Photograph 1995 © T.A. Moore

Coal as an unconventional ore: mining critical elements for a green economy

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KEY POINTS OF PRESENTATION

- What are Critical Minerals?
- What are they used for?
- Who produces them and what is market price?
- Does coal host any Critical Minerals?
- How do they occur in coal?
- Are they economic to extract from coal?

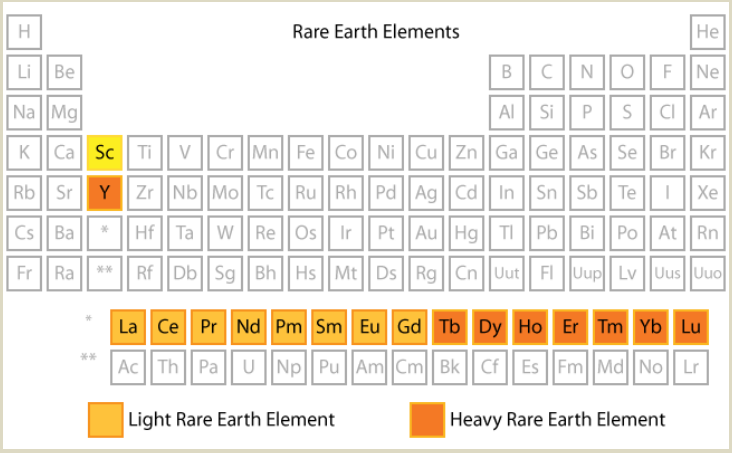
Some Clarifications in Terminology

Critical Minerals

Critical Elements

→ Used interchangeably to identify *minerals* or *elements*

Rare Earth Elements → A group of 15 elements in the periodic table known as the Lanthanide series. Rare earth Elements (REE) are categorised into light elements (lanthanum to samarium) and heavy elements (europium to lutetium). The latter are less common and consequently more expensive. (Sometimes Scandium & Yttrium are known as REE)



Germanium ingot sourced from coal fly ash from Seredin et al., 2013

What is a Critical 'Mineral'?

Geoscience Australia defines Critical 'Minerals' as:

"A critical 'mineral' is a metallic or non-metallic element that has two characteristics:

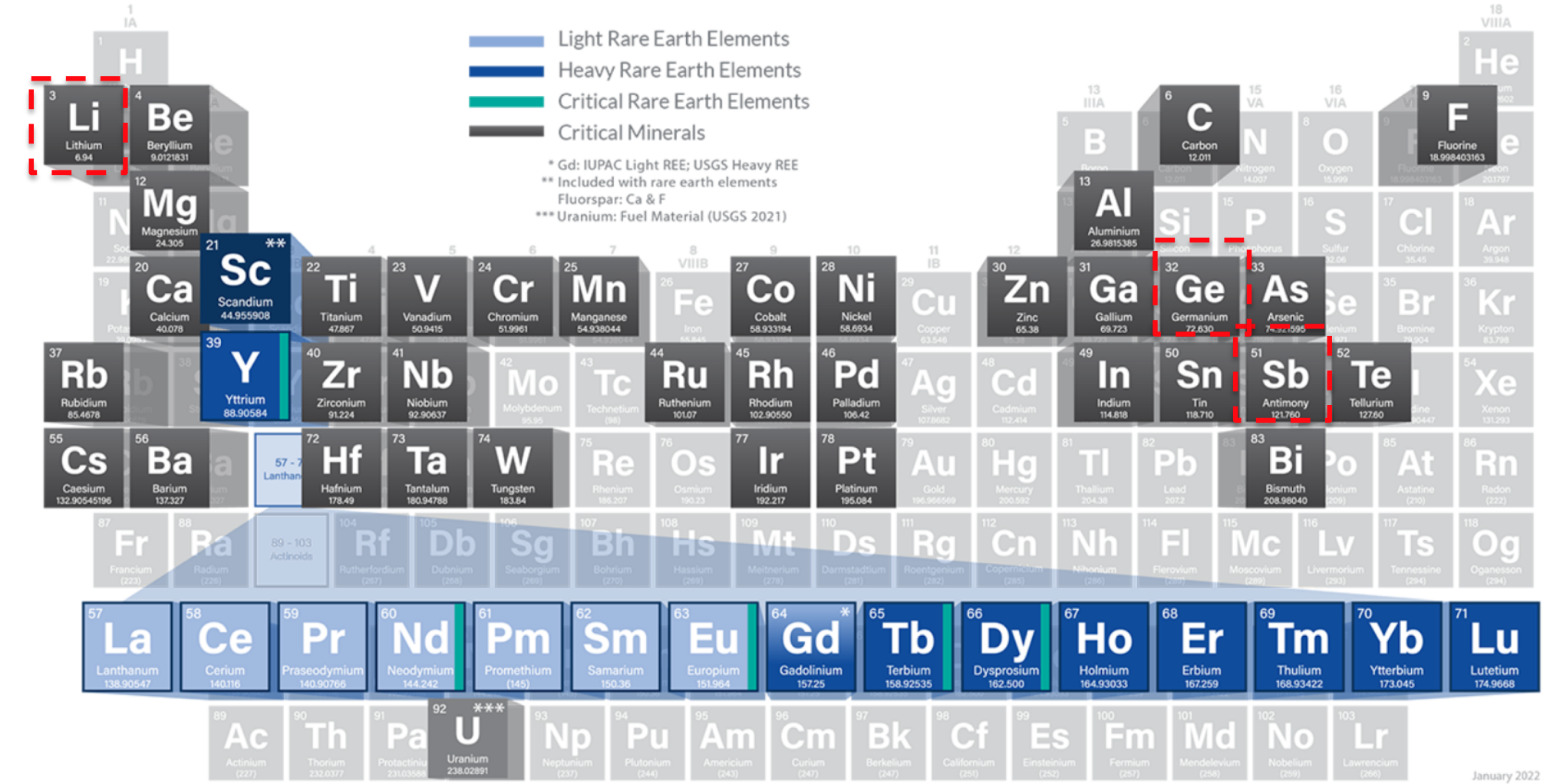
1. *It is essential for the functioning of our modern technologies, economies or national security and*
2. *There is a risk that its supply chains could be disrupted."*

Germanium ingot sourced from coal fly ash

from Seredin et al., 2013

https://www.ga.gov.au/scientific-topics/minerals/critical-minerals

Critical Elements



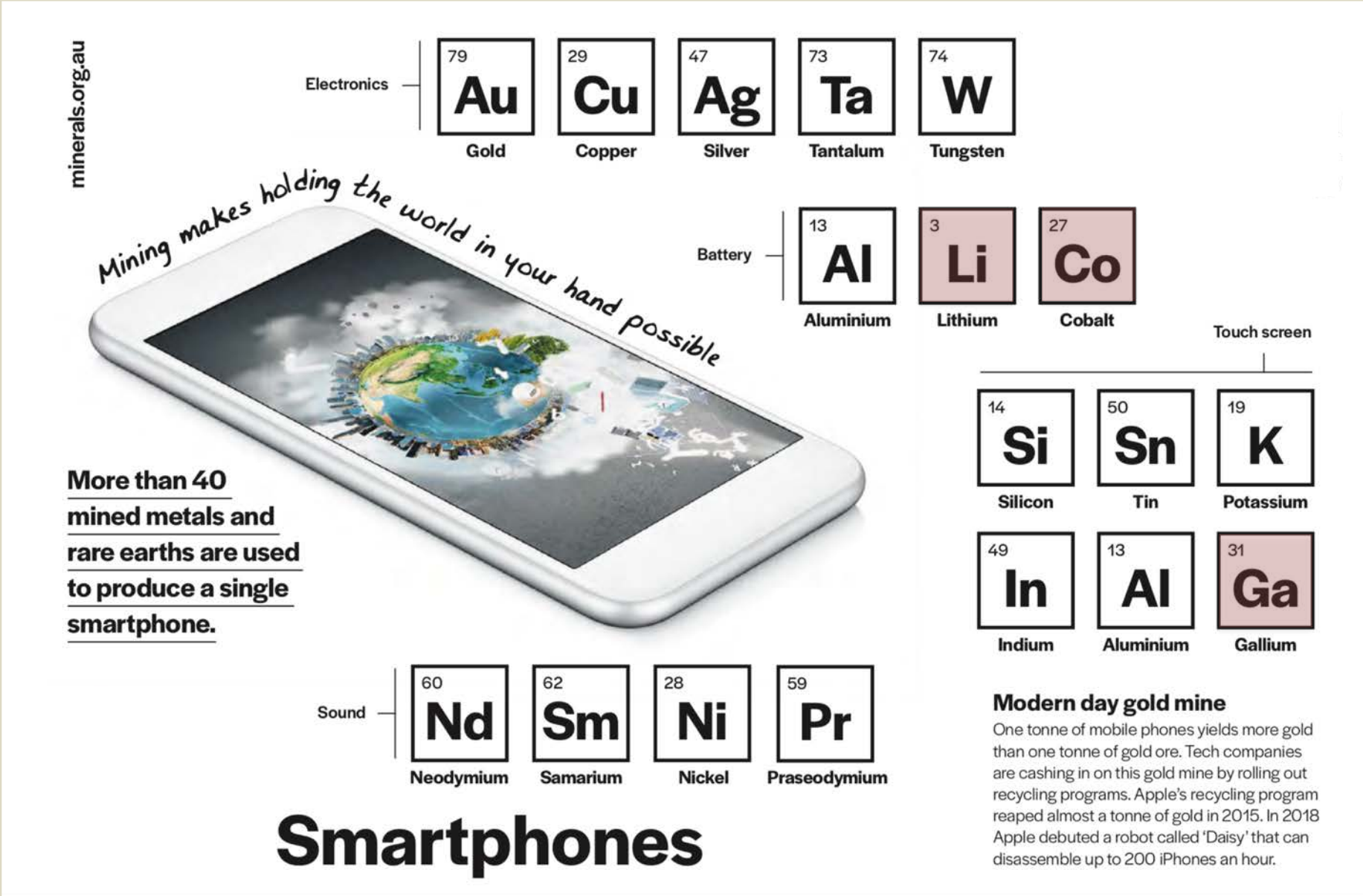
From: https://netl.doe.gov/coal/rare-earth-elements/program-overview/background

