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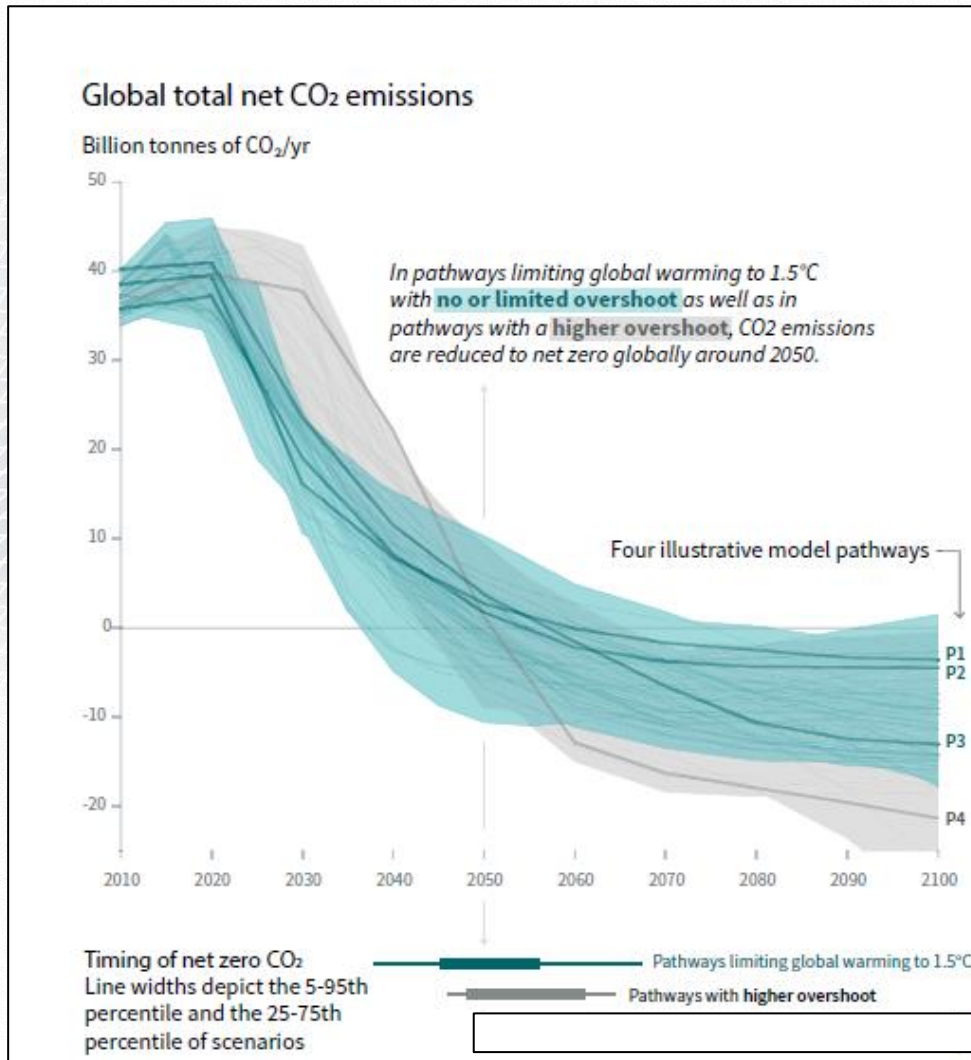
Gateway to the Earth

The geology of decarbonisation

Kathryn Goodenough



Why decarbonisation?



- Figure from the IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels
- Shows global emissions pathways required to keep warming at these levels
- All scenarios require decarbonisation of energy and transport

Decarbonisation of energy and transport



End of the diesel and petrol car

All new vehicles must be fully electric by 2040

Ben Webster Environment Editor

Sales of new diesel and petrol cars and vans will be banned from 2040, the government is to announce today.

The scrapping of new hybrid vehicles that have an electric motor and a petrol or diesel engine will also end in a move that comes after a similar pledge this month by President Macron of France. Less than 1 per cent of new cars sold in Britain run only on electric power.

The ban is part of a government plan to improve air quality. It includes £250million to help local authorities to deal with toxic nitrogen dioxide (NO₂) from diesel vehicles. The decision about electric vehicles came at a meeting of the Royal College of Physicians last year, which said that it had "neither sought nor received" reassurances from ministers on trade arrangements after Britain leaves the EU.

In a further boost after Brexit, Donald Trump promised to strike a "major" trade deal with Britain, leading to the creation of more jobs.

Under plans to be outlined today by Michael Gove, the environment secretary, diesel cars will be made to meet a new, more stringent legal limit for NO₂ by 2040. Two weeks ago the government said that, for this target to be achieved, sales of new petrol and diesel cars would need to stop in 2040.

The scrapping plan, announced today is part of a £7-billion programme, of which £2.7 billion had already been revealed including £1 billion in grants. Continued on page A C11

It is councils to decide how to tackle the problem, appointing air-quality campaigners, who say that the only effective measure is to require cities to impose entry fees on diesel drivers.

The plan will include a commitment to hold a consultation on a scrapping scheme for older diesel vehicles that will have few details on how it might be funded. Mr Gove will announce that a "comprehensive clean-air" strategy to tackle the full range of pollutants will be published next year.

The High Court ordered the government to publish today's plan after ruling that a previous version failed to comply with an EU directive to reduce emissions in the "shortest possible time". A report by the Royal College of Physicians last year estimated that air pollution — linked to cancer, asthma, stroke and heart disease, diabetes, obesity and dementia — caused 40,000 premature deaths a year.

The announcement comes two weeks after Mr Macron pledged to outline the sale of vehicles that use an internal combustion engine from 2040. The government's commitment to a similar ban is a strengthening of its previous position. The Conservative manifesto stated: "We want almost every car and van to be zero-emission by 2040".

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The scrapping plan, announced today is part of a £7-billion programme, of which £2.7 billion had already been revealed including £1 billion in grants. Continued on page A C11



Shaham, not detained Daniel Craig is expected to play James Bond for a fifth time, having said that he would rather slash his wrists than take the role again. Page 7

The Economist

Electric cars

The death of the internal combustion engine

It had a good run. But the end is in sight for the machine that changed the world

ENVIRONMENT SECRETARY Michael Gove will today reveal plans to ban sales of new petrol and diesel cars by 2040 to reduce toxic air pollution.

BY MICHAEL GOVE

It is a landmark moment in the history of the car. The internal combustion engine, which has powered the world for more than a century, will be phased out. The ban will mean that by 2040, only electric cars will be sold in Britain. The government will also introduce a "clean air" strategy to tackle the full range of pollutants.

1892 Date first petrol car was built in Britain

Foolish to punish us

BY NICK FRANCIS

It is a pity that, as a result of the ban, the government will be punishing us for the sins of our fathers. The ban will mean that by 2040, only electric cars will be sold in Britain. The government will also introduce a "clean air" strategy to tackle the full range of pollutants.

End of the road for gas guzzler motors

2040 ban part of plan to slash pollution

users face last gasp clobbering

BY MICHAEL GOVE

It is a landmark moment in the history of the car. The internal combustion engine, which has powered the world for more than a century, will be phased out. The ban will mean that by 2040, only electric cars will be sold in Britain. The government will also introduce a "clean air" strategy to tackle the full range of pollutants.

