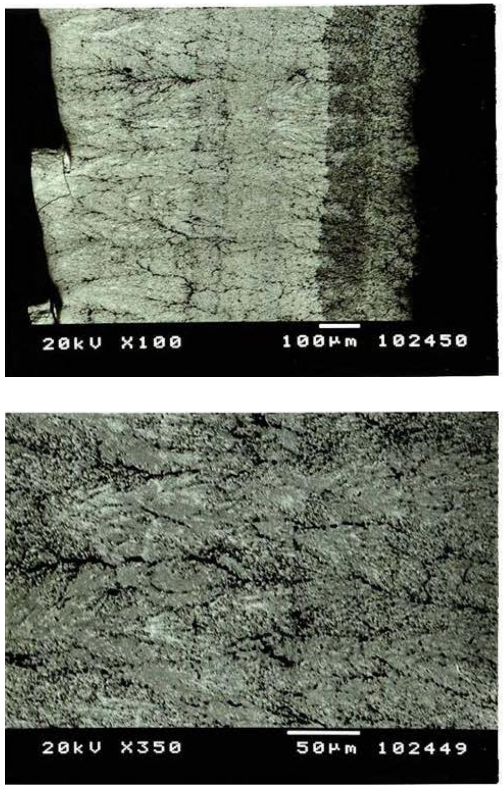
4. Reservoir in-situ leaching using re-injected fluids

1. Mechanical extraction of scale

- Solute precipitation during fluid extraction to surface
- Mostly SiO_2 + sulfide/sulfates, carbonates
- Polymetallic 'high-grade ore' – potential feedstock
- Well-bore scales conventionally dissolved away to maintain productivity
- WD1a brines (55 wt% $NaCl_{eq}$) recovered at 3700 m