U.S. Geological Survey's List of 50 Critical 'Minerals' as of 2022

Aluminum, used in almost all sectors of the economy
Antimony, used in lead-acid batteries and flame retardants
Arsenic, used in semi-conductors
Barite, used in hydrocarbon production.
Beryllium, used as an alloying agent in aerospace and defense industries
Bismuth, used in medical and atomic research
Cerium, used in catalytic converters, ceramics, glass, metallurgy, and polishing compounds
Cesium, used in research and development
Chromium, used primarily in stainless steel and other alloys
Cobalt, used in rechargeable batteries and superalloys
Dysprosium, used in permanent magnets, data storage devices, and lasers
Erbium, used in fiber optics, optical amplifiers, lasers, and glass colorants
Europium, used in phosphors and nuclear control rods
Fluorspar, used in the manufacture of aluminum, cement, steel, gasoline, and fluorine chemicals
Gadolinium, used in medical imaging, permanent magnets, and steelmaking
Gallium, used for integrated circuits and optical devices like LEDs
Germanium, used for fiber optics and night vision applications
Graphite , used for lubricants, batteries, and fuel cells
Hafnium, used for nuclear control rods, alloys, and high-temperature ceramics
Holmium, used in permanent magnets, nuclear control rods, and lasers
Indium, used in liquid crystal display screens
Iridium, used as coating of anodes for electrochemical processes and as a chemical catalyst
Lanthanum, used to produce catalysts, ceramics, glass, polishing compounds, metallurgy, and batteries
Lithium, used for rechargeable batteries
Lutetium, used in scintillators for medical imaging, electronics, and some cancer therapies
Magnesium, used as an alloy and for reducing metals
Manganese, used in steelmaking and batteries
Neodymium, used in permanent magnets, rubber catalysts, and in medical and industrial lasers
Nickel, used to make stainless steel, superalloys, and rechargeable batteries
Niobium, used mostly in steel and superalloys
Palladium, used in catalytic converters and as a catalyst agent
Platinum, used in catalytic converters
Praseodymium, used in permanent magnets, batteries, aerospace alloys, ceramics, and colorants
Rhodium, used in catalytic converters, electrical components, and as a catalyst
Rubidium, used for research and development in electronics
Ruthenium, used as catalysts, as well as electrical contacts and chip resistors in computers
Samarium, used in permanent magnets, as an absorber in nuclear reactors, and in cancer treatments
Scandium, used for alloys, ceramics, and fuel cells
Tantalum, used in electronic components, mostly capacitors and in superalloys
Tellurium, used in solar cells, thermoelectric devices, and as alloying additive
Terbium, used in permanent magnets, fiber optics, lasers, and solid-state devices
Thulium, used in various metal alloys and in lasers
Tin, used as protective coatings and alloys for steel
Titanium, used as a white pigment or metal alloys
Tungsten, primarily used to make wear-resistant metals
Vanadium, primarily used as alloying agent for iron and steel
Ytterbium, used for catalysts, scintillometers, lasers, and metallurgy
Yttrium, used for ceramic, catalysts, lasers, metallurgy, and phosphors
Zinc, primarily used in metallurgy to produce galvanized steel
Zirconium, used in the high-temperature ceramics and corrosion-resistant alloys.

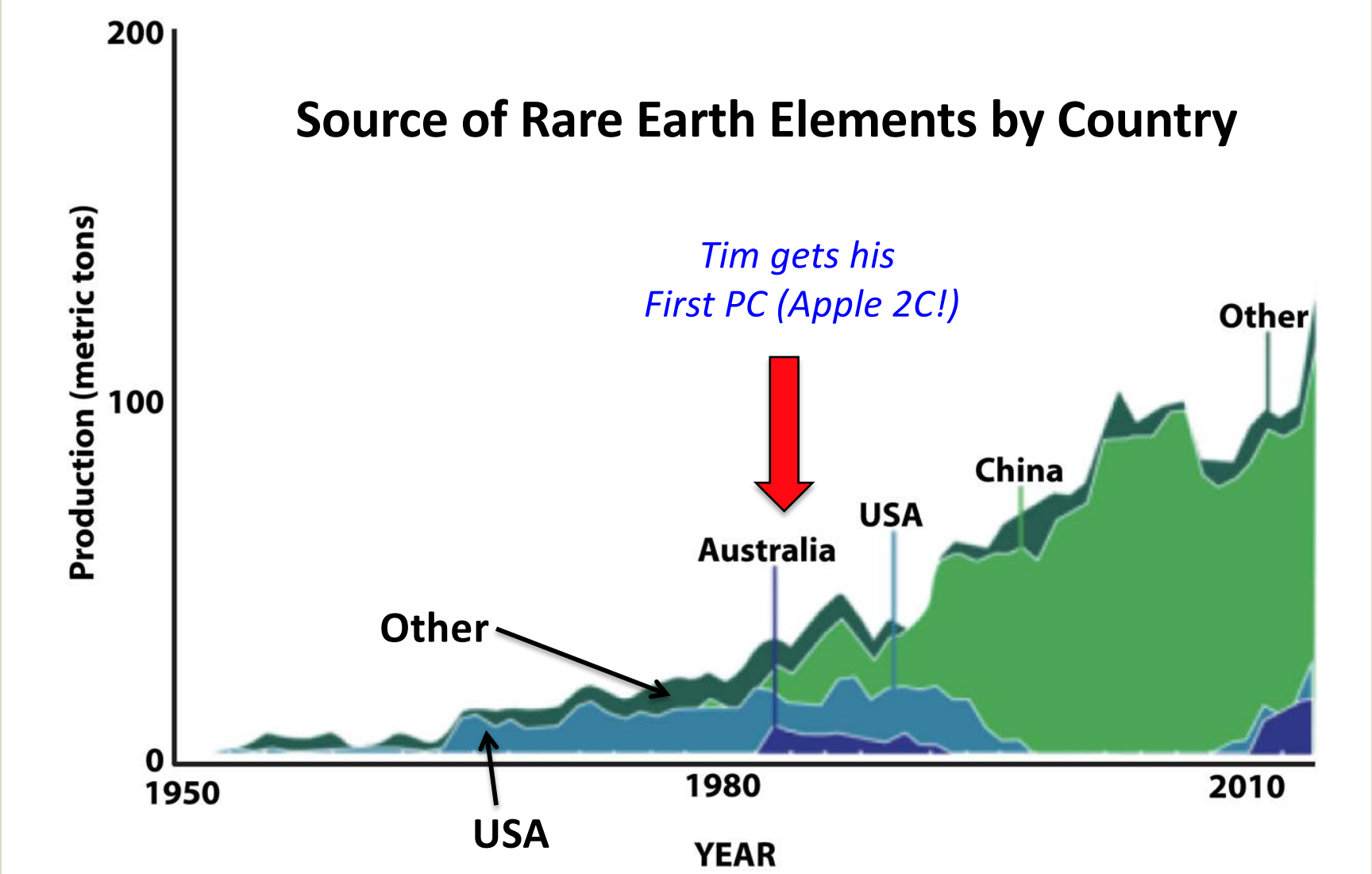
https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals

Why Do We Care About Critical Elements?



