

Mining-related land degradation



1st aspect: contamination (chemistry, pH-Eh conditions and toxicity)

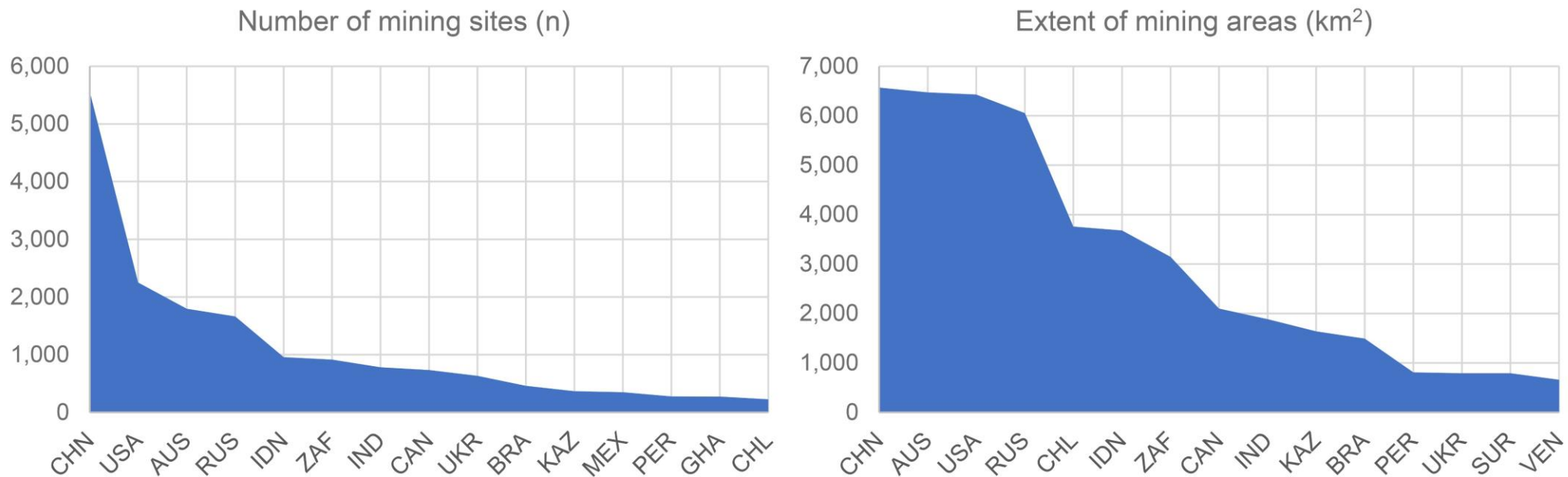
- mining, processing and industry → hazardous and potentially toxic substances have been introduced into the environment
- there are many sites at which mining and processing of metal ores have led to significant acidification of local environment
- hazardous substances (and risk elements) may impose a significant threat for the quality of environment and human health, mainly at local or regional level
- soil and water contamination, toxicity, loss of biodiversity, adverse effects on ecosystem services, soil/land degradation
- brownfields – abandoned (often industrial) areas or sites with industrial and mining waste deposits (tailings or mine dumps), surface mining areas, etc. have been left untreated (no measures were taken to treat somehow waste deposits or prevent the contaminant from spreading)

2nd aspect: physical processes causing land degradation

- striking disturbance of landscape (especially in case of strip/surface mining)
- mining for purpose of acquiring construction materials (sand, gravel) causes land degradation; for example, significant extent of land has been negatively affected/damaged due to the intense mining of sand in south-east Asia (for example, areas along Mekong river)
- mining and production of mining waste generates lot of dust; the particles are being spread into environment in dry and windy conditions; negative effects on human health due to dust breathing

Mining (general info)

- current intensity of mining is the highest (considering global scale) → we mine more now than we ever have before
- copper, iron, aluminum, zinc, lead and nickel → 98 % (by mass) of all mined metals
- global mining area $\approx 57,278 \text{ km}^2$ (Croatia = $55,960 \text{ km}^2$) number of mining sites = 21,060



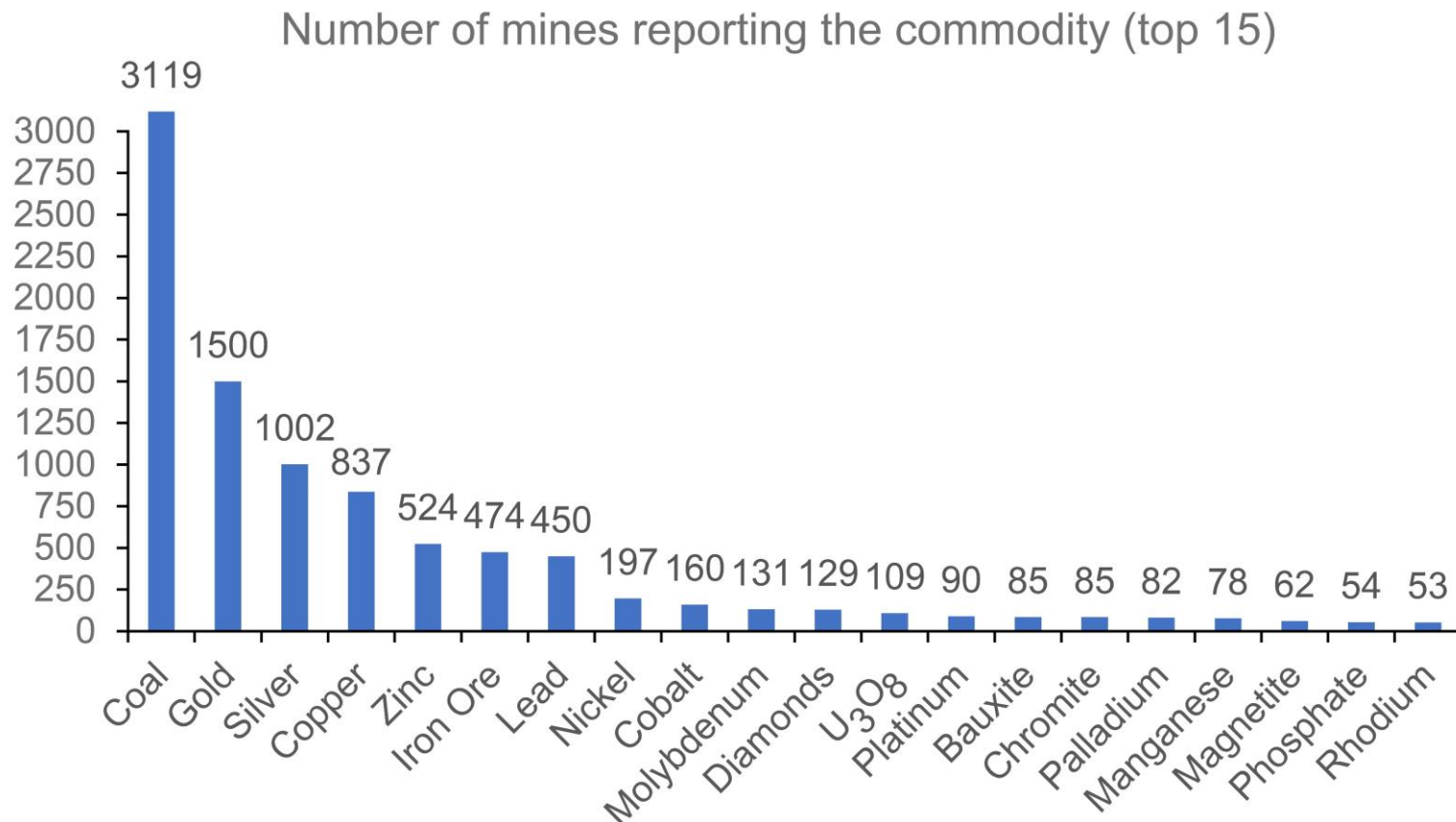
Maus et al. (2020), A global-scale data set of mining areas. Scientific Data 7,289.