CARMAGEDDON





“A transition to a low-carbon society, a change that will require vast amounts of metals and minerals. Mineral resourcing and climate change are inextricably linked..... because the world cannot tackle climate change without an adequate supply of raw materials to manufacture clean technologies”

Ali et al., 2017, Nature

Raw materials for decarbonisation



Magnets in motors

- Neodymium
 - Dysprosium
 - Praseodymium
- } **REE**



Solar panels

- Gallium
- Indium
- Tellurium
- Selenium
- Copper

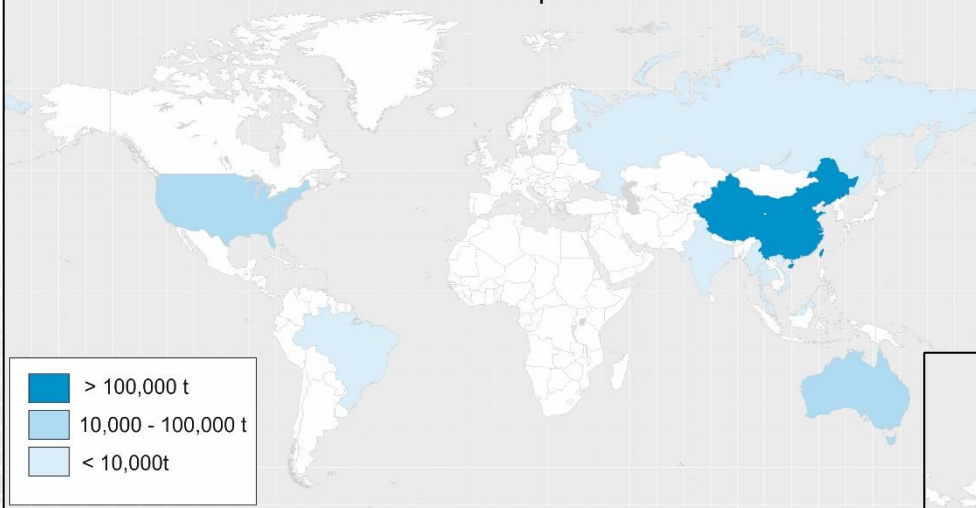


Batteries

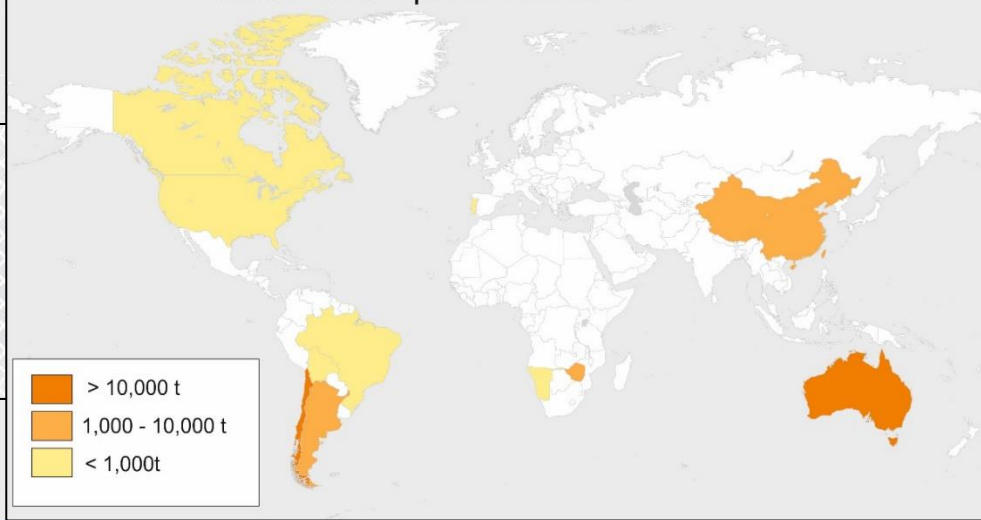
- Lithium
- Cobalt
- Graphite
- Nickel
- Manganese

Where do these critical raw materials come from?

Global rare earth oxide production 2018

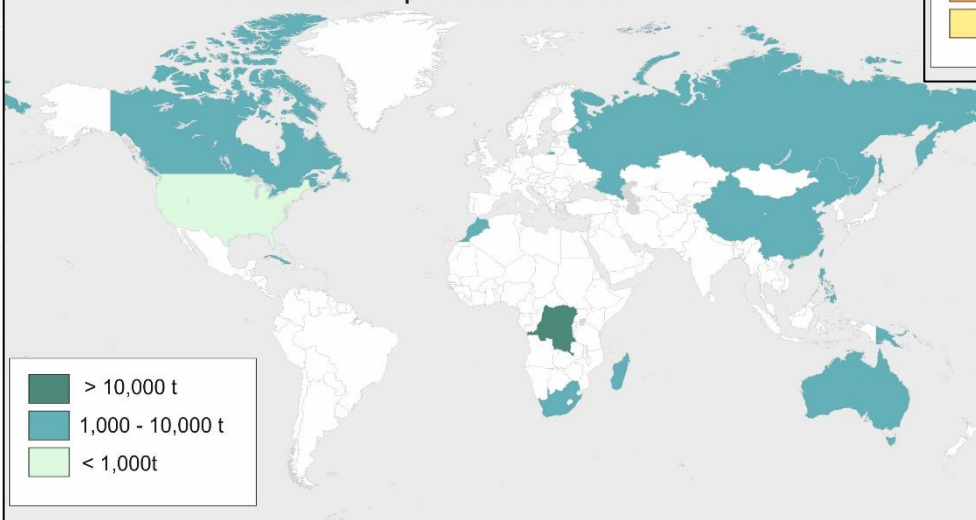


Global lithium production 2018



Figures from USGS

Global cobalt production 2018



Many factors affect the location of critical metal mines, but the most fundamental is the geology

Controls on ore deposits: the mineral system

- Enriched source (mantle or crust)
- Emplacement of elements into the crust
- Focusing/ trapping of the elements
- Exposure at or near the surface
- Enhancement/preservation through weathering and erosion