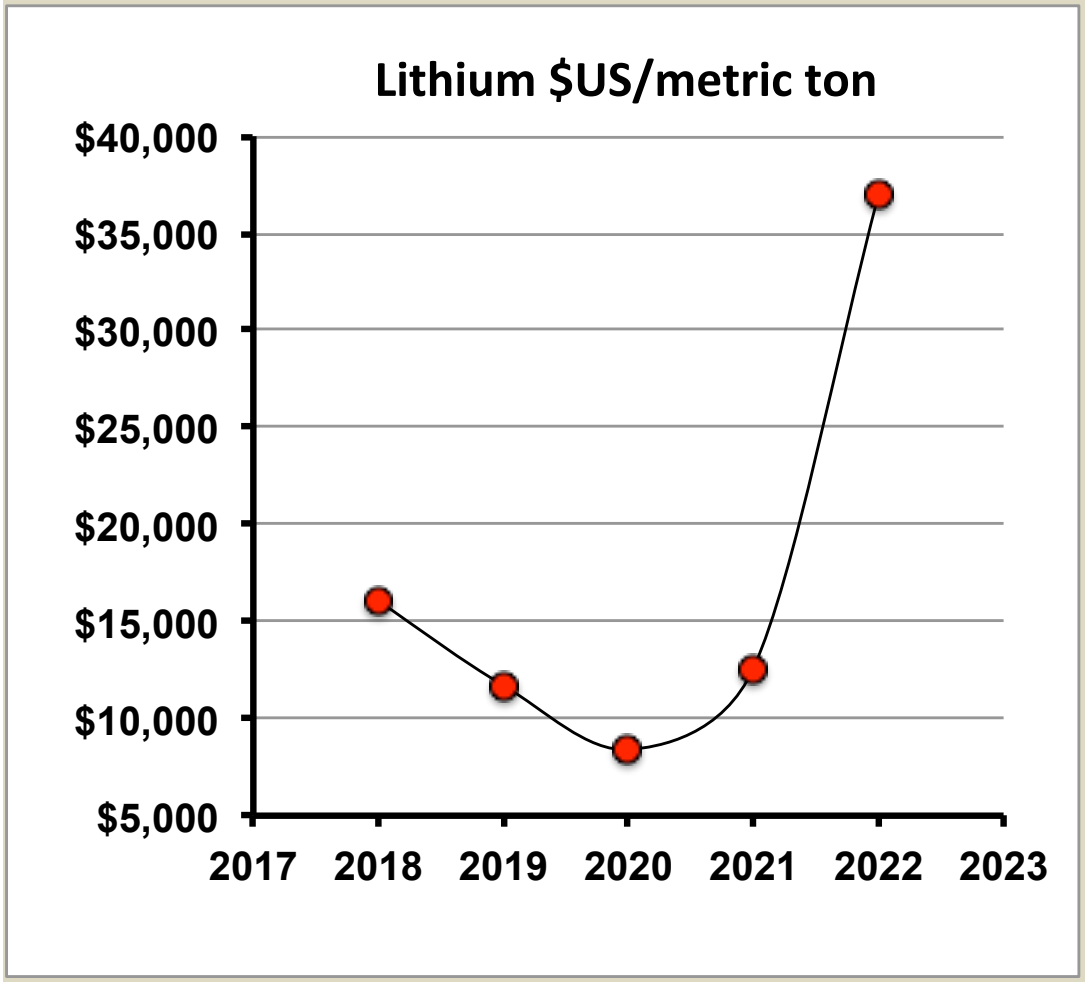
Source: Minerals Council of Australia, 2022

The Digital World and REE Sources



from: https://netl.doe.gov/coal/rare-earth-elements/program-overview/background

Lithium – Critical Mineral

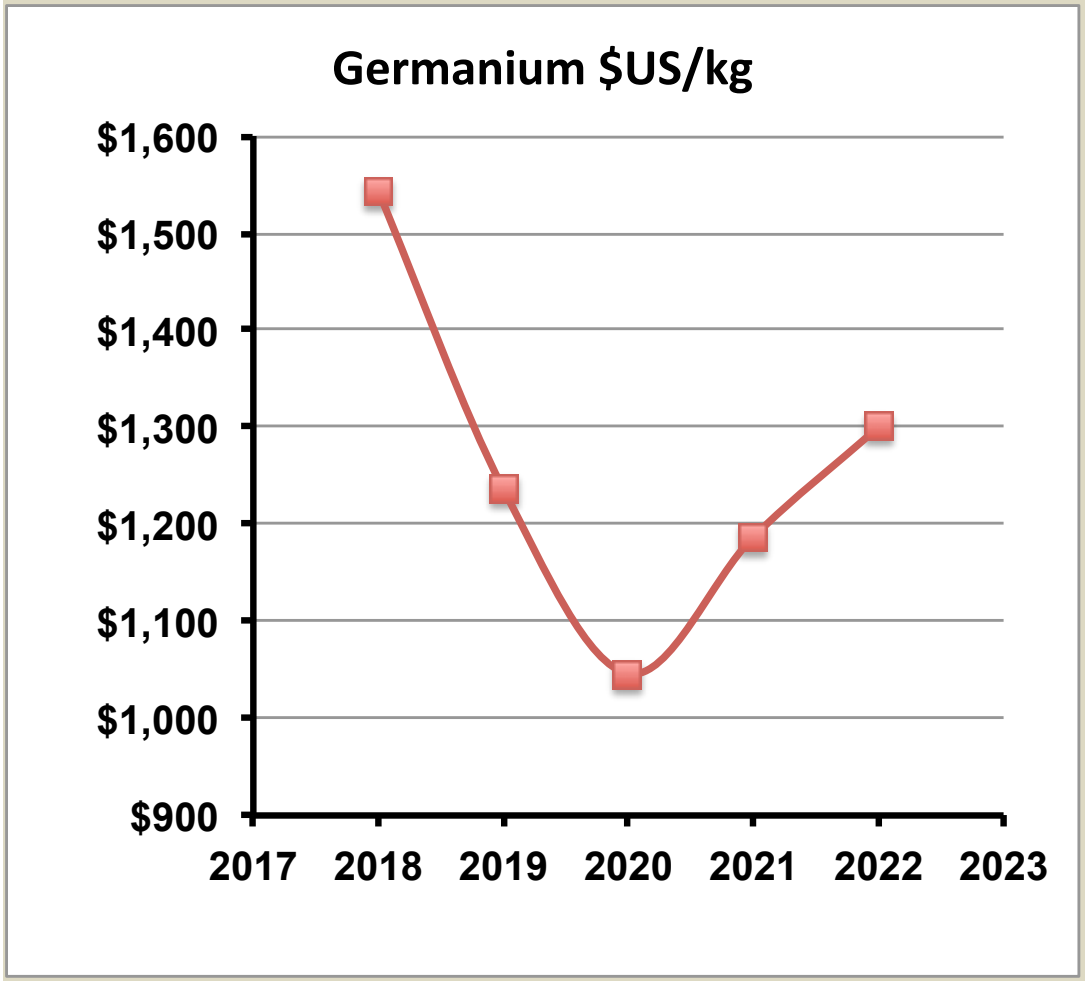


- **Lithium**: rechargeable batteries (Cars!), ceramics, glass, chemical compounds

https://netl.doe.gov/coal/rare-earth-elements/program-overview/background

https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals

Germanium – Critical Mineral

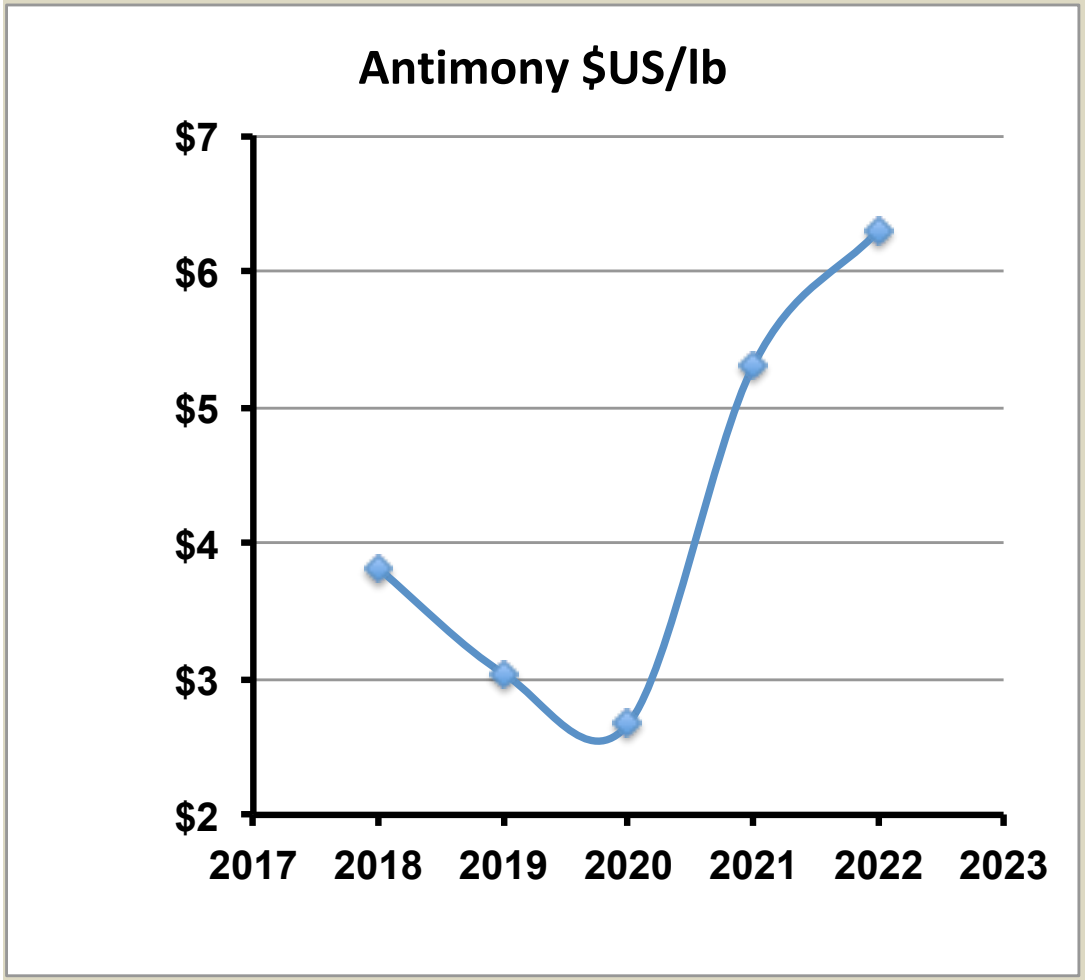


- **Germanium**: fiber optics, infrared optics, solar cells, other solar energy applications