Mining (general info)

most mined materials / ores (by mass) →

1. Gravel and Sand (> 50 billion t annually)
2. Coal (7.5 billion t annually)
3. Iron Ore (2.5 billion t annually)
4. Bauxite (350-400 million t annually)
5. Phosphate rock (276 million t annually)
6. Gypsum (267 million t annually)
7. Manganese Ore (50 million tons annually)
8. Copper (20 million t annually)
- ...

most mined materials / ores (by mine counts)



Maus et al. (2020), A global-scale data set of mining areas. Scientific Data 7,289.



ALL THE METALS WE MINED

IN 2021

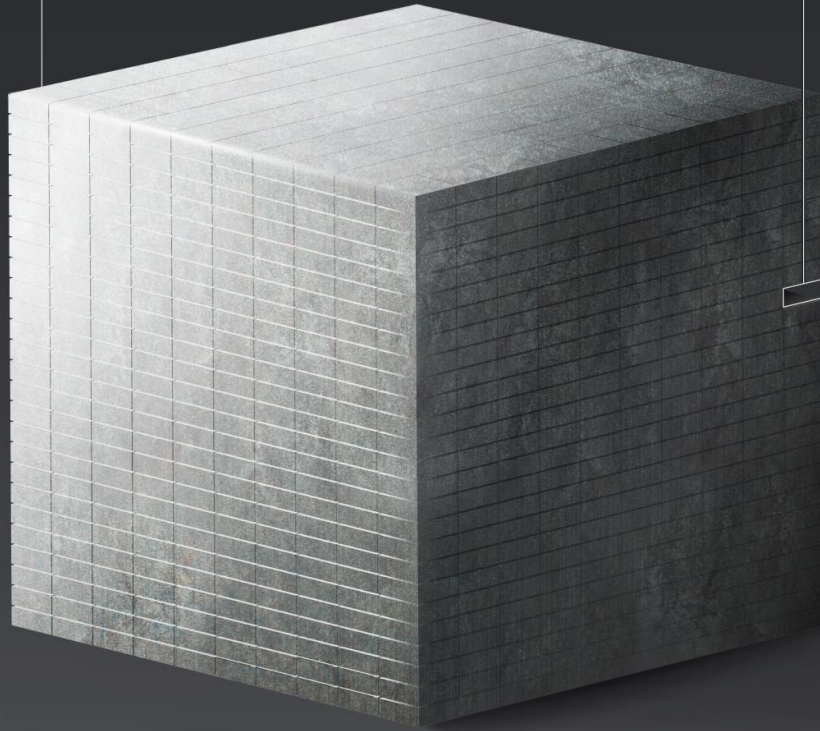
The world produced roughly **2.8 billion tonnes** of metals in 2021. Here are all the metals we mined, visualized on the same scale.