Controlled by tectonic/ magmatic processes

Controlled by surface processes

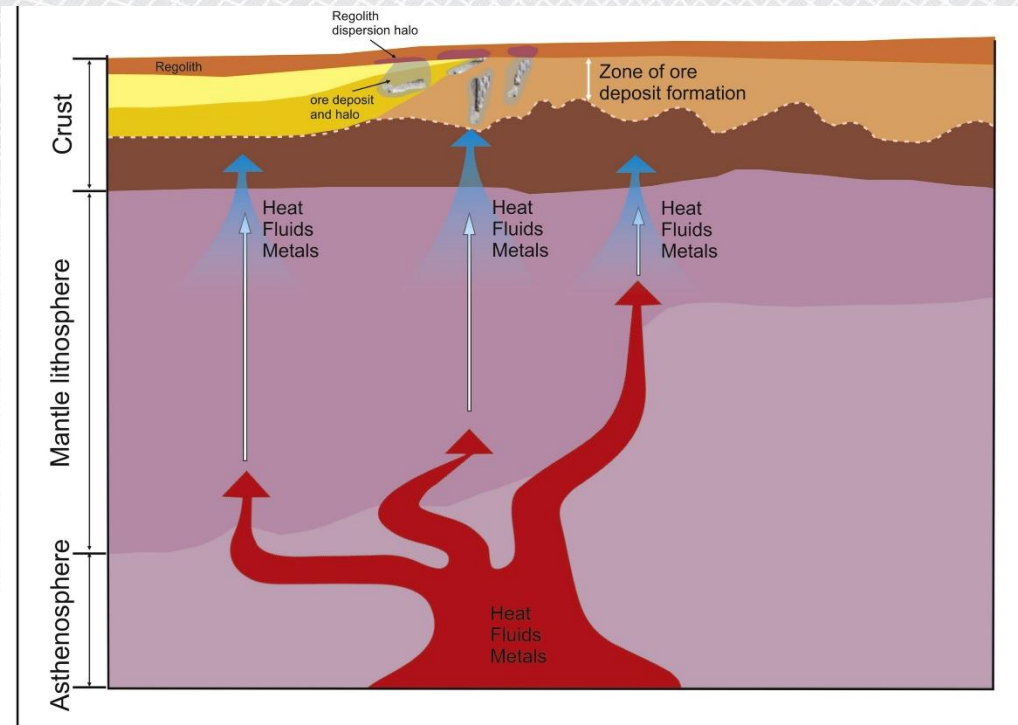
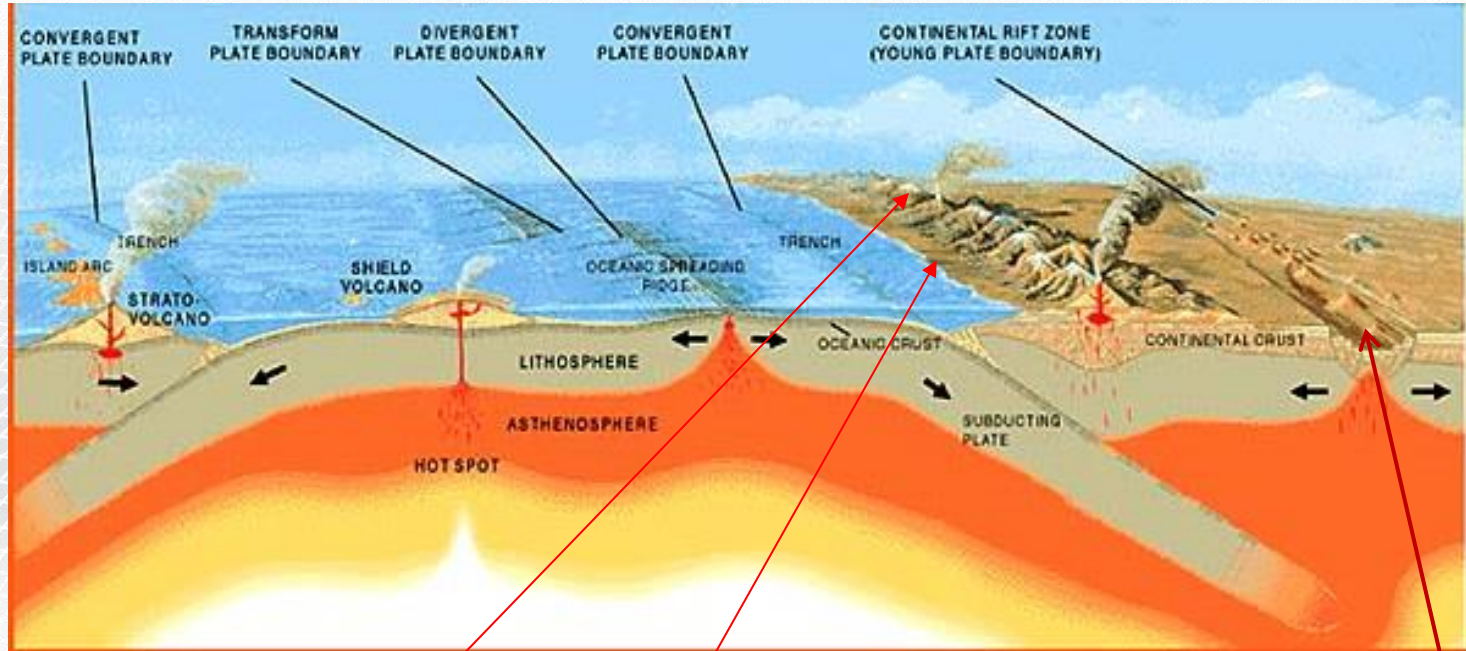


Figure from
Champion & Huston 2016,
Ore Geo Rev

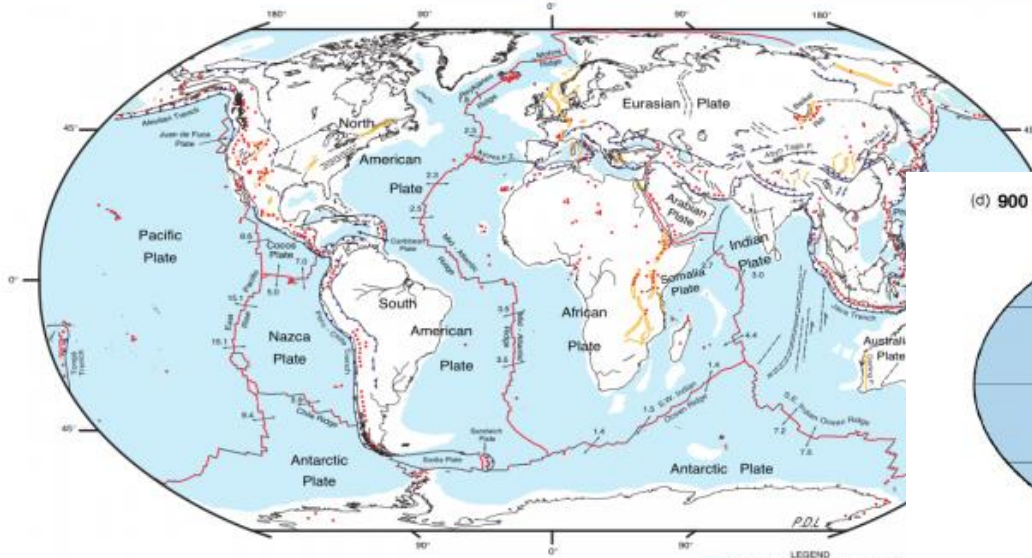
Tectonic setting of deposits: the simple view



Li deposits – associated with collisional settings

REE deposits - alkaline igneous rocks & carbonatites in continental rift zones

Co deposits – marginal marine settings (sediment-hosted, hydrothermal)



GLOBAL TECTONIC ACTIVITY MAP OF THE EARTH
Tectonism and Volcanism of the Last One Million Years
DTAM - 1



NASA/Goddard Space Flight Center
Greenbelt, Maryland 20771

Robinson Projection
 Mainly oceanic crust
 Mainly continental crust
 October 2002

- LEGEND
- Actively spreading ridges and transects
 - Total spreading rate, only/year
 - Major active fault or fault zone; dash location, or activity uncertain
 - Normal fault or rift; hachures on down
 - Reverse fault (overthrust, subduction
 - basins on upthrown side
 - Volcanic centers active within the last
 - generalized. Minor basaltic centers