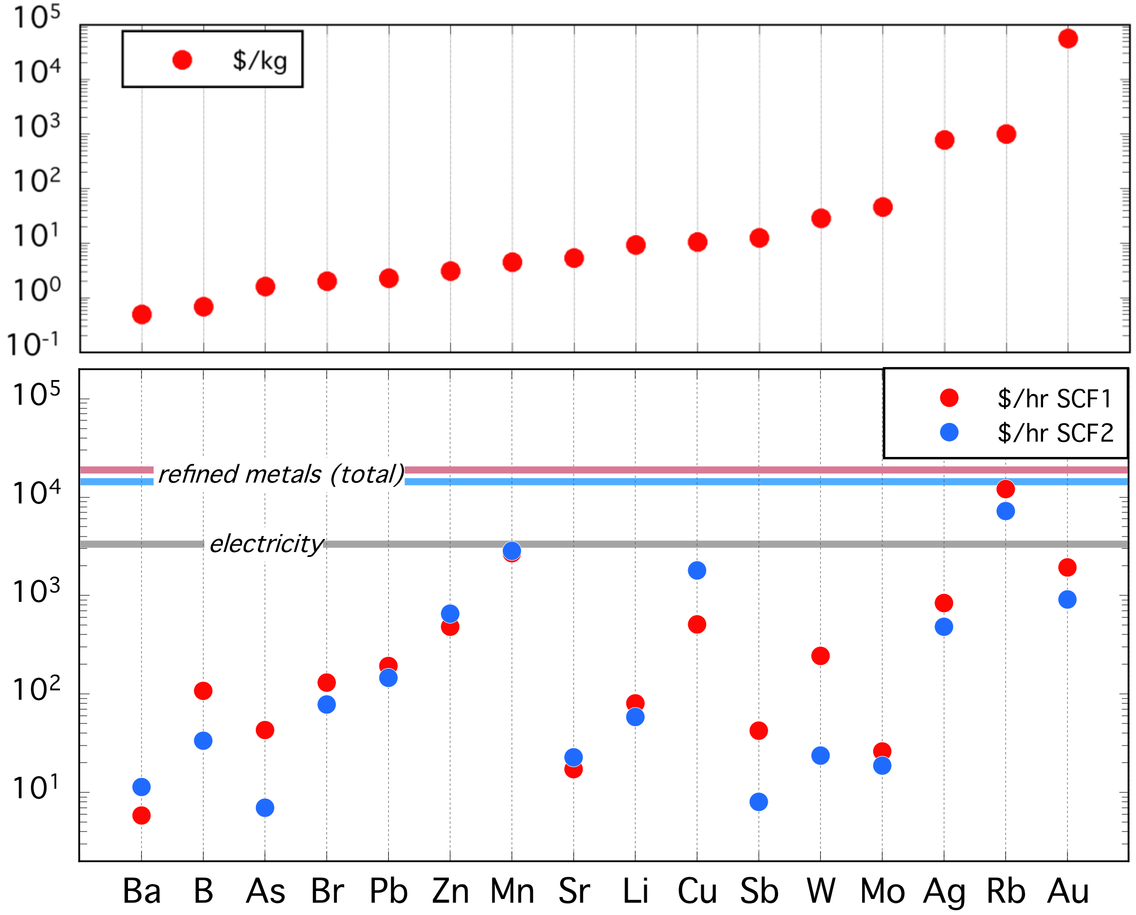


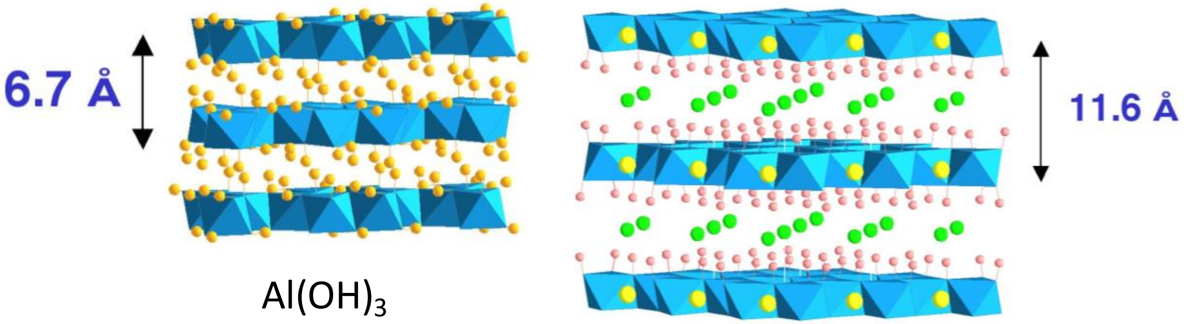
Yanagisawa et al, 2000; Kasai et al, 1998

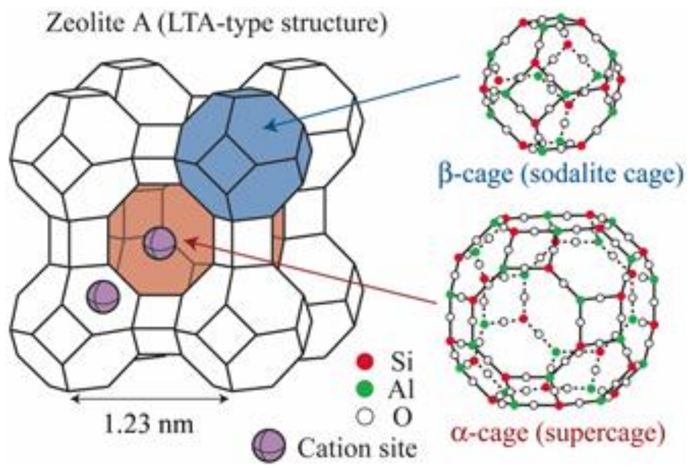


(b)1999 : Tetrahedrite (dendritic growth)

2. Down-hole metals sequestration







- Supercritical fluid (SCF - 8% $NaCl_{eq}$): 500 °C, 35 MPa, **200 t/hr** per well
- Value: current *refined* metal prices, $0.10/kWh electricity
- Down-hole chemical modification of produced fluids
- Precipitation of metal-sequestering **smart materials**: silicates, zeolites, gibbsite

Engineering and Physical Sciences Research Council

3. Spent geothermal fluid processing

- Ohaaki-Broadlands 100 MW geothermal plant, New Zealand
- World-first, commercial plant processes 6,300 tonnes of geothermal fluid per day
- 650 ppm silica dissolved in spent fluids >90 °C, delivered via side-spur to injection well
- Recovers up to 330 tonnes per month of 4-14 nm colloidal silica particles
- Applications: construction, coatings and adhesives, precision casting, pulp and paper…
- Prelude to lithium, boron and antimony recovery