IRON ORE

2,600,000,000 tonnes*

 = 1,000,000 tonnes

Iron Ore*
2.6B



LARGEST END-USE



Steelmaking



Construction



Chemicals



Alloying Agents



Energy/Batteries



Magnets



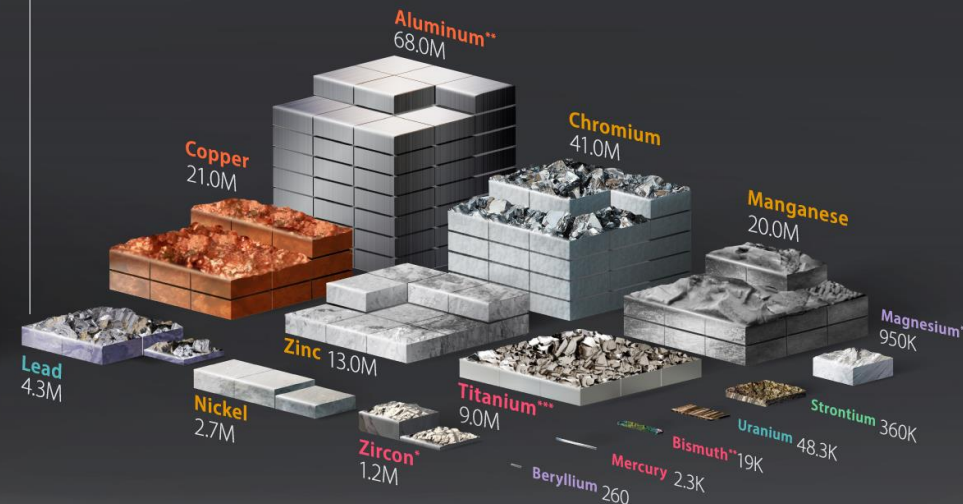
Electronics



Other

INDUSTRIAL METALS

181,579,892 tonnes



TECHNOLOGY AND PRECIOUS METALS

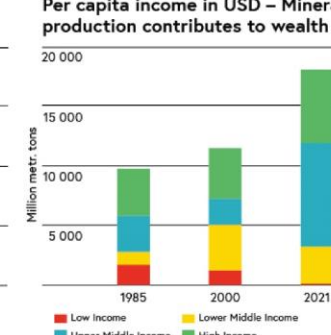
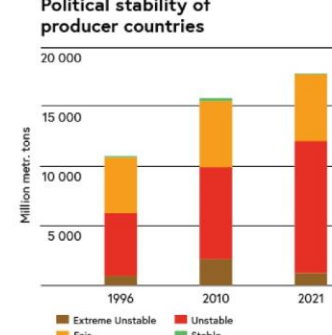
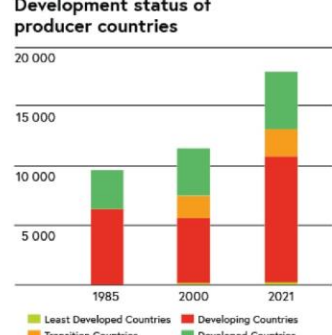
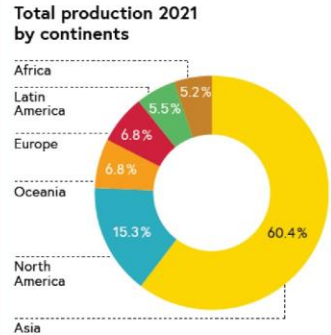
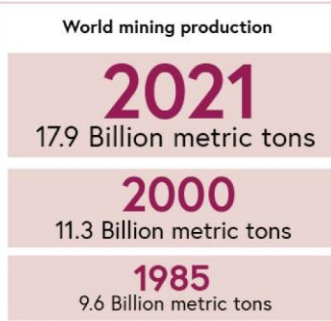
1,474,889 tonnes



World mining data

(finance ministry of Austria)

Major developments
in global mining
production based
on World Mining
Data 2023



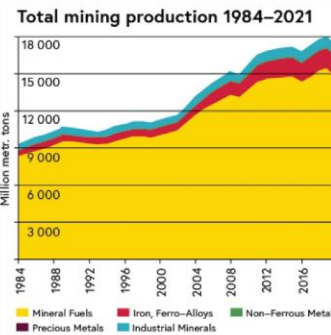
Iron and Ferro-Alloy Metals:
Fe, Cr, Co, Mg, Mo, Ni, Nb, Ta, Ti, W, V

Non-Ferrous Metals:
Al, Sb, As, Bauxite, Be, Bi, Cd, Cu, Ga, Ge, In, Pb, Li, Hg, Rare Earth Minerals, Rh, Se, Te, Sn, Zn

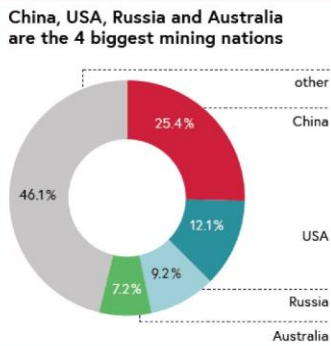
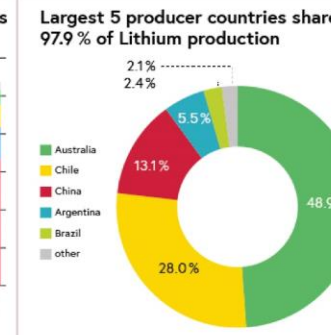
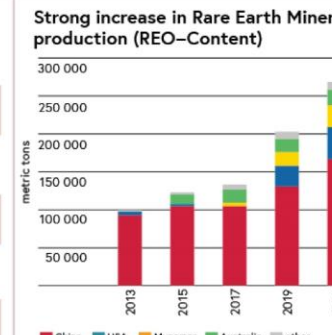
Precious Metals:
Au, Pt-Group Metals (Pd, Pt, Rh), Silver

Industrial Minerals:
Asbestos, Baryte, Bentonite, B Minerals, Diamond (Gem/Industrial), Diatomite, Feldspar, Fluorspar, Graphite, Gypsum and Anhydrite, Kaolin (China-Clay), Magnesite, Perlite, Phosphate Rock (incl. Guano), Potash, Salt, S, Talc (incl. Steatite and Pyrophyllite), Vermiculite, Zr

Mineral Fuels:
Steam Coal (incl. Anthracite and Sub-Bituminous Coal), Coking Coal, Lignite, Natural Gas, Petroleum (incl. Natural Gas Liquids), Oil Sands, Oil Shales, Uranium



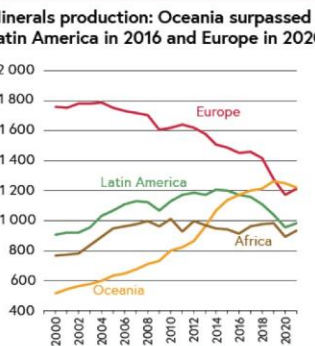
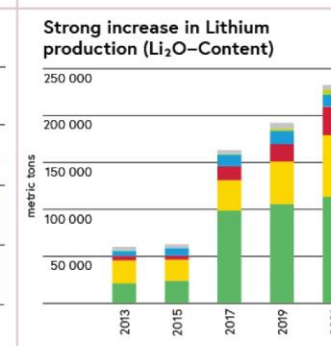
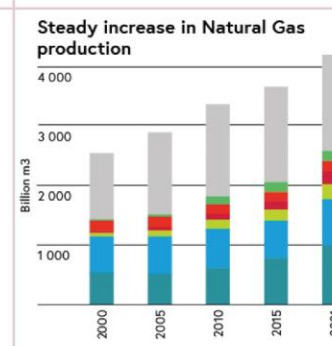
Non-Ferrous Metals
Ratio of 4 base metals Al, Cu, Zn, Pb to all other Non-Ferrous Metals
99.1% to 0.9%
Growth rate of Non-Ferrous Metals production 2000/2021 (2017/2021)
115.3% (3.0%)
Growth rate of Copper production 2000/2021 (2017/2021)
66.2% (6.6%)