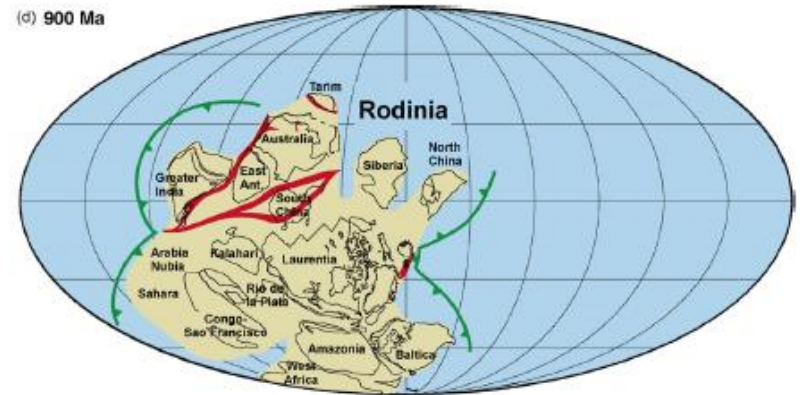
G821.001

Modern tectonics

VS

Past tectonics

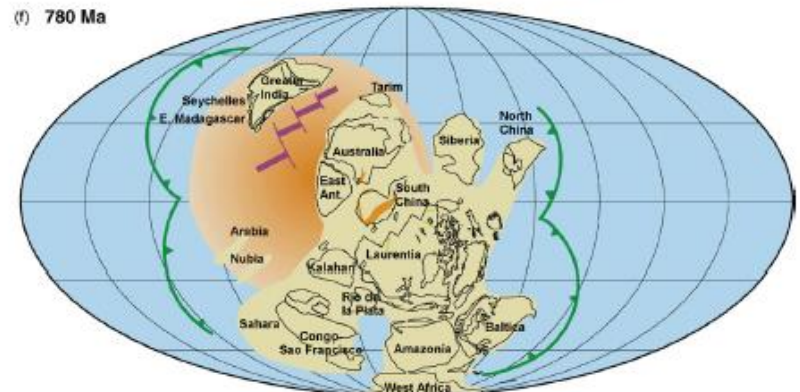
(d) 900 Ma



(e) 825 Ma



(f) 780 Ma



Types of primary REE resources

High-temperature deposits formed by magmatic and hydrothermal processes

- Alkaline igneous rocks
- Carbonatites
- Vein & skarn (hydrothermal)
- Fe oxide-apatite
- Granite & pegmatite

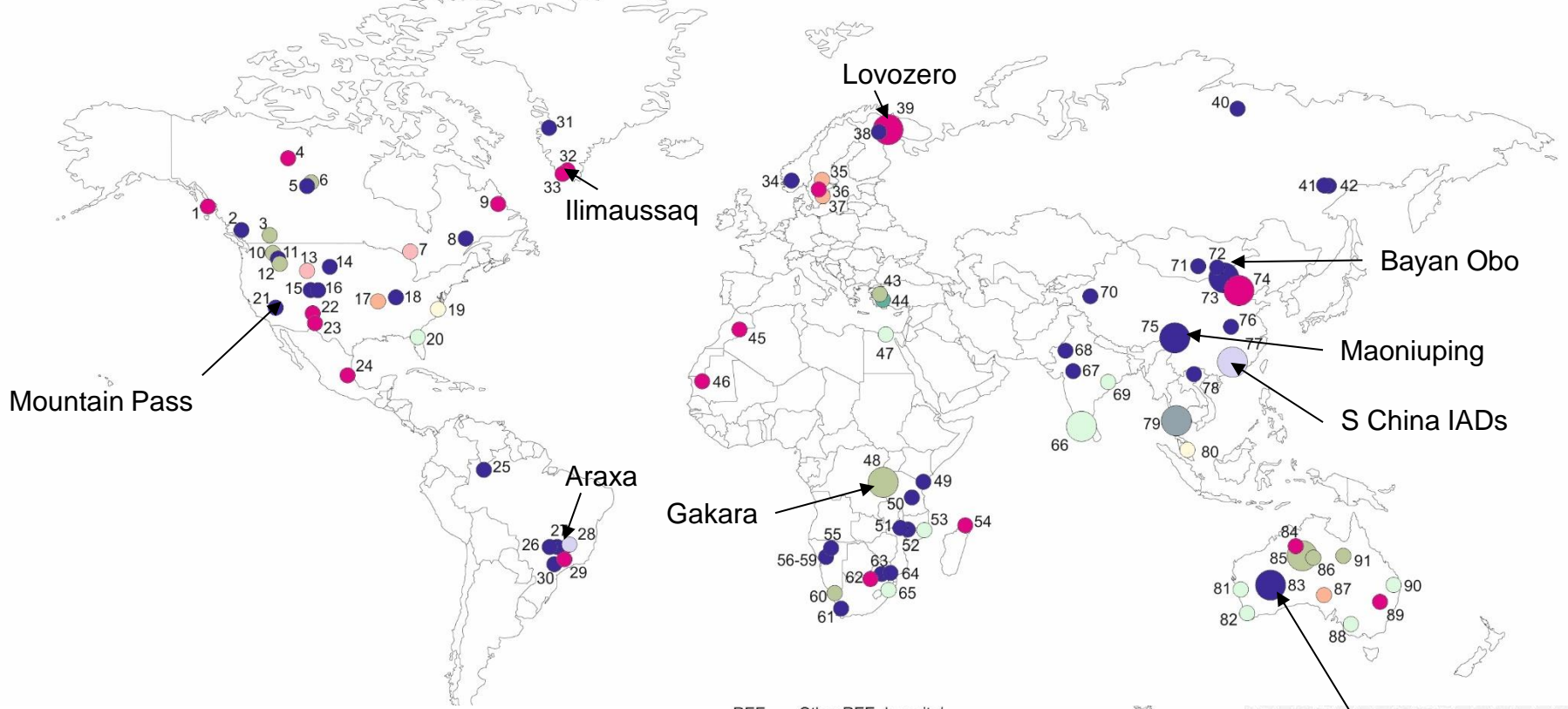


Low-temperature deposits formed by erosion and weathering

- Bauxites
- Placers
- Laterites & ion-adsorption clays
- Other deposits (phosphorites etc)