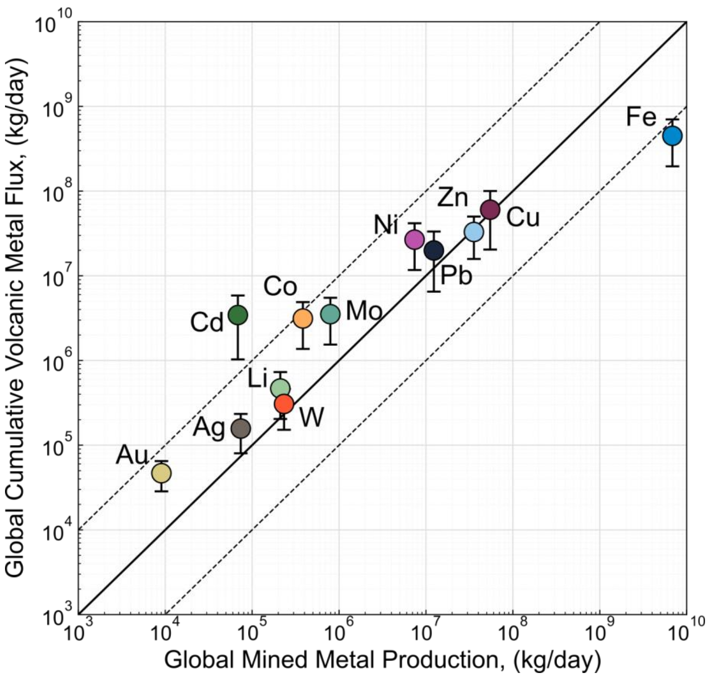
4. Reservoir *in situ* leaching

Volcanic tuffs

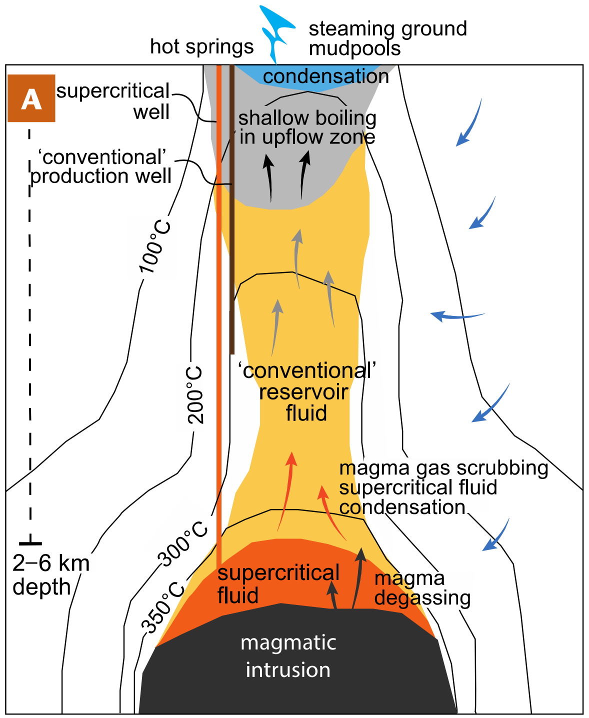
	Ethiopia	Altiplano	NZ
SiO_2	72%	78%	76%
Li	31	840	24
B	-	113	20
Rb	156	596	110
Cs	1.5	580	3.6
U	8	17	2
Ba	397	264	875
Sn	13	46	2
Zn	475	70	39
Zr	1655	67	172
Hf	42	2	3
Nb	264	20	9
Ta	16	7	2
Ce	475	30	55
Pr	52	-	5.3
Nd	215	14	19
Tb	6.5	0.3	0.7
Dy	38	2	4
Y	190	9	26

- Three main acid tuff varieties with variable metals endowment – different tectonic settings
- Metals dissolved in volcanic glass; *in situ* leaching by hot (acid) fluids in the reservoir
- Inhibition of sulfide, phosphate etc precipitation by dosing re-injected fluids
- Potential new source of rare earths

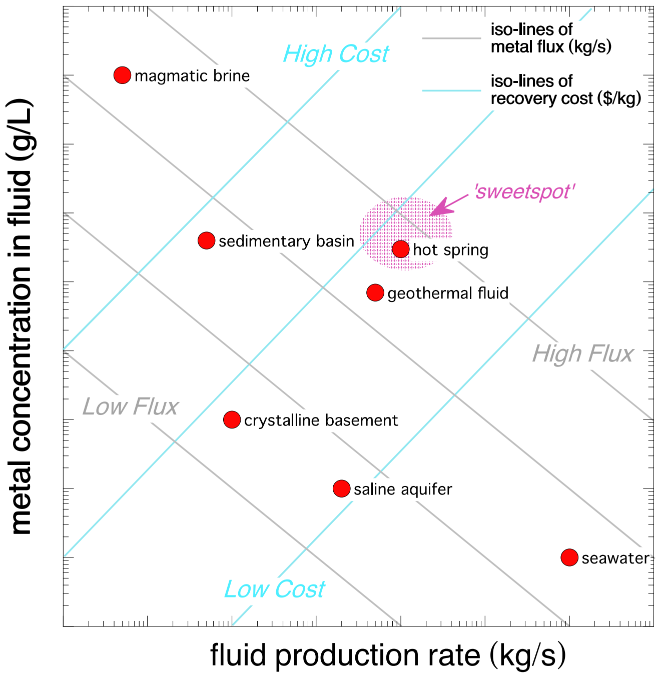
Magmatic Metals



Geothermal Energy



Geofluids Resource Landscape



Thank you for your attention

Oxford Martin Programme on Rethinking Natural Resources