Iron and Ferro-Alloy Metals
Ratio of Iron Ore to all other Ferro-Alloy Metals
97.2% to 2.8%
Growth rate of Iron Ore production 2000/2021 (2017/2021)
169.9% (7.3%)
Growth rate of Nickel production 2000/2021 (2017/2021)
149.3% (13.5%)

Big changes

	Δ 2000/2021	Δ 2017/2021
Lithium	753.5%	42.9%
Gallium	734.6%	40.0%
Tellurium	278.4%	19.7%
Antimony	-18.8%	-36.9%
Lignite	-20.4%	-16.3%
Diam. (Ind)	-23.2%	-38.3%

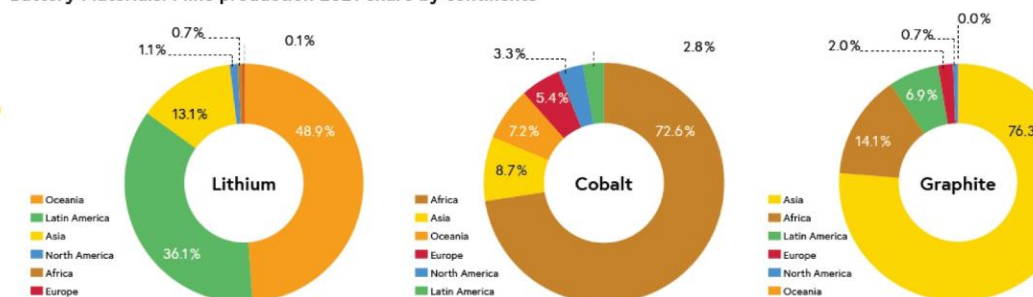


- China is world's largest producer of 29 different commodities:
- 4 Iron and Ferro-Alloy Metals: Mo, Ti, W, V
 - 15 Non-Ferrous Metals: Al, Sb, As, Bi, Cd, Ga, Ge, In, Pb, Hg, REE, Se, Te, Sn, Zn
 - 1 Precious Metal: Au
 - 7 Industrial Minerals: Fluorspar, Graphite, Gypsum, Magnesite, Phosphate Rock, Salt, Sulfur
 - 2 Mineral Fuels: Steam Coal, Coking Coal

Δ 2000/2021 – declining production rates since 2000 only in Europe



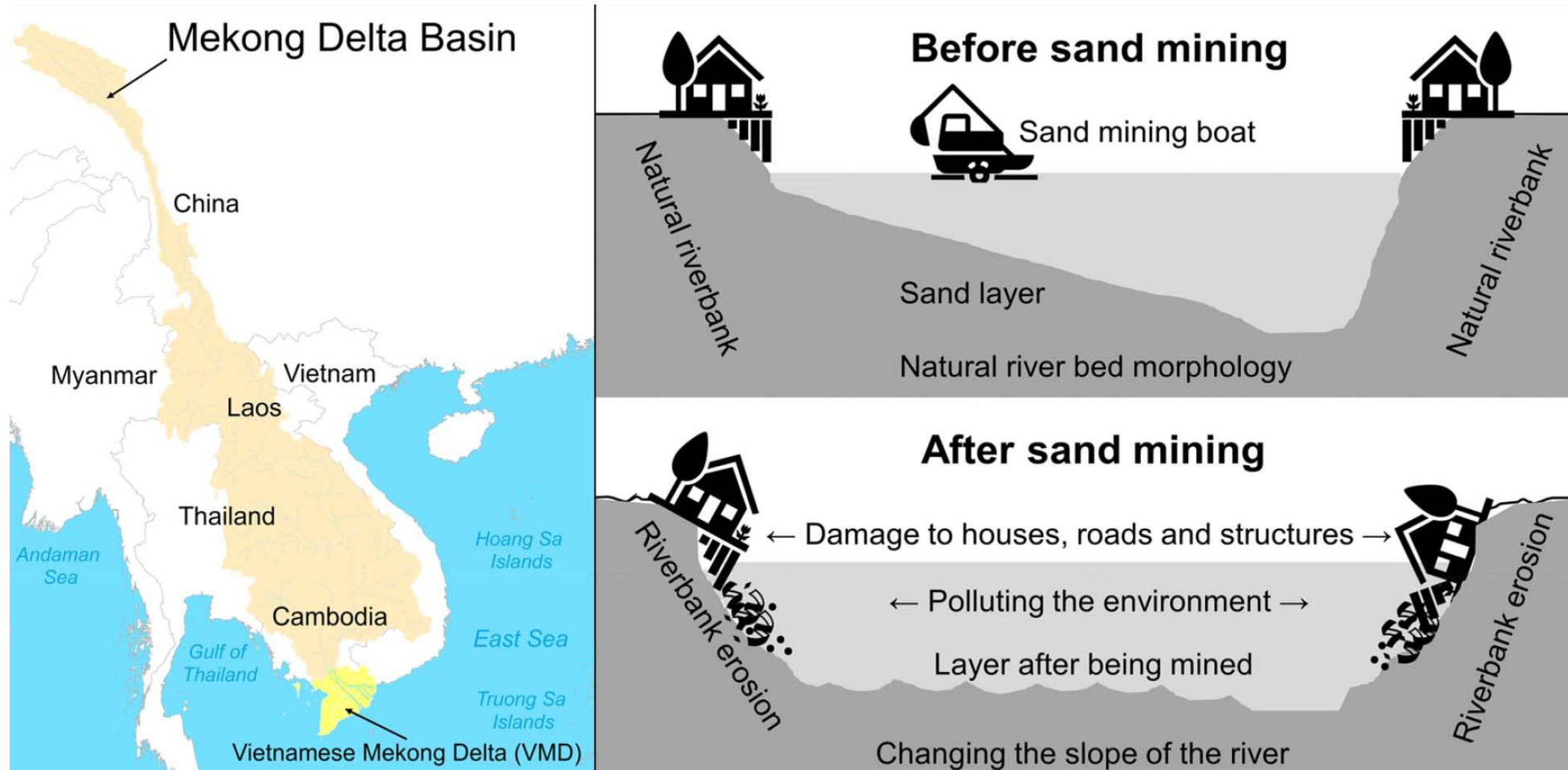
Battery Materials: Mine production 2021 share by continents