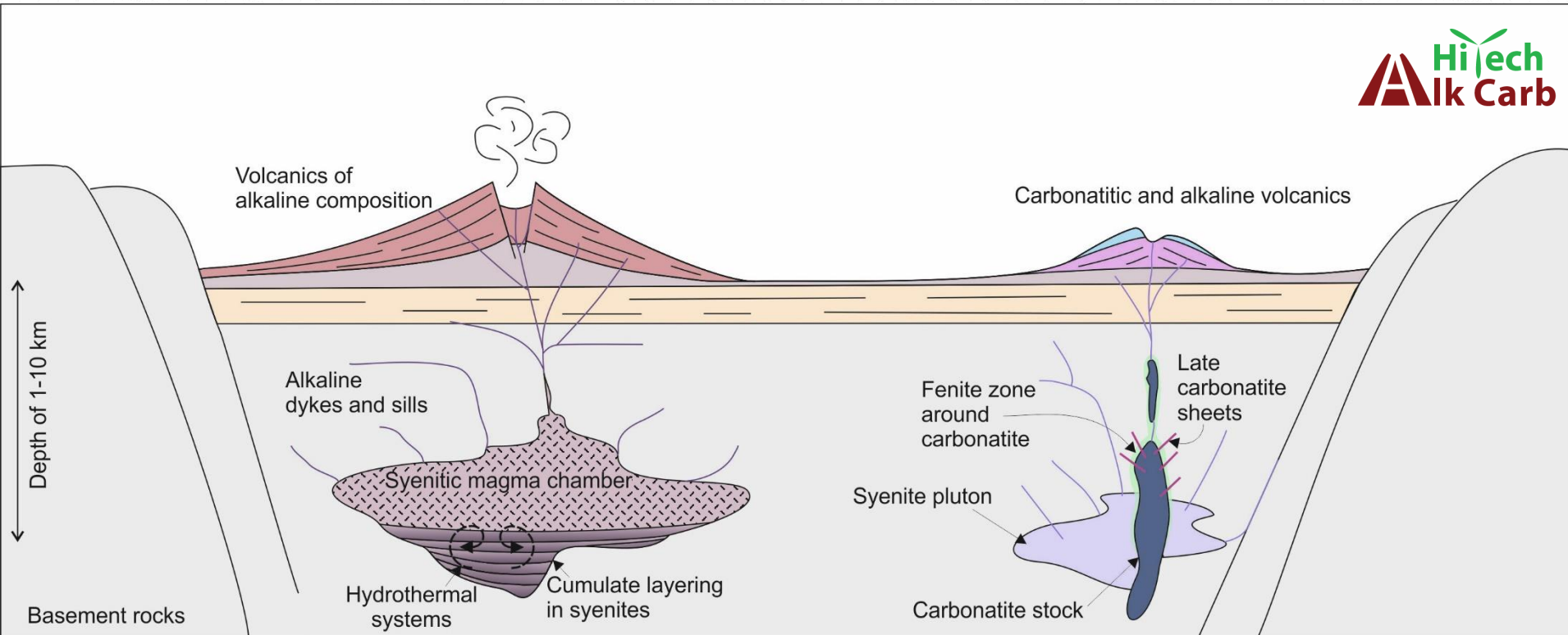
Global REE resources



Map after Elliott et al. 2018

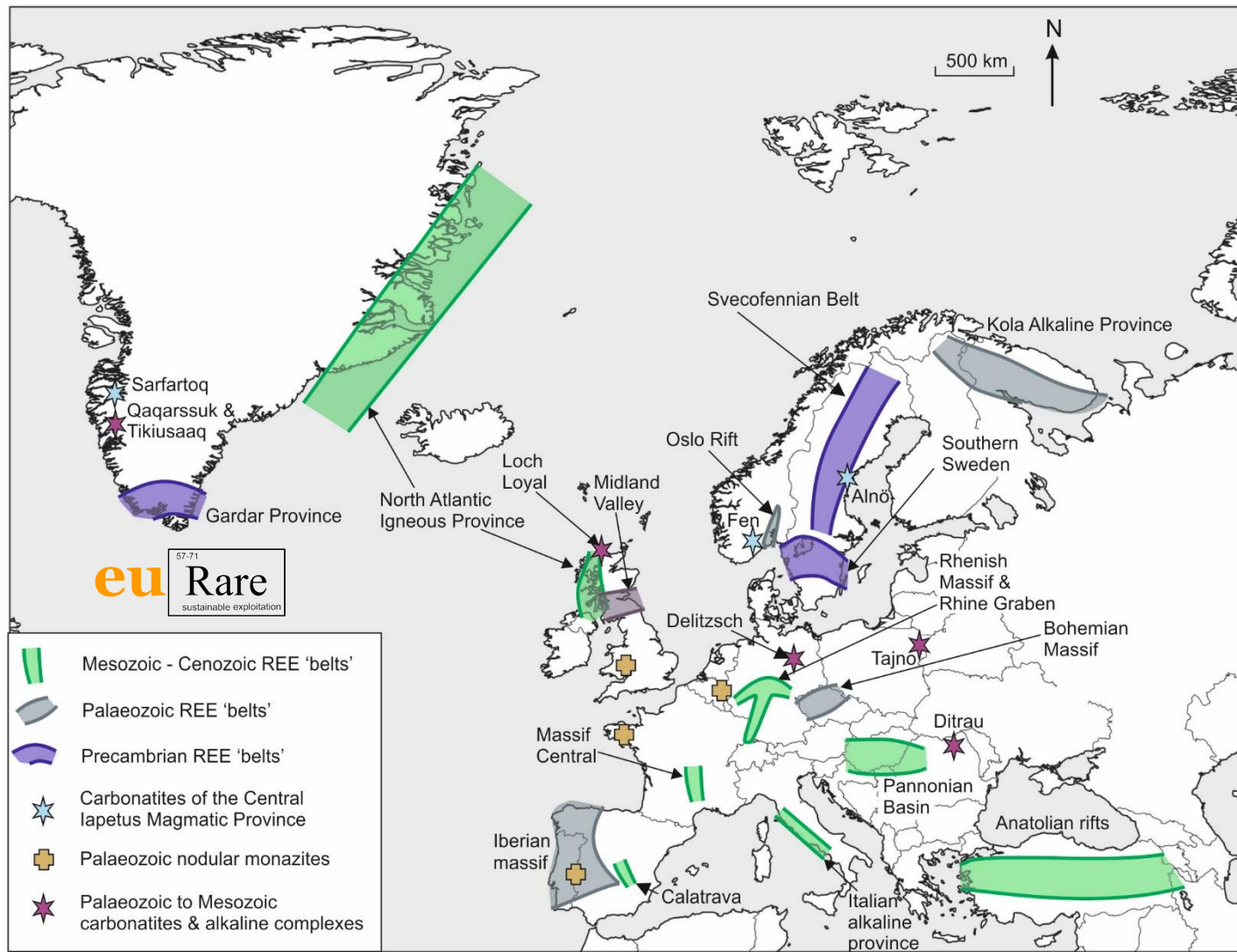
The rare earth elements are not rare!

- | REE mines | Other REE deposits/ occurrences | |
|-----------|---------------------------------|---|
| | | Carbonatite-associated |
| | | Alkaline igneous rock-associated |
| | | Iron-REE deposits |
| | | Hydrothermal deposits exclusive alkaline settings |
| | | Marine placers |
| | | Alluvial placers |
| | | Paleoplacers |
| | | Ion-adsorption clays |
| | | Ash-fall placers |
| | | By-product of tin mining |
- Primary deposits (Carbonatite-associated, Alkaline igneous rock-associated, Iron-REE deposits, Hydrothermal deposits exclusive alkaline settings)
- Secondary deposits (Marine placers, Alluvial placers, Paleoplacers, Ion-adsorption clays, Ash-fall placers, By-product of tin mining)



- Alkaline igneous rocks & carbonatites are often associated, most commonly in continental rift settings
- REE deposits in large peralkaline (agpaitic) undersaturated syenite intrusions, or in carbonatites and alkaline intrusions with carbonate metasomatism
- Other settings are available..... Especially post-collisional