https://netl.doe.gov/coal/rare-earth-elements/program-overview/background

 https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals

Antimony – Critical Mineral



- **Antimony**: ceramics, glass, rubber products, fire retardants

https://netl.doe.gov/coal/rare-earth-elements/program-overview/background

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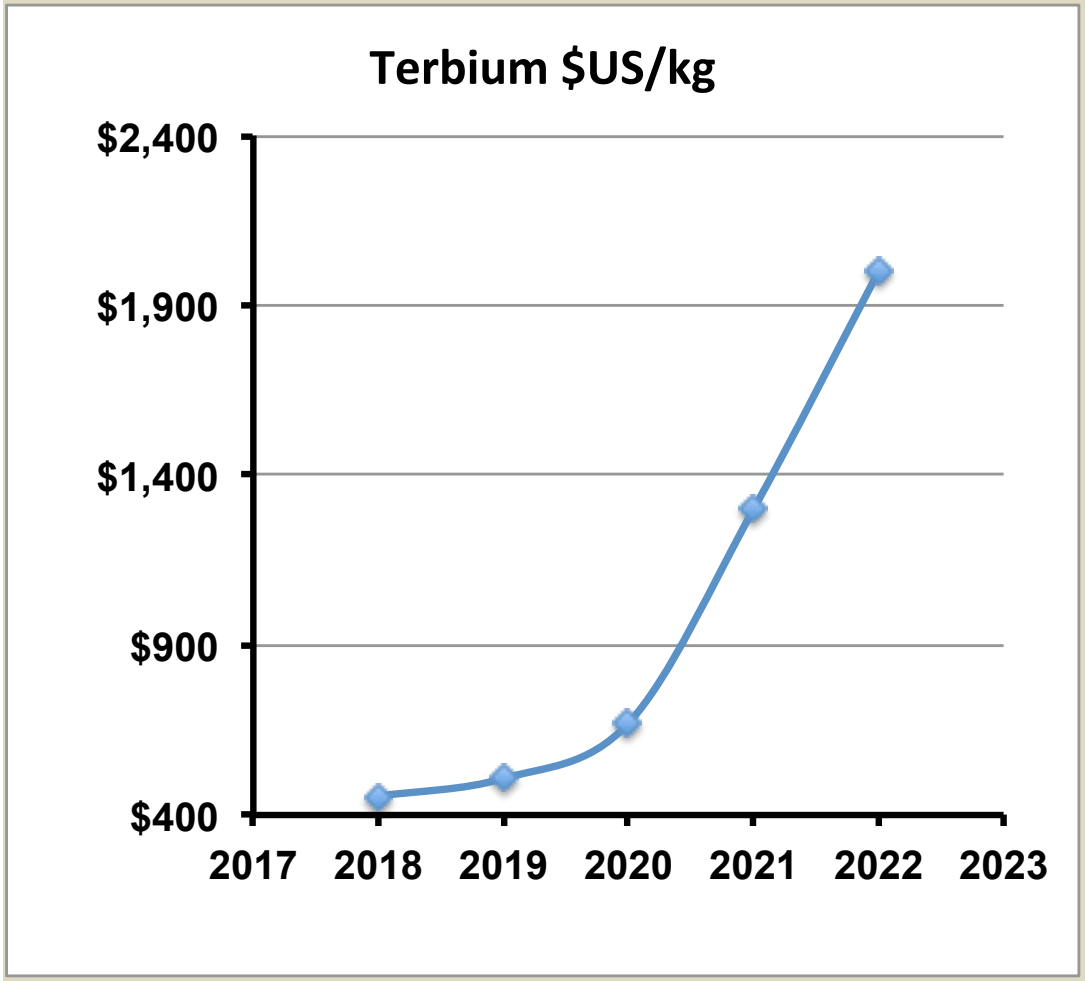
Terbium – Rare Earth Element



- **Terbium:** used in permanent magnets, fiber optics, lasers, and solid-state devices

https://netl.doe.gov/coal/rare-earth-elements/program-overview/background

 https://www.usgs.gov/news/national-news-release/us-geological-survey-releases-2022-list-critical-minerals

Frame of Reference: Gold Price ($US/kg)

https://goldprice.org/charts/history/gold_10_year_k_usd_x.png

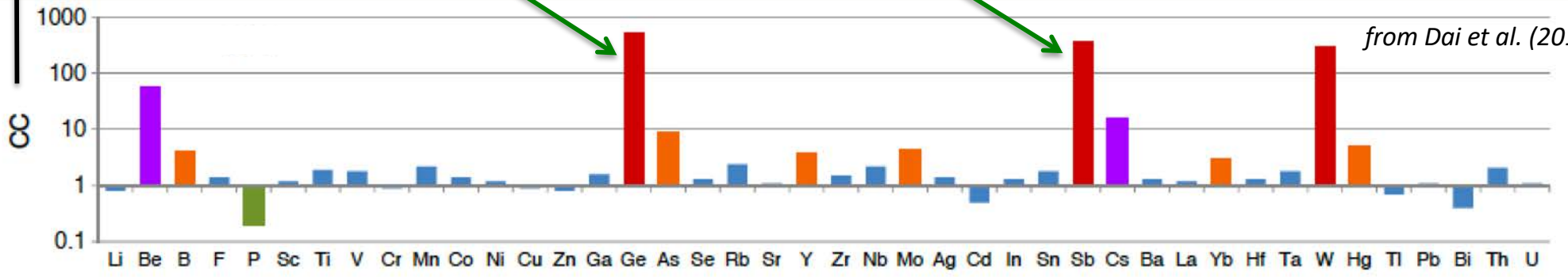
Can and Do Critical Minerals Occur in Coal?

YES

CC = Concentration Coefficient (as per Dai et al., 2012)

Common Examples are:

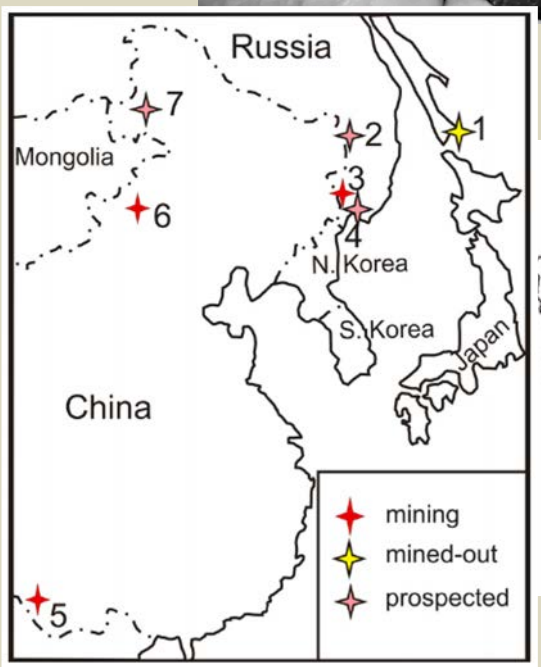
Germanium & **Antimony**



from Dai et al. (2014)

China is the Major Producer of Germanium

- China and Russia are the largest supplier of Germanium contributing over 50% of the world's production (Dai et al., 2014).
- Most of that production is from coal (Seredin , 2012; Seredin et al., 2013)
- Main uses: fiber optics communication networks, infrared night vision systems, and polymerization catalysts
- Predominantly taken from fly ash after coal combustion, which further concentrates it, recovery of Ge is seen as economic especially when used in tandem with heat generation (Razaei et al., 2022).