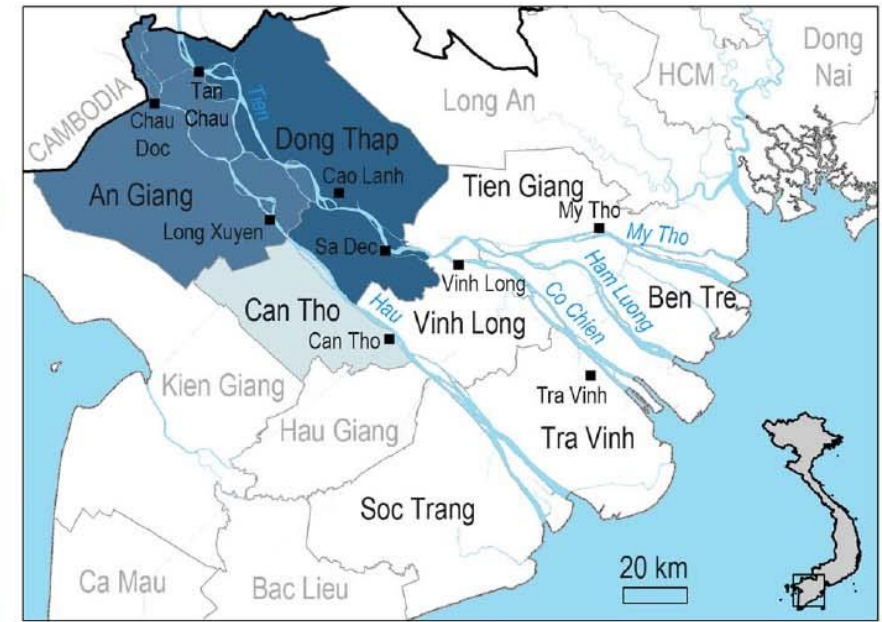


Environmental impacts of (river) sand mining

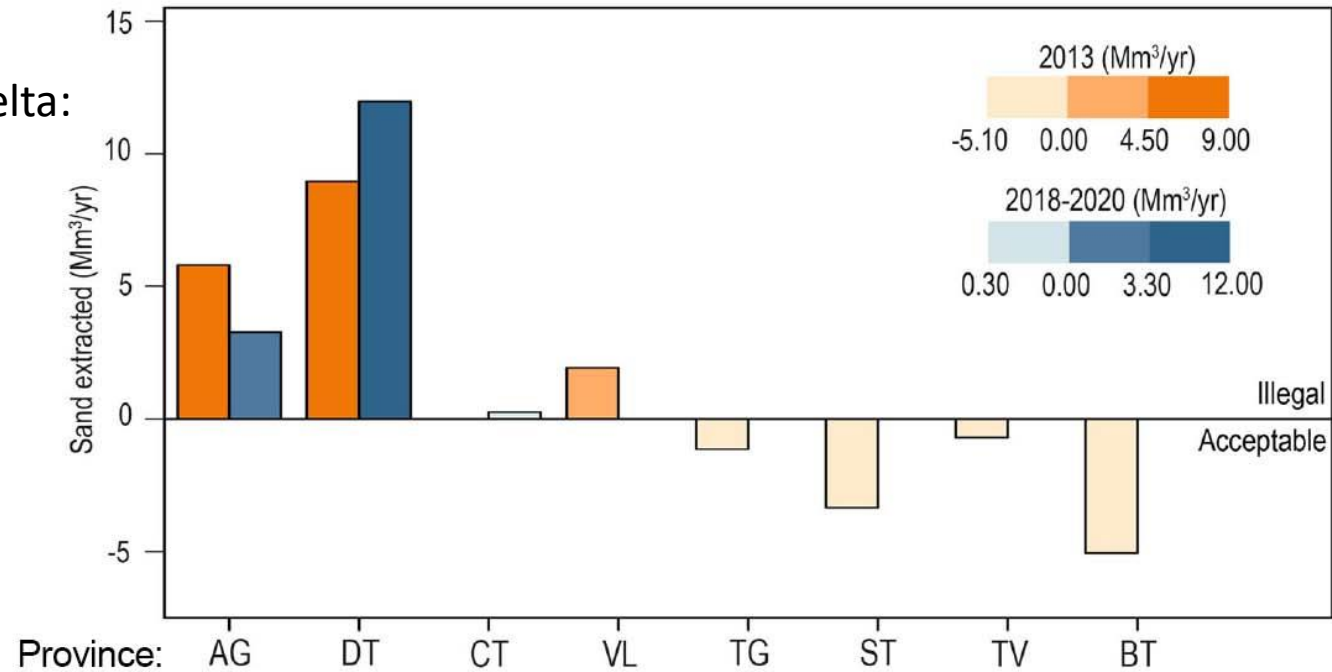
- sand from aeolian sediments (such as those in Sahara desert) usually do not meet the criteria required in construction; Sahara sands have rounded shape and often small diameter; on the other hand, marine sands are alkaline, which is (also) not desirable from construction viewpoint
- when it comes to construction materials, most of the sand and gravel are mined from riverine/fluvial deposits, which often causes alluvium destruction/degradation
- physical consequences of sand mining: riverbed deepening, coarsening and widening, riverbed (riverbank) and slope instability, increased erosion, reduced sand replenishment, altered water table, increased turbidity and suspended solids, noise
- biological consequences: habitat loss, water organisms suffer from reduced respiration and photosynthesis, decreased activity/absence of benthic organisms
- chemical consequences: pollution