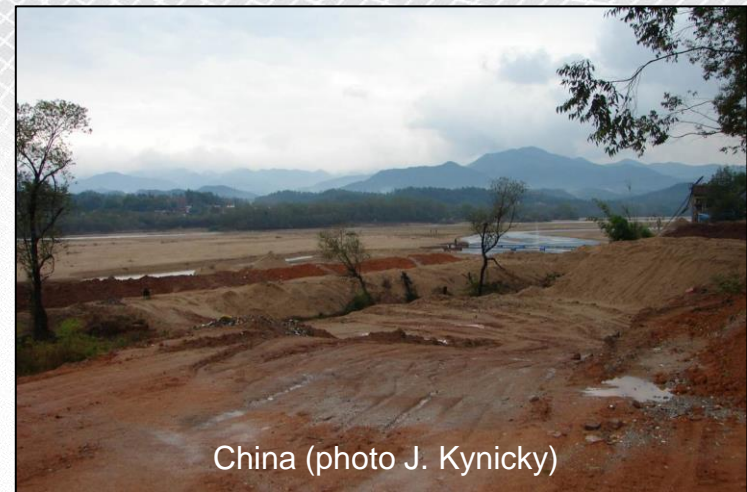
REE metallogenetic belts in Europe



Goodenough et al. 2016, Ore Geology Reviews

Importance of surface processes

- A large percentage of the world's REE come from weathered deposits or from placers
- Deposits are typically low-grade but can be large
- Processing and extraction of the REE from these deposits can be easier than from hard rock deposits
- Notably, placers and ion adsorption deposits with minable REE can occur in areas of very 'standard' geology – forming on granites



Ion Adsorption REE Deposits (IADs)

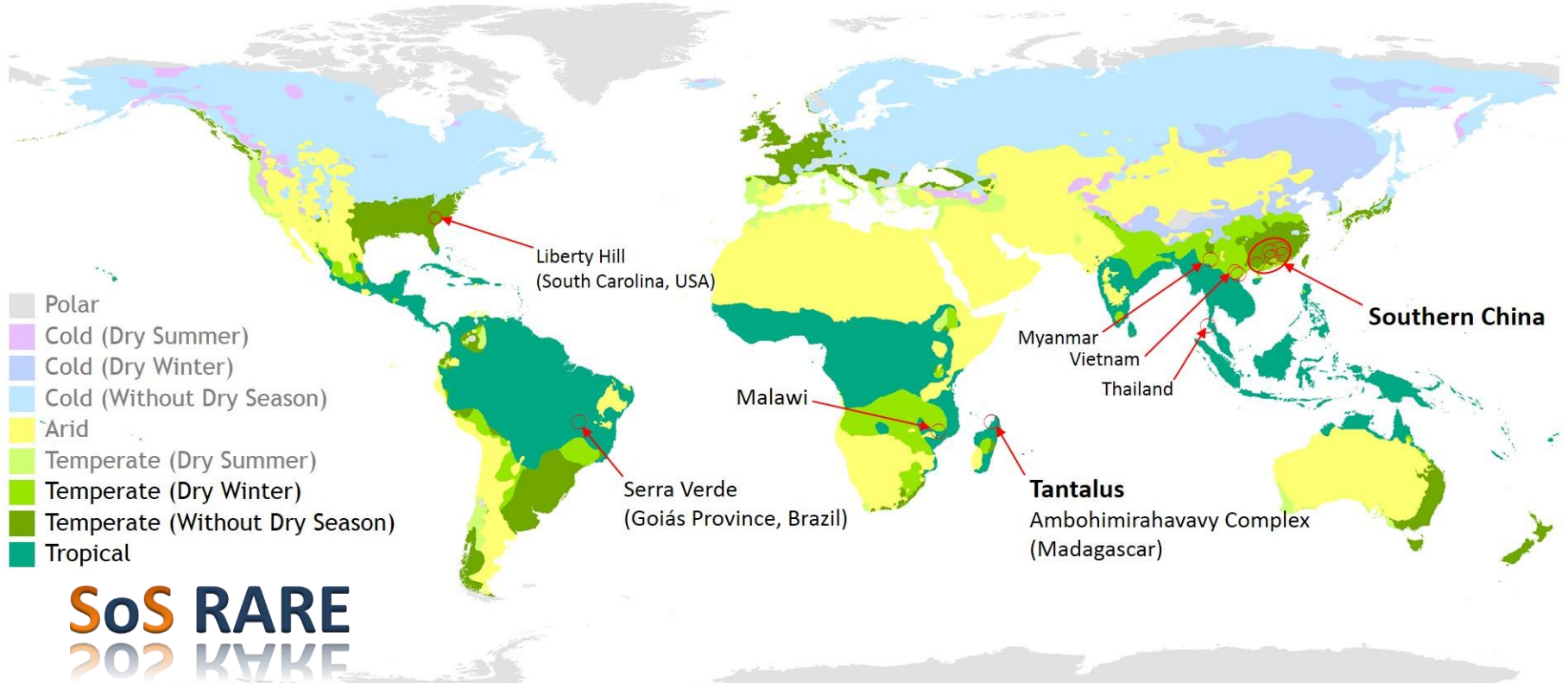


Diagram by Eva Marquis after Peel et al. 2017, Sanematsu & Watanabe 2016

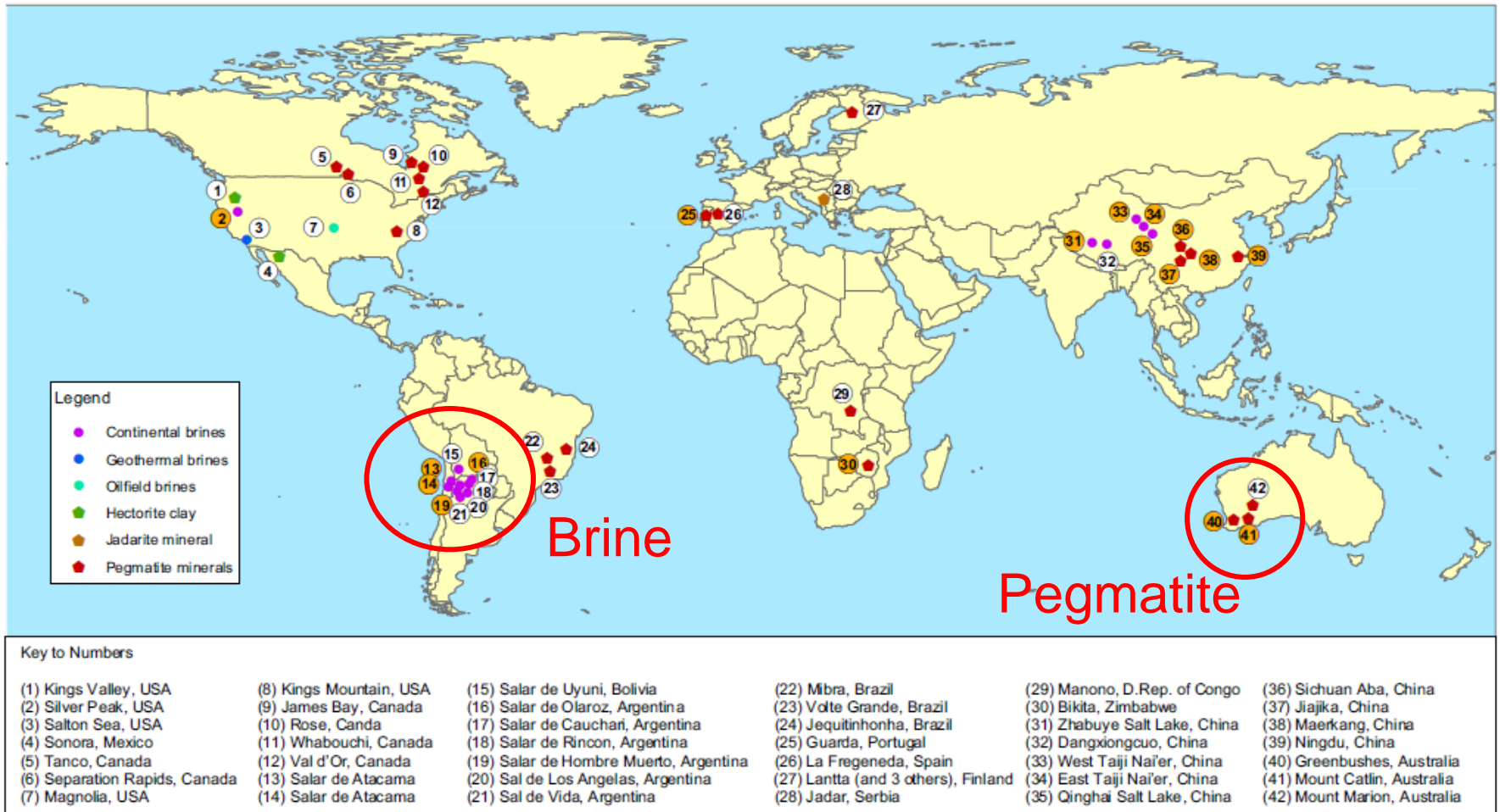
Formed in areas of temperate-tropical weathering
Main source of the world's HREE in Southern China,
increasing production elsewhere in SE Asia
Recovered by in situ or heap leaching