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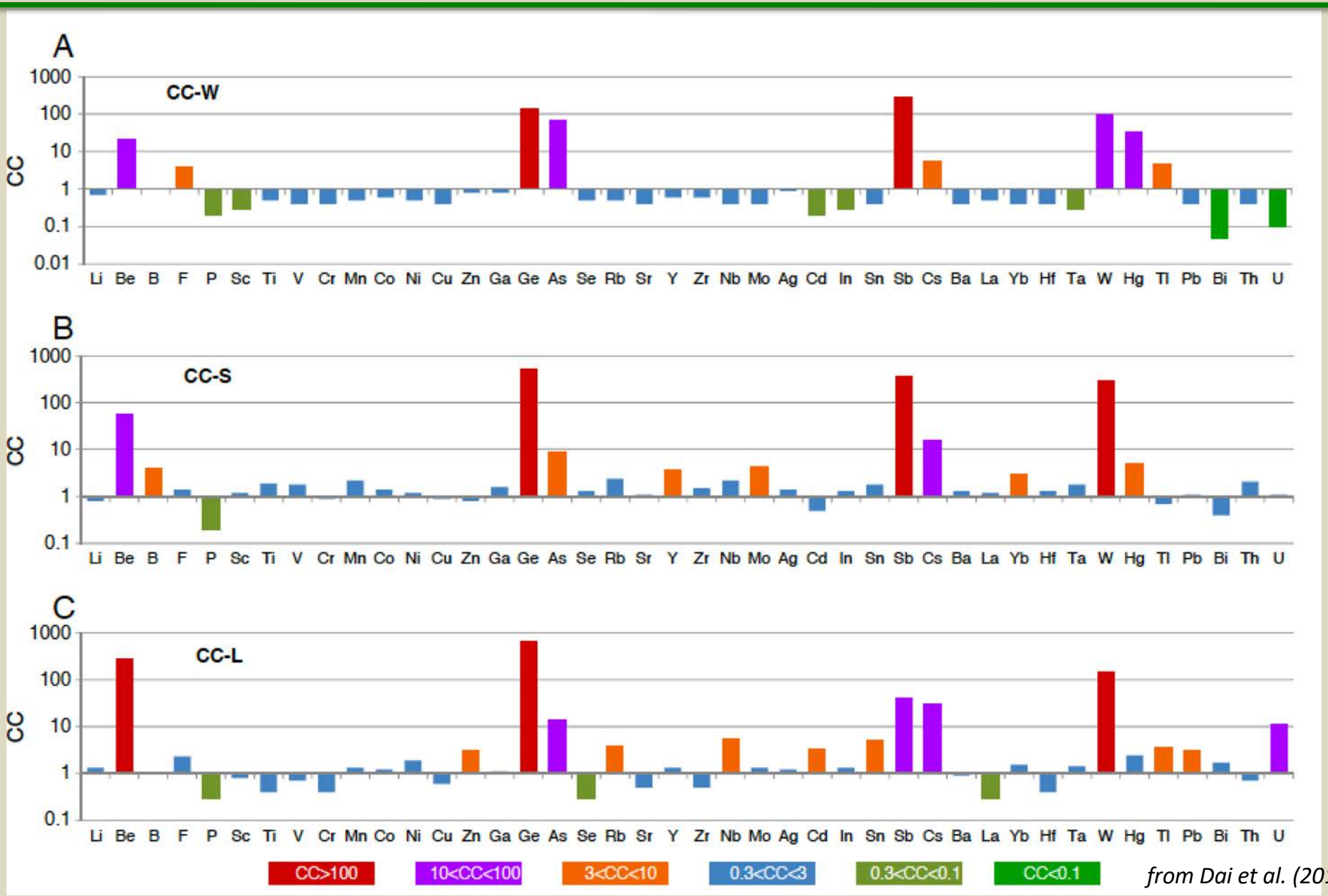
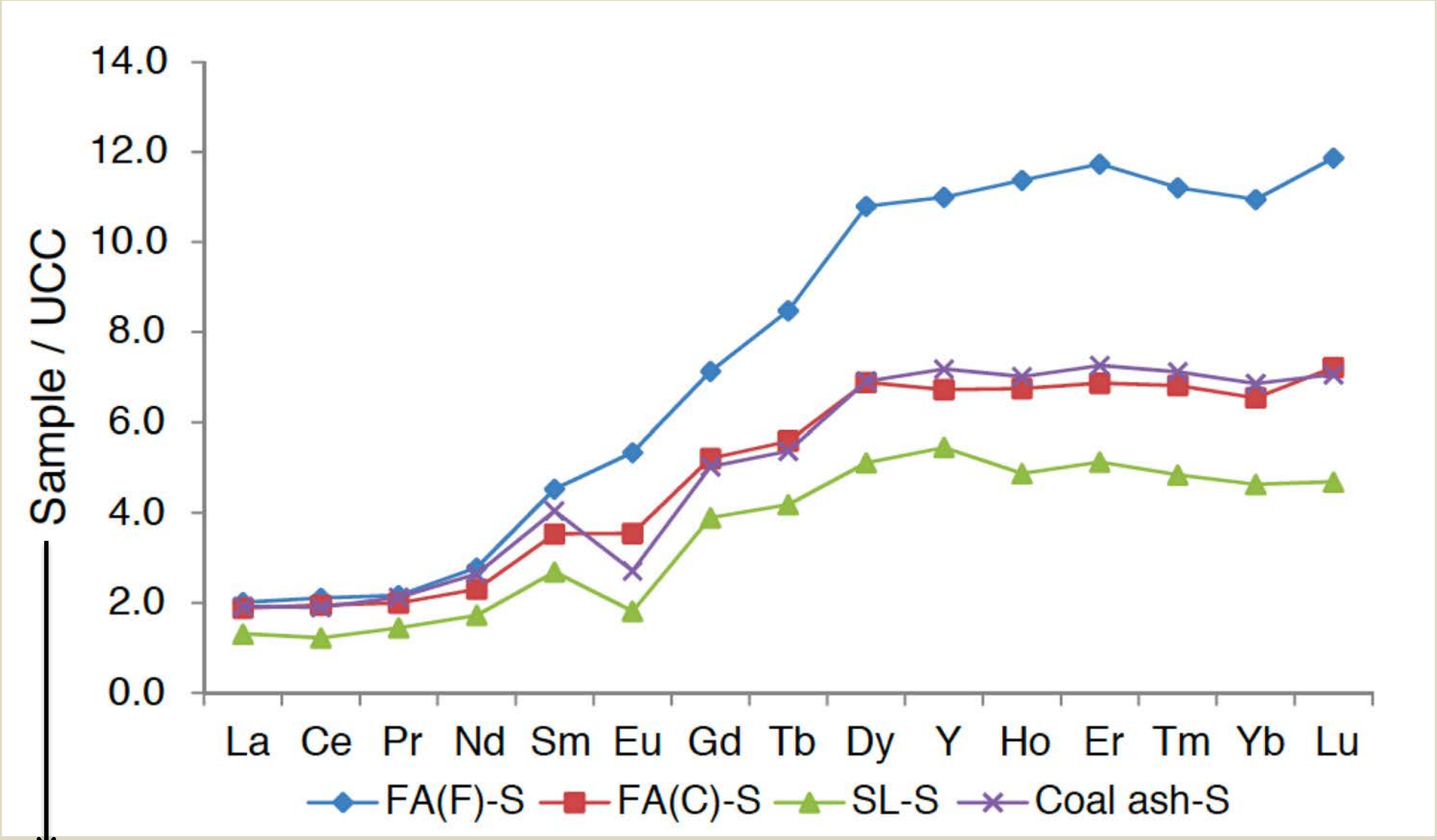


from Dai et al. (2014)

Many Chinese Coals also Contain Significant REE Concentrations

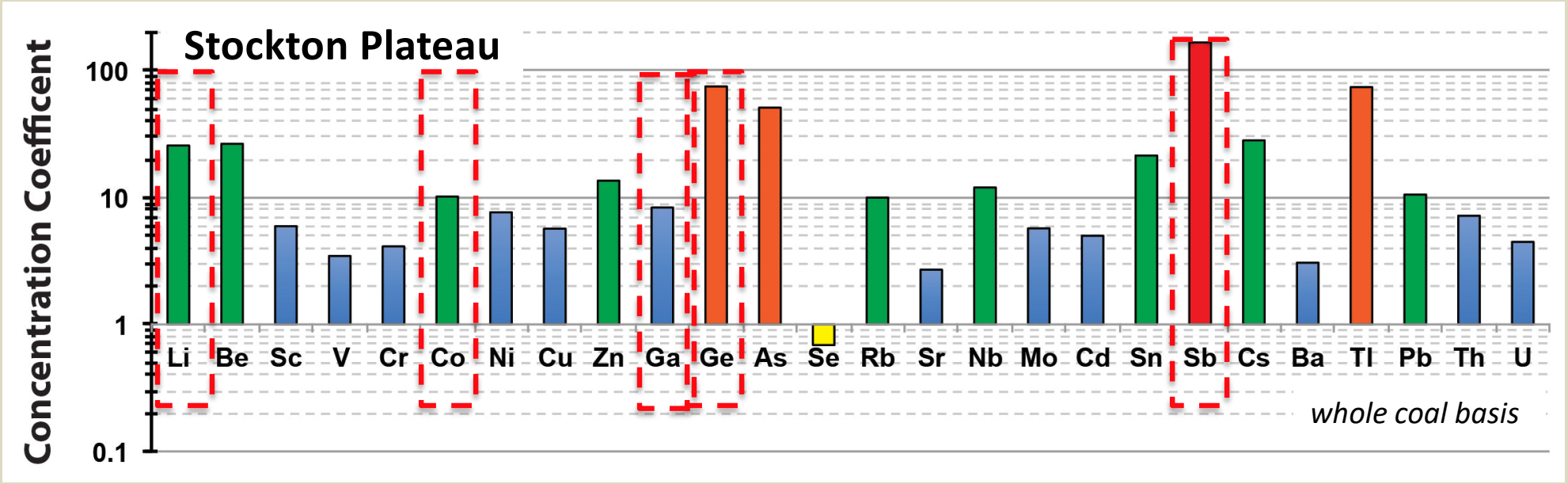


Sample/UCC = sample concentration relative to average Upper Continental Crust Concentration

from Dai et al. (2014)