Environmental impacts of (river) sand mining – example: Mekong delta





Extent of illegal sand mining in the Mekong Delta:

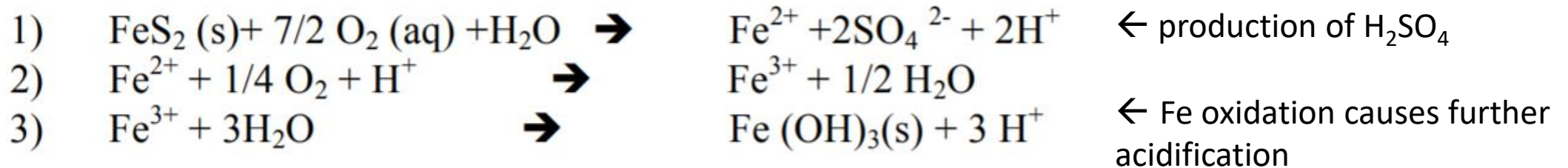


Poyang area (China): sand mining of river deposits (1995 vs 2013)

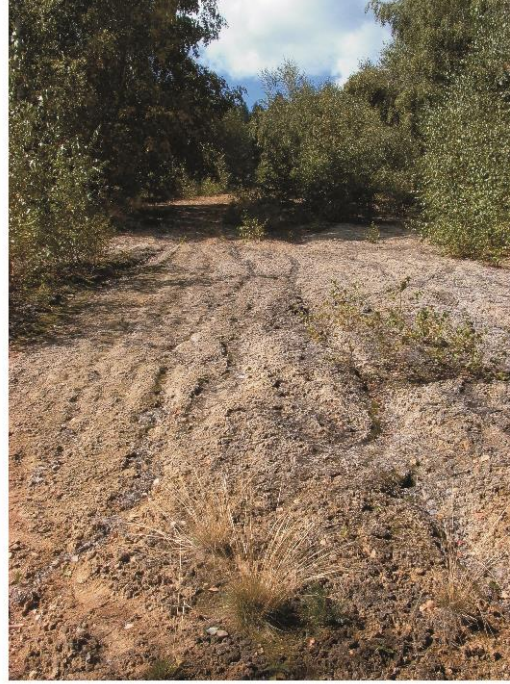


Environmental impacts of **metal ore mining** (mining waste deposits react with atmosphere)

- mining wastes/tailings → contain higher amounts of risk (trace) elements / heavy metals: Cd, Pb, Hg, As, Sb, Cr, Ni, Cu, Co,...
- examples of hazardous elements are Cd, Pb or Hg, but toxicity and mobility of risk elements (Cr, As) is affected also by the valency (oxidation state); for example, Cr^{6+} is (much) more toxic than Cr^{3+}
- in many cases pH of the tailings is acidic because metal ore minerals are sulfides (pyrite, pyrrhotite, chalcopyrite, sphalerite, galena,...)
- usually there are still significant amounts of sulfides left in mining waste deposits; sulfides exposed to atmospheric conditions are oxidized and dissolved, which results in significant drop of pH value (< 3)



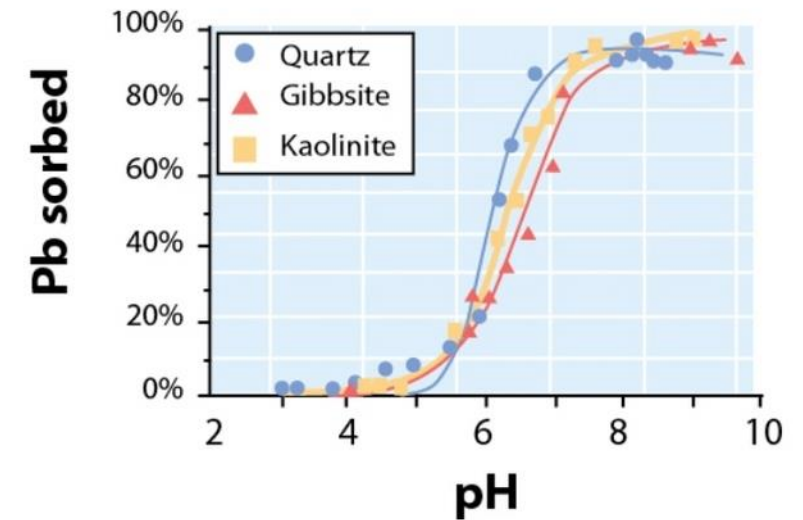
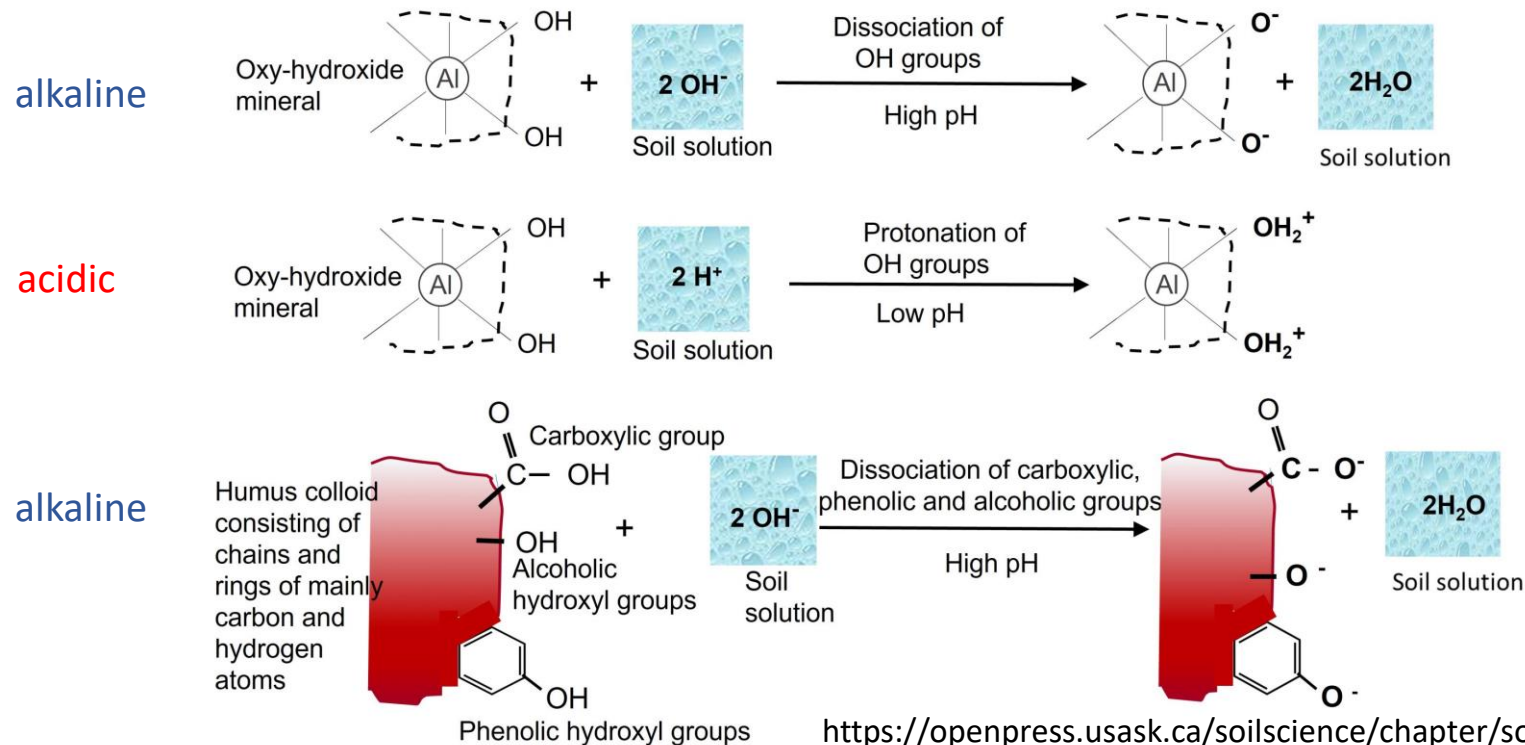
- obviously not all ores are acidic, there are alkaline or neutral ores (carbonates, oxides, bauxite, lateritic ores) → they do not cause acidification; they may alkalize water and soil in some cases