Types of primary lithium resources

- Pegmatite (hard-rock); around 50% of global production
- Evaporative brines, largely in South America; around 50% of global production
- Some other geothermal brines
- Clays (hectorite, jadarite)

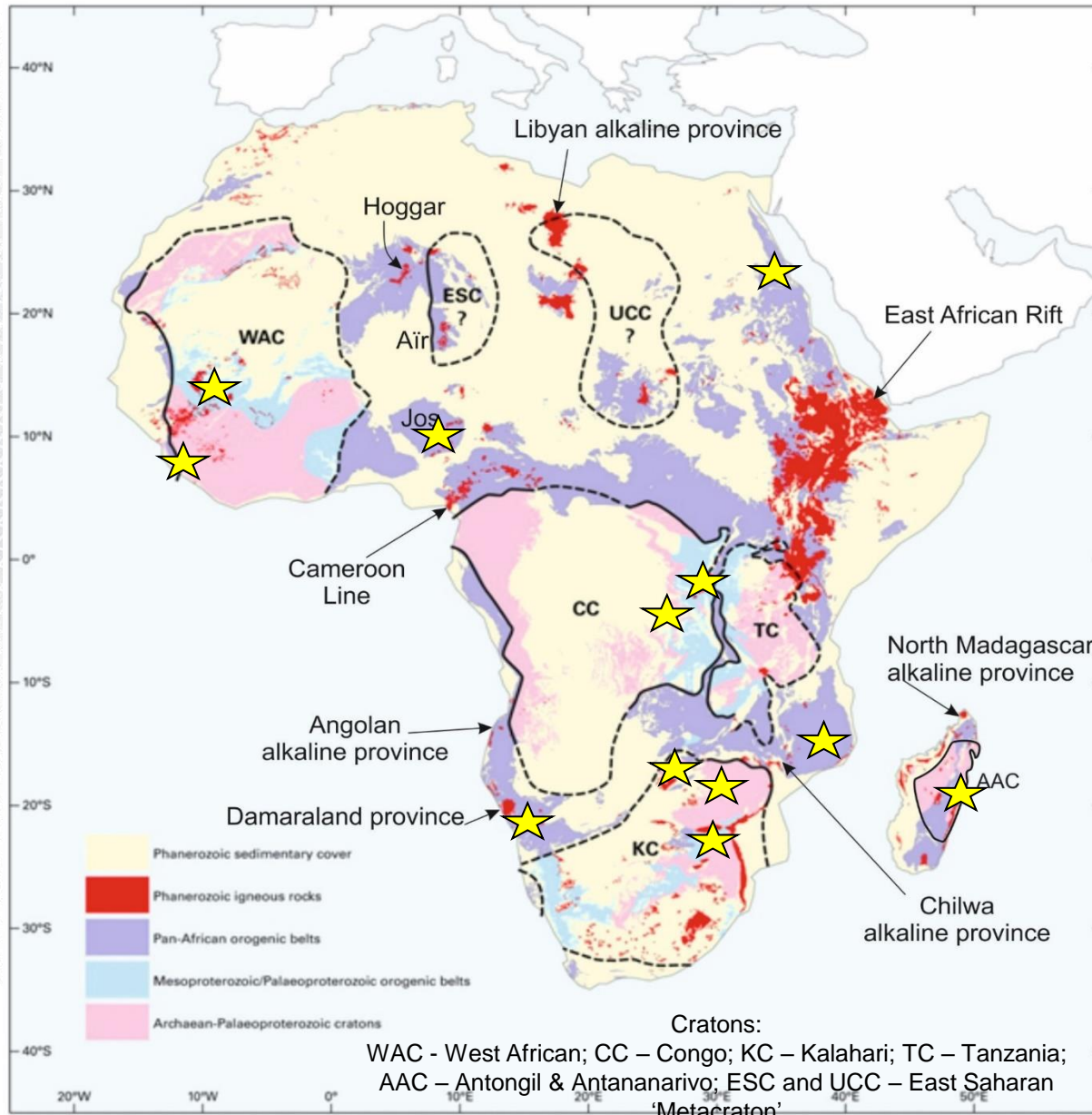


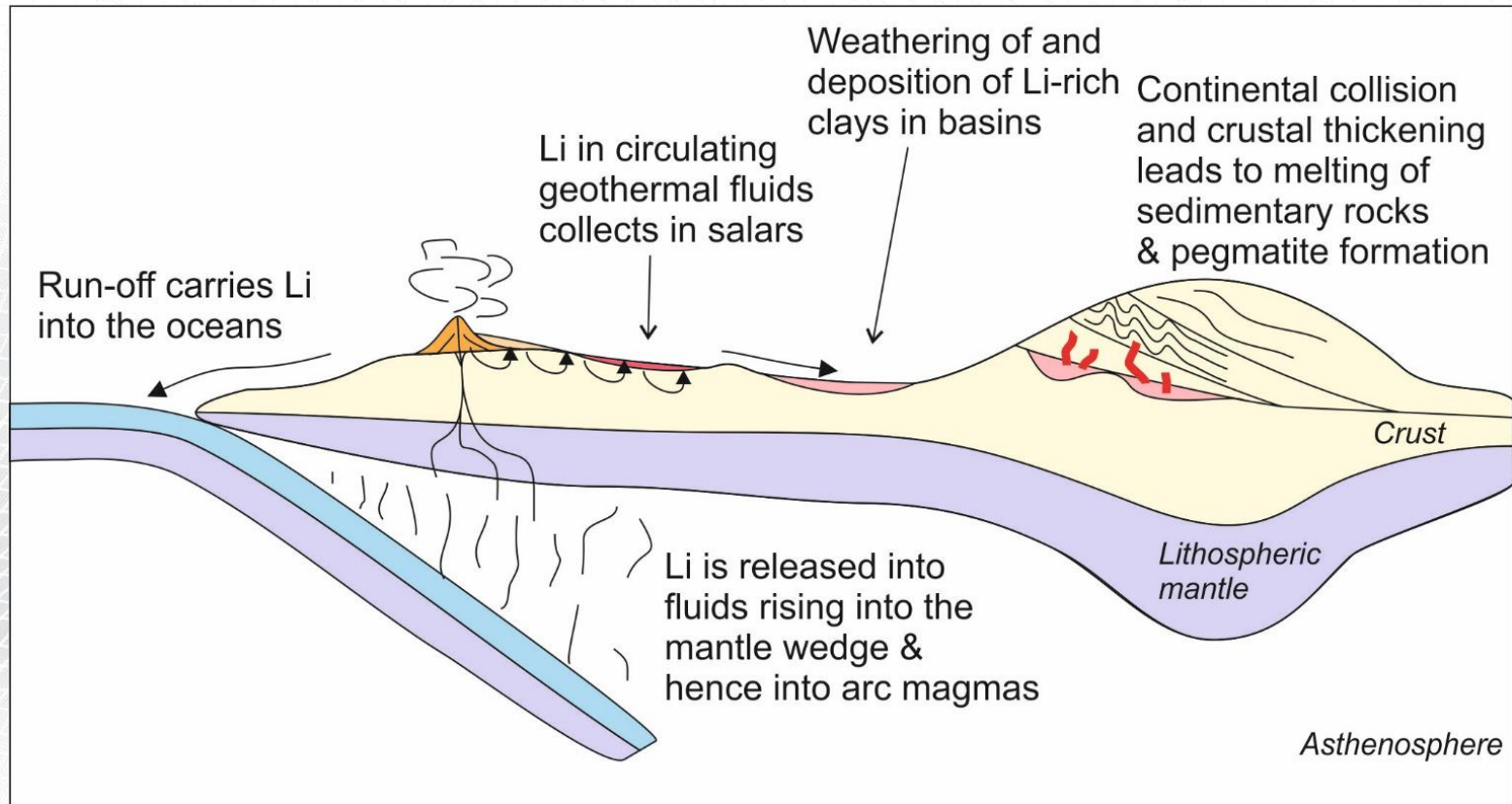
Lithium resources



Map from BGS Mineral Profile for lithium

LCT pegmatites in Africa





- Lithium deposits dominantly occur in areas of continental collision
- Both surface and tectonic processes interact to form deposits

Main pegmatite mineralisation

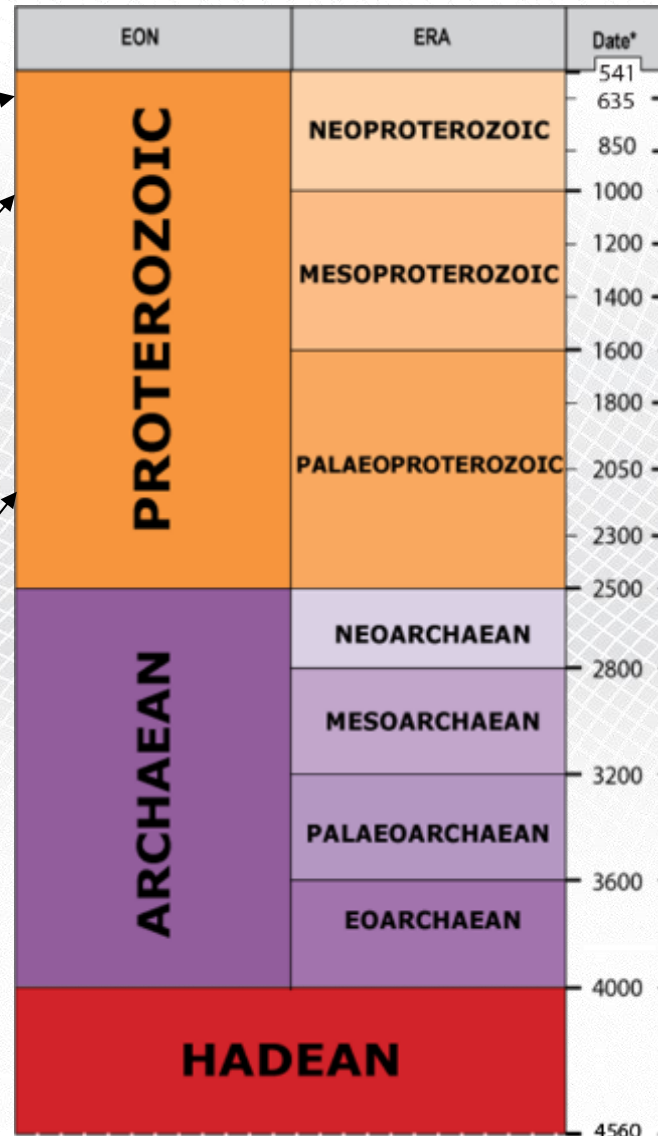
Main orogenic events

Pegmatites in Madagascar, Mozambique, Ethiopia, Nigeria

Extensive pegmatites (Rwanda, DRC, Zimbabwe, Namibia)

Some LCT pegmatites, eg Mali

Archaean pegmatites (Zimbabwe, SA, SL?)



Pan-African

Kibaran

Birimian/ Eburnean