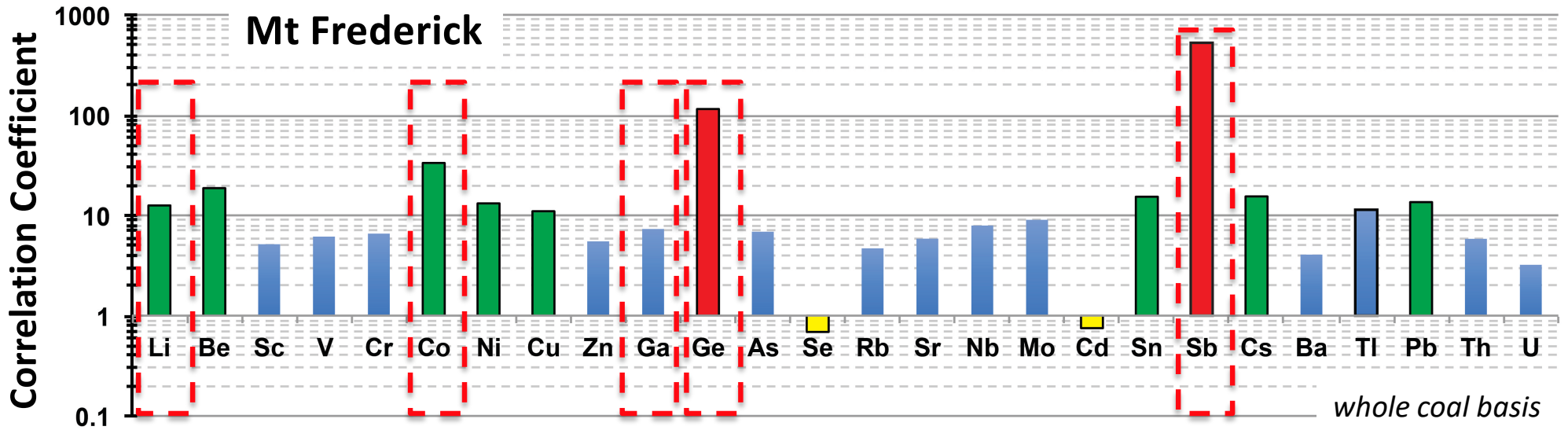
Do Other Regions have Critical Elements in Coal?

Yes. *China is not the only region, though other areas have not been prospected or developed – for example, New Zealand*



Data from Moore et al. (2005) plot as per Dai et al. (2012) and Ketris & Yudovich (2009)

Concentration Coefficients



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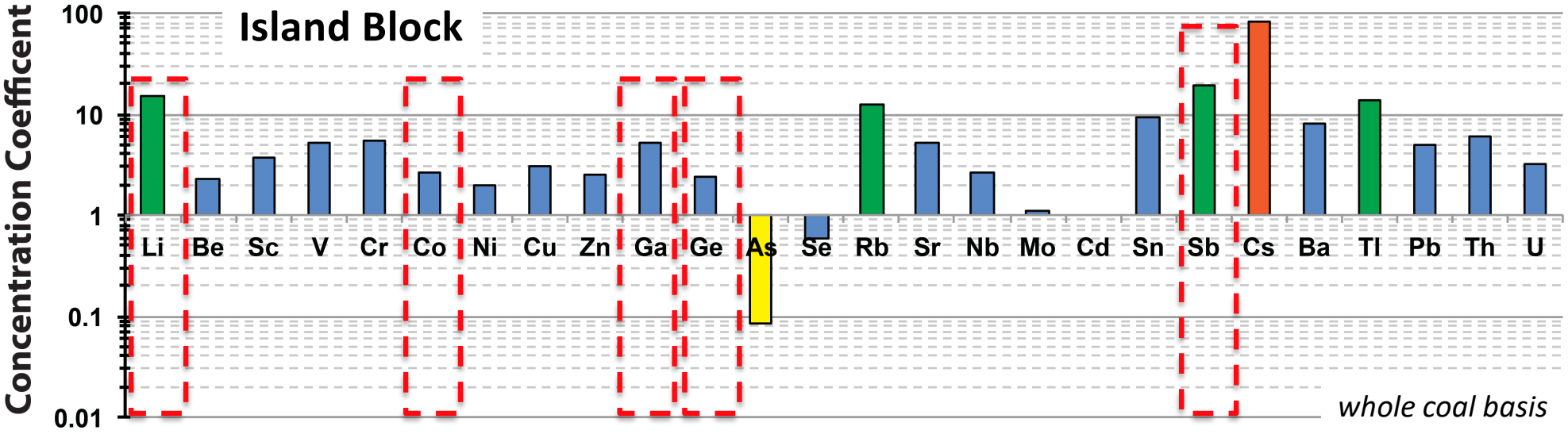
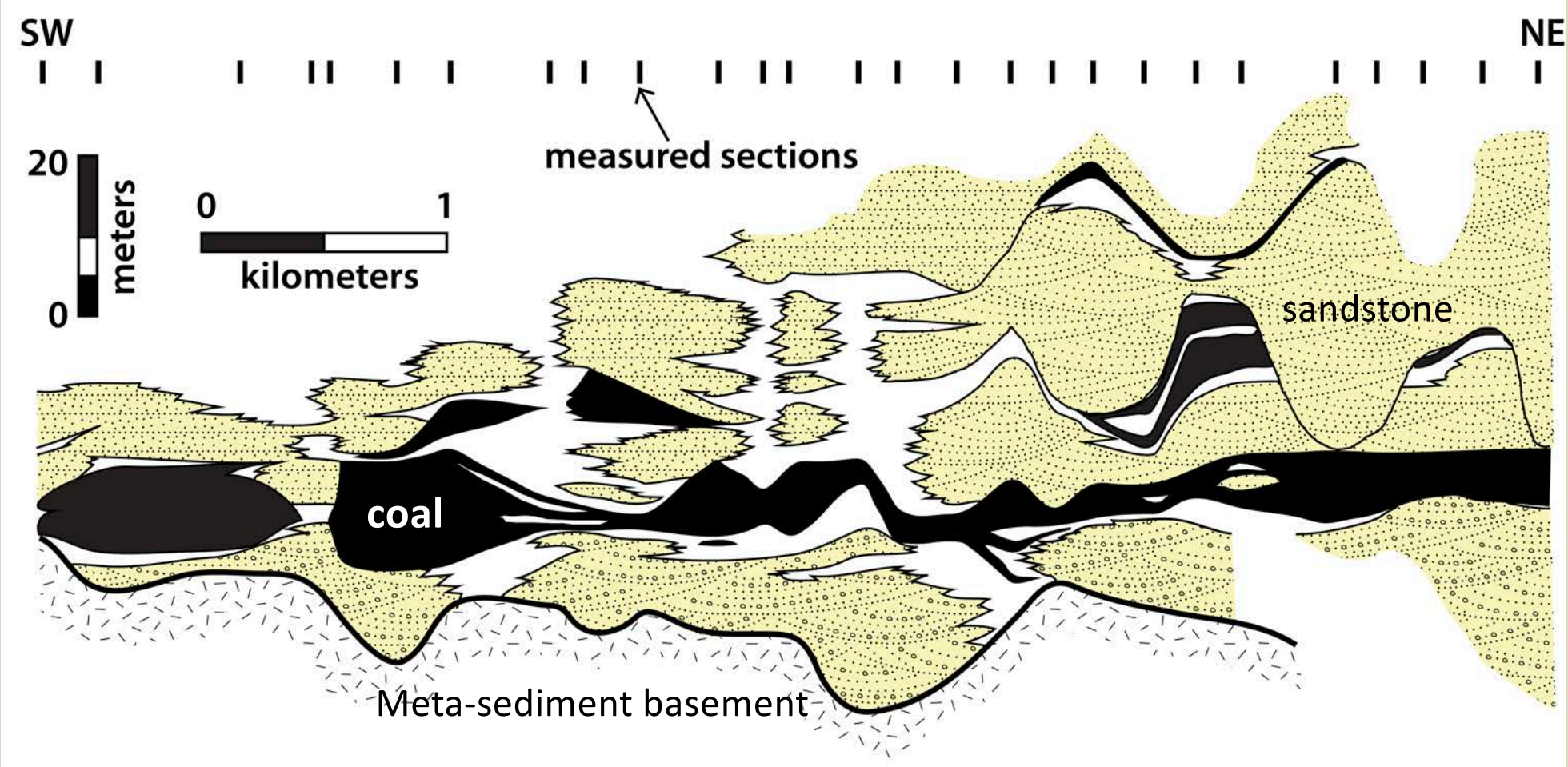
Concentration Coefficients



Data from Moore et al. (2005) plot as per Dai et al. (2012) and Ketris & Yudovich (2009)