- example of intense acidification originating from old sulfidic mining waste weathering (Šobov, Banská Štiavnica, Slovakia)
- due to soil acidity and aluminum toxicity growth of plants is limited in such conditions → soil erosion

Mobility and toxicity of risk elements at mining-affected sites (role of pH)

- mobility and availability of risk elements that are present in form of cations (Cd, Pb, Ni, Co, Hg, Cu) increases with lowering of pH
- on the other hand, in case of elements that are in anionic form (As, Mo, Sb), their mobility is higher in neutral or alkaline pH
- soil colloids show positive charge in acidic conditions (limited sorption of cations); on contrary, if pH values are higher → functional groups in soil colloids are dissociated → negative charge → sorption of cations increases



<https://www.nature.com/scitable/knowledge/library/introduction-to-the-sorption-of-chemical-constituents-94841002/>

<https://openpress.usask.ca/soilscience/chapter/soil-chemistry/>

Mobility and toxicity of risk elements at mining-affected sites (role of pH and colloid charge)

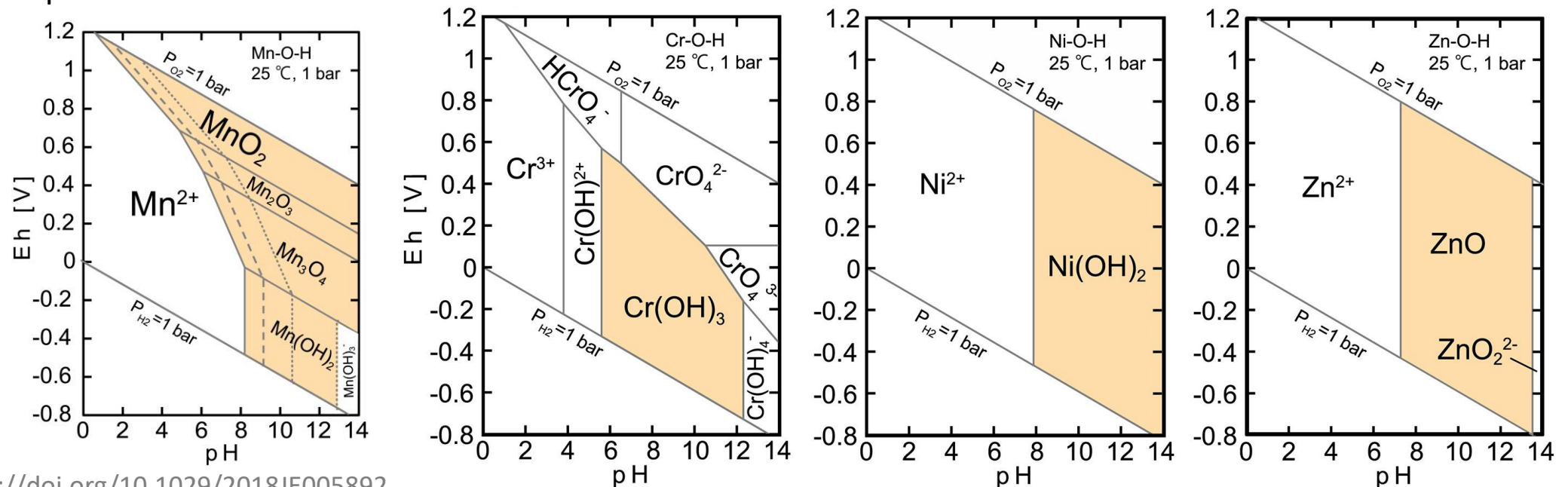
Example:

- There is a difference in mobility of the common nuclear fission products, radioactive ^{137}Cs , ^{90}Sr , ^{99}Tc and ^{129}I .
- In aqueous environments ^{137}Cs and ^{90}Sr ionize to the monovalent $^{137}\text{Cs}^+$, and divalent $^{90}\text{Sr}^{2+}$ cations, while ^{129}I and ^{99}Tc ionize to the monovalent anions ($^{129}\text{I}^-$ or $^{129}\text{IO}_3^-$) and $^{99}\text{TcO}_4^-$.
- If accidental release of fission products occurs in soils dominated by negatively charged sorbents (i.e., layer silicate clays), the cations $^{137}\text{Cs}^+$ and $^{90}\text{Sr}^{2+}$ are retained closer to the point of contamination, whereas the anions $^{129}\text{I}^-$ and $^{99}\text{TcO}_4^-$ pass rapidly through the soil and can threaten groundwater sources (Zachara et al. 2007).
- In contrast, anionic fission products are comparatively less mobile due to the prevalence of metal (oxyhydr)oxide sorbents, which possess significant positively charged sites in acidic (low pH) soils of this region (Kaplan 2003).

Zachara, J. M. et al. Geochemical processes controlling migration of tank wastes in Hanford's vadose zone. *Vadose Zone Journal* 6, 985-1003 (2007).
Kaplan, D. I. Influence of surface charge of an Fe-oxide and an organic matter dominated soil on iodide and pertechnetate sorption. *Radiochimica Acta* 91, 173-178 (2003).

Mobility and toxicity of risk elements at mining-affected sites

- if we want to be precise, we must consider not only pH but redox potential (Eh) as well
- redox potential express electron activity, or in simple terms, whether there are oxidating or reducing conditions in the sample (environment); it is measured with platinum electrode and the values are given as voltage against standard reference (calomel) electrode
- although in soils redox is related to degree of water saturation (water saturation → lower Eh values), we should bear in mind that Eh value is affected also by presence (concentration) of dissolved species
- for given chemical system pH – Eh diagrams may be constructed indicating which chemical forms are stable in specific pH and Eh values

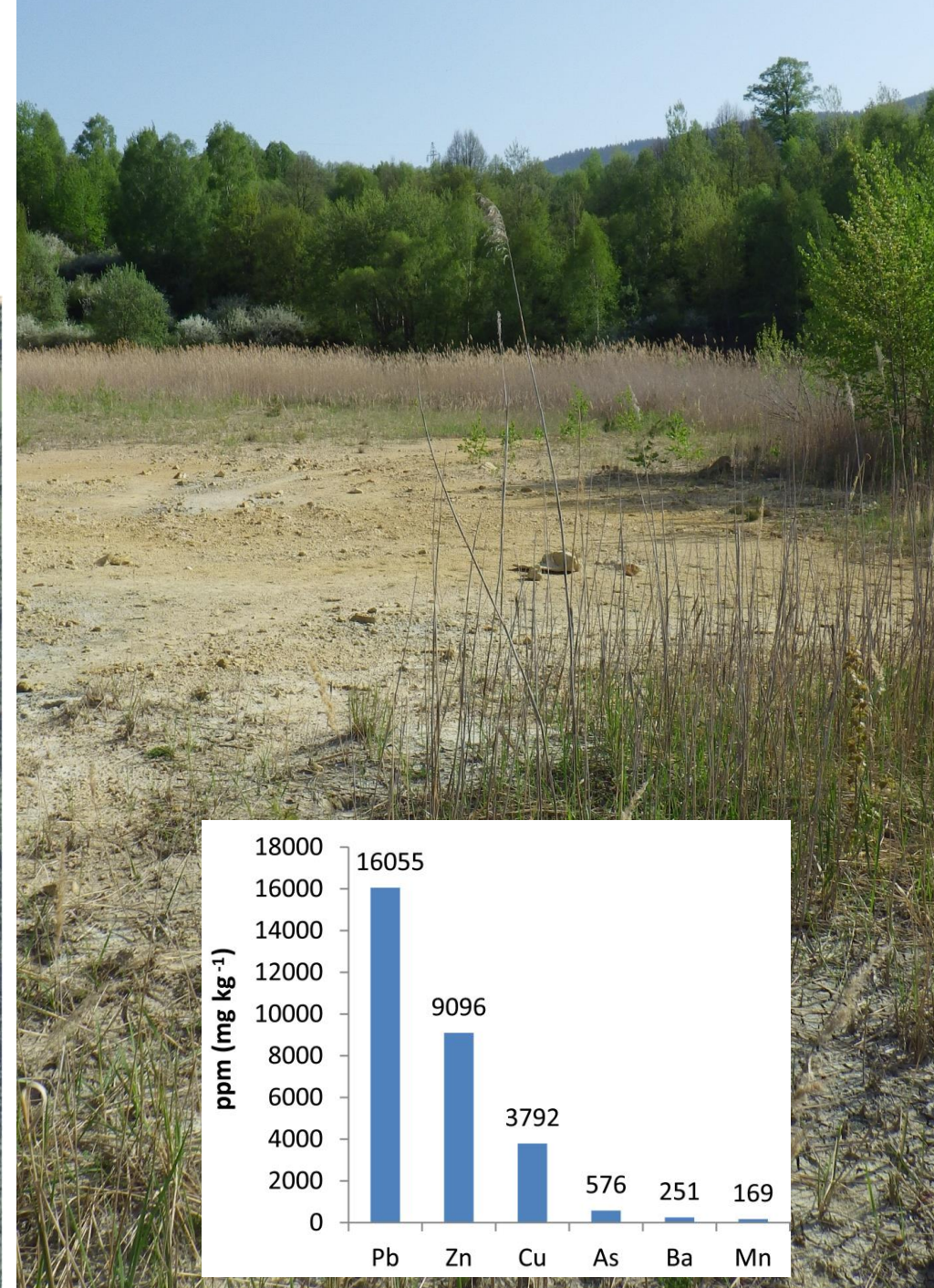