Archaean orogenic events

Oldest life on Earth

Oldest rocks on Earth

Oldest zircons on Earth

Types of primary cobalt resources

- Sediment-hosted deposits (cobalt produced as a by-product of copper)
- Wide range of hydrothermal and volcanogenic deposits (polymetallic)
- Magmatic sulphide deposits (polymetallic)
- Laterite deposits (copper produced as a by-product of nickel)
- Seafloor nodules and crusts

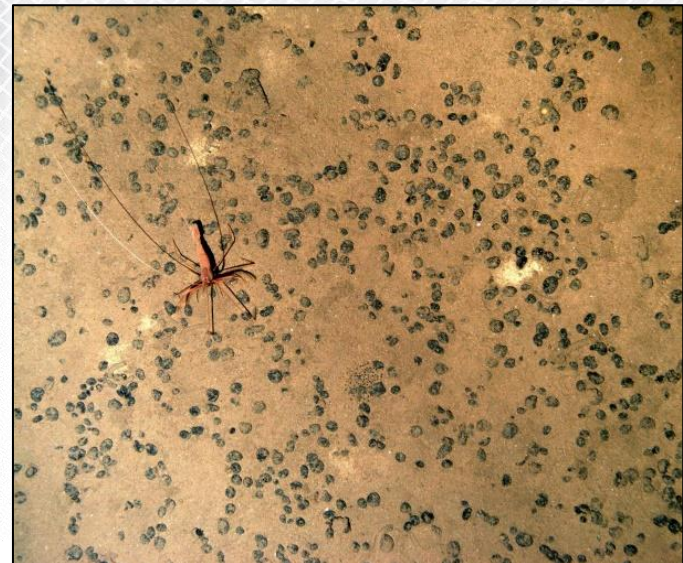


Photo from Pierre Josso

Conclusions

- Some of the most important critical metals for decarbonisation form in very different geological settings
- Plate tectonics at the time the mineralisation was formed provide a first-order control on where metallogenetic belts occur
- Surface processes (erosion, weathering, groundwater circulation) are also of crucial importance
- The talks to come will explore some of the details!