Coals Not Far from Possible Sources



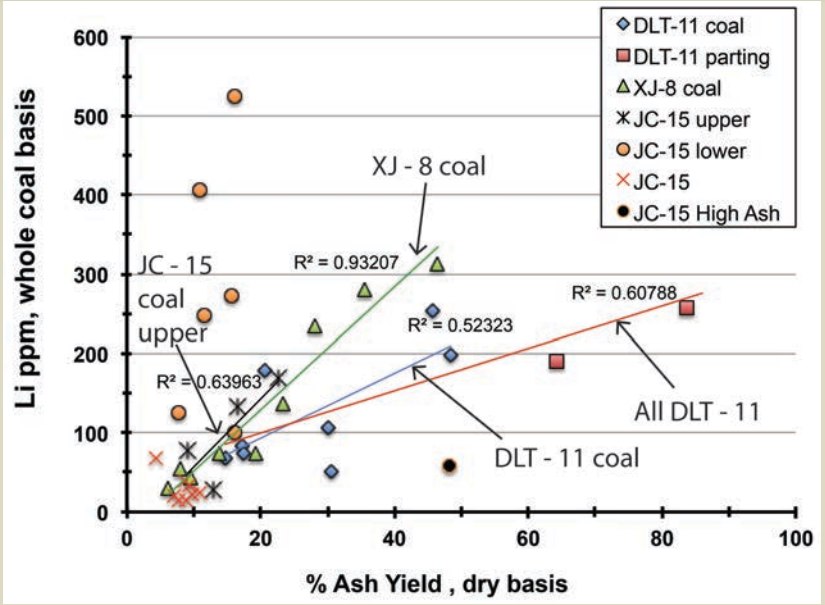
from Flores & Moore (2024) modified from Flores & Sykes (1996)

Mode of Occurrence in Coal: Various!

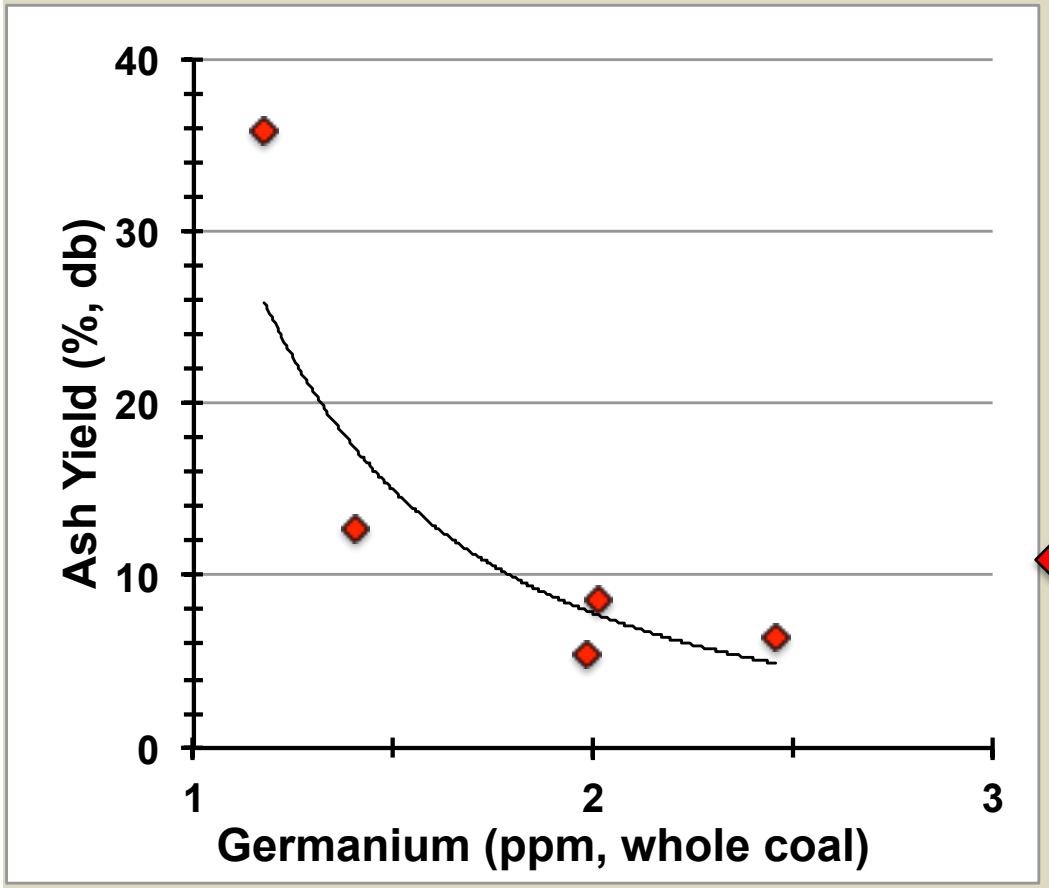
Lithium

Critical mineral

Inorganically bound



from Sun et al. (2022)



from Moore et al. (2022)

Germanium

Critical mineral

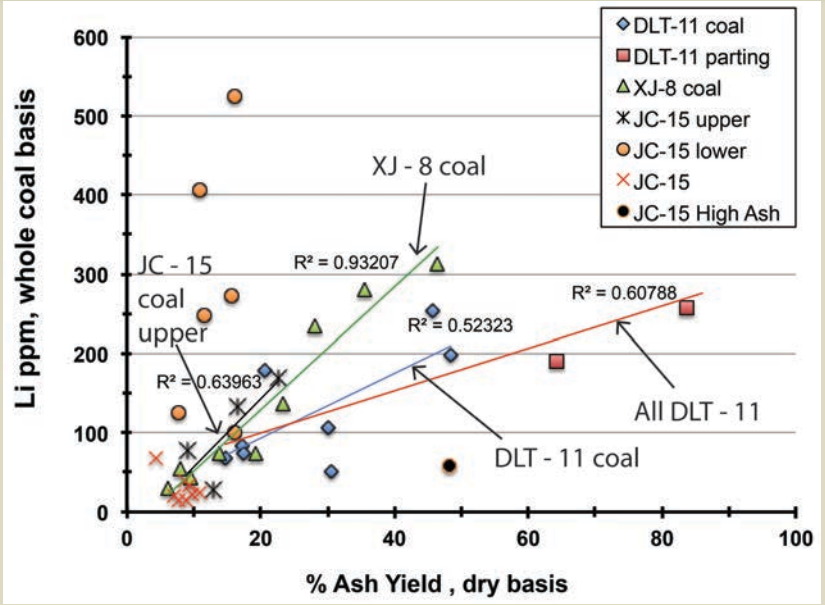
Organically bound

Mode of Occurrence in Coal: Various!

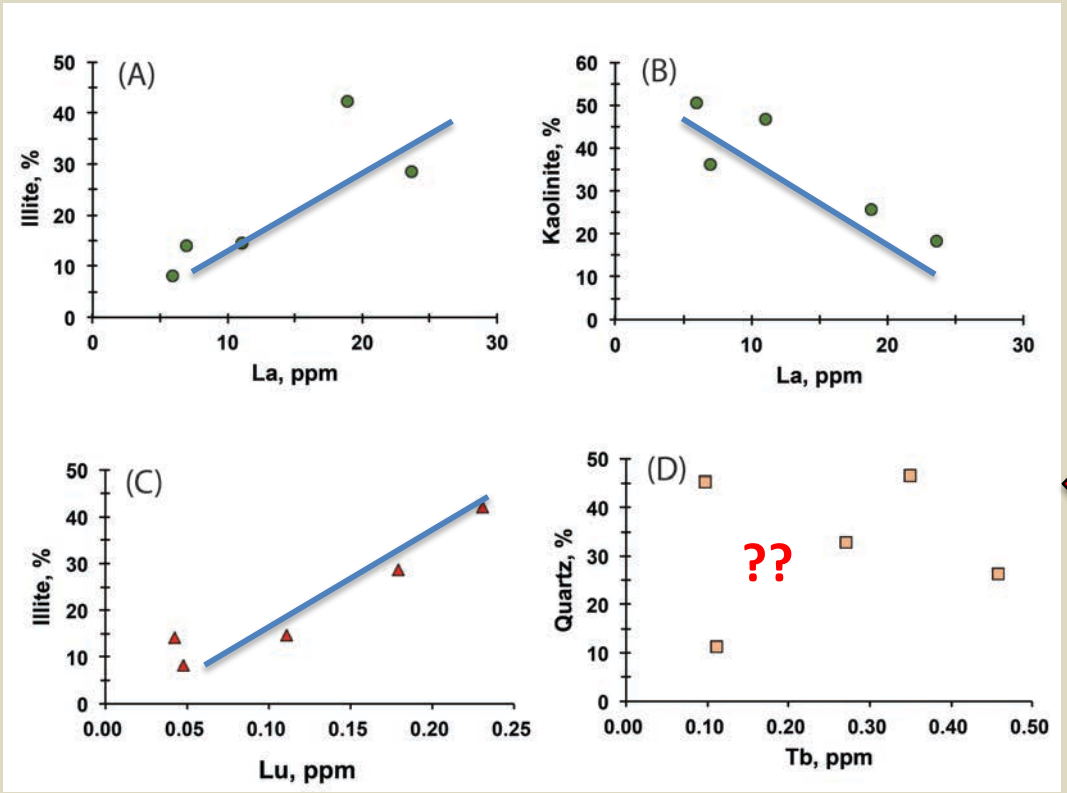
Lithium

Critical mineral

Inorganically *bound*



from Sun et al. (2022)



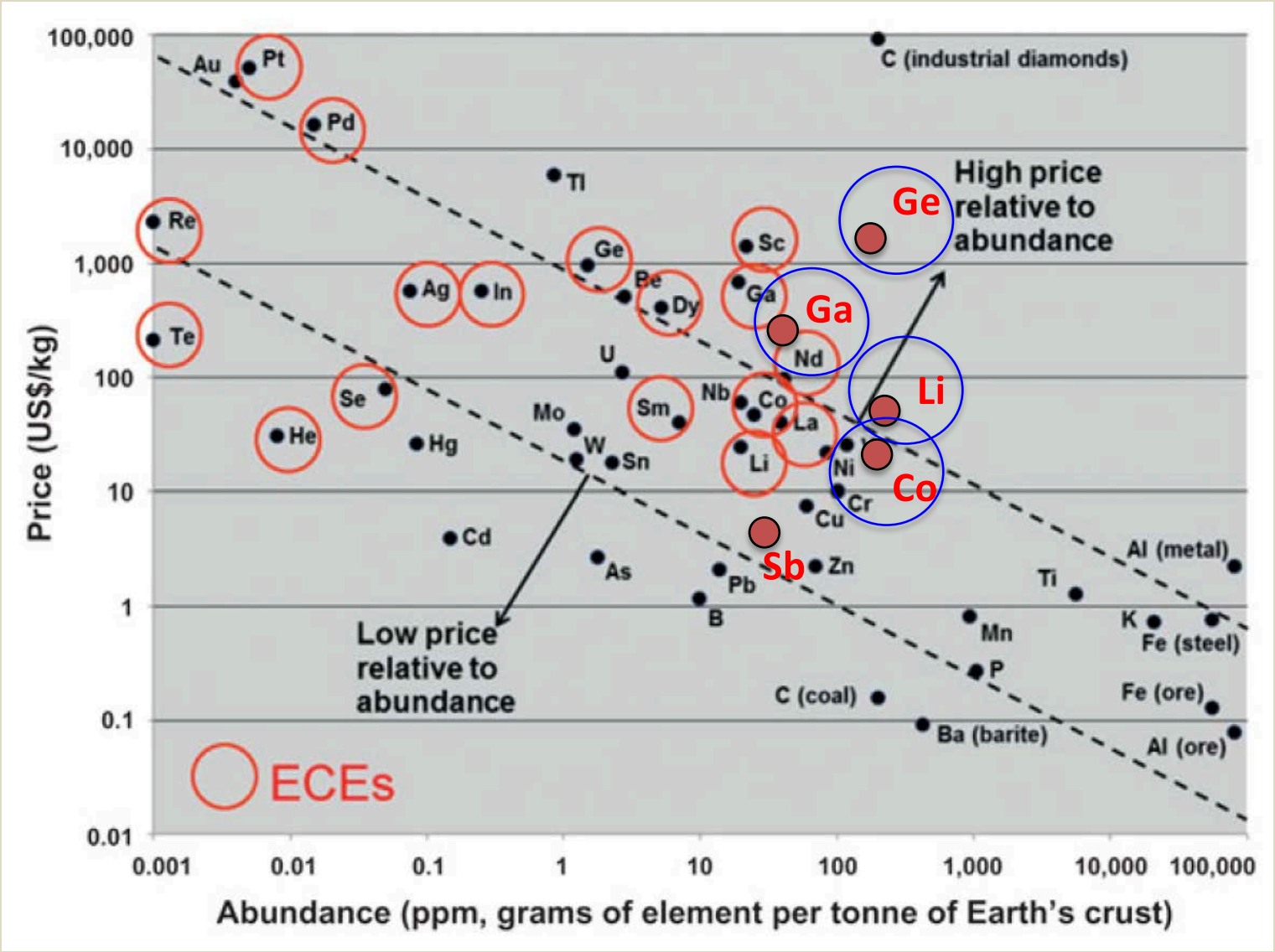
Inorganically *bound &*

Mineral selective

Rare Earth Elements

from Moore et al. (2022)

Is It Enough to be Economic?



Hurd et al., 2012

ECEs = Energy Critical Elements

Summary

- Critical ‘Minerals’ are a vital and growing commodity
- China produces a disproportionate amount of the world’s Critical Minerals, which includes Rare Earth Elements
- For energy and technology security many countries are activity exploring for Critical Minerals, which includes coal as host.
- For example, **Germanium** in the Buller area of New Zealand is indicative of a coal-hosted Ge-ore deposit. If so, the coal could be used for **Ge** extraction.
- The element assemblage is very similar to those in other being mined coal-hosted Ge deposits, for example, Lincang and Wulantuga in China and Spetzugli in Russia
- The economics of extraction of Critical Elements from coal is not really known, but if favorable could be a viable alternative source

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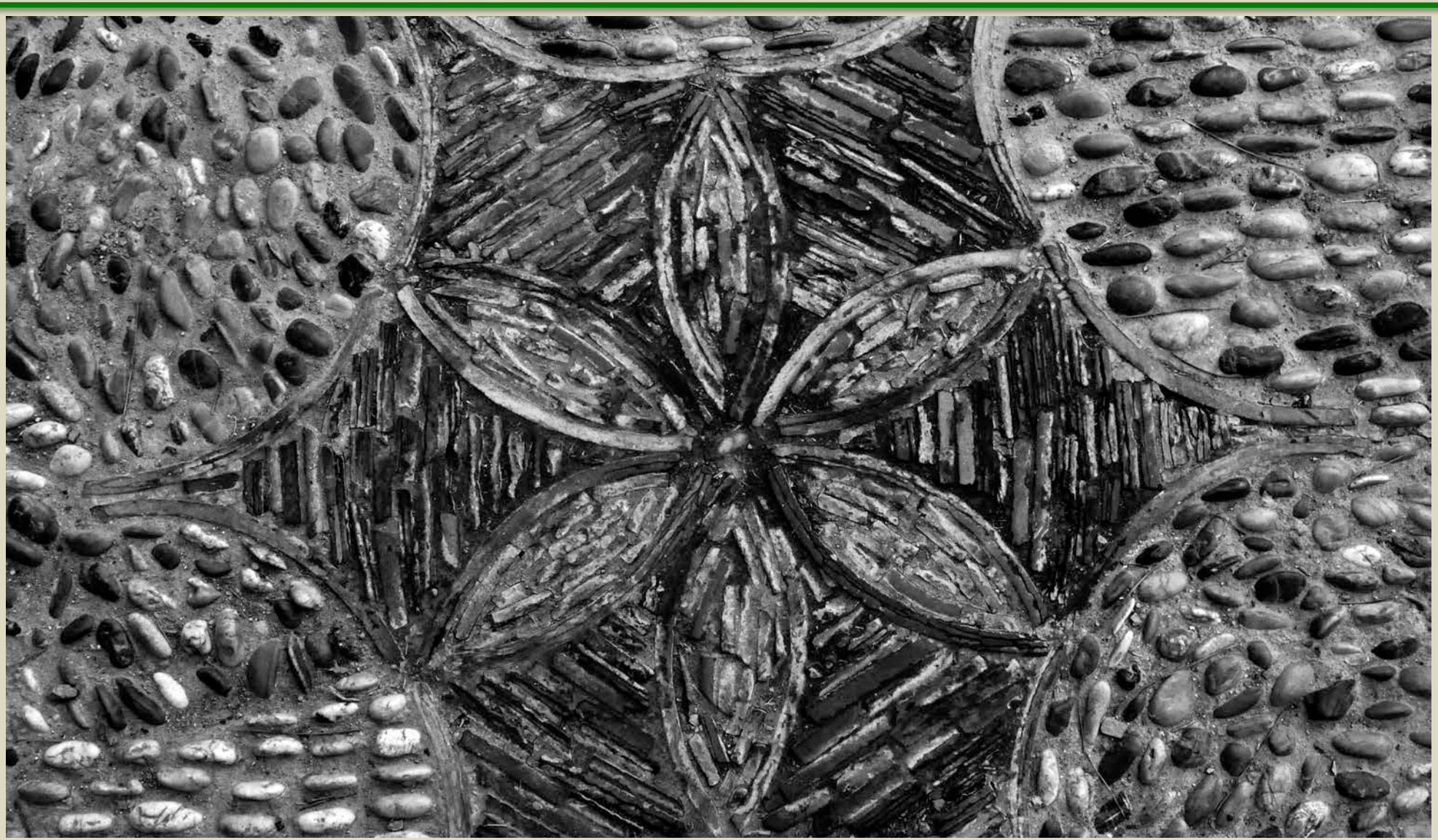
Questions/Discussion



Sidewalk pattern, Guishan Han Tomb, Xuzhou, Jiangusu, China (photo, Tim A. Moore, 2016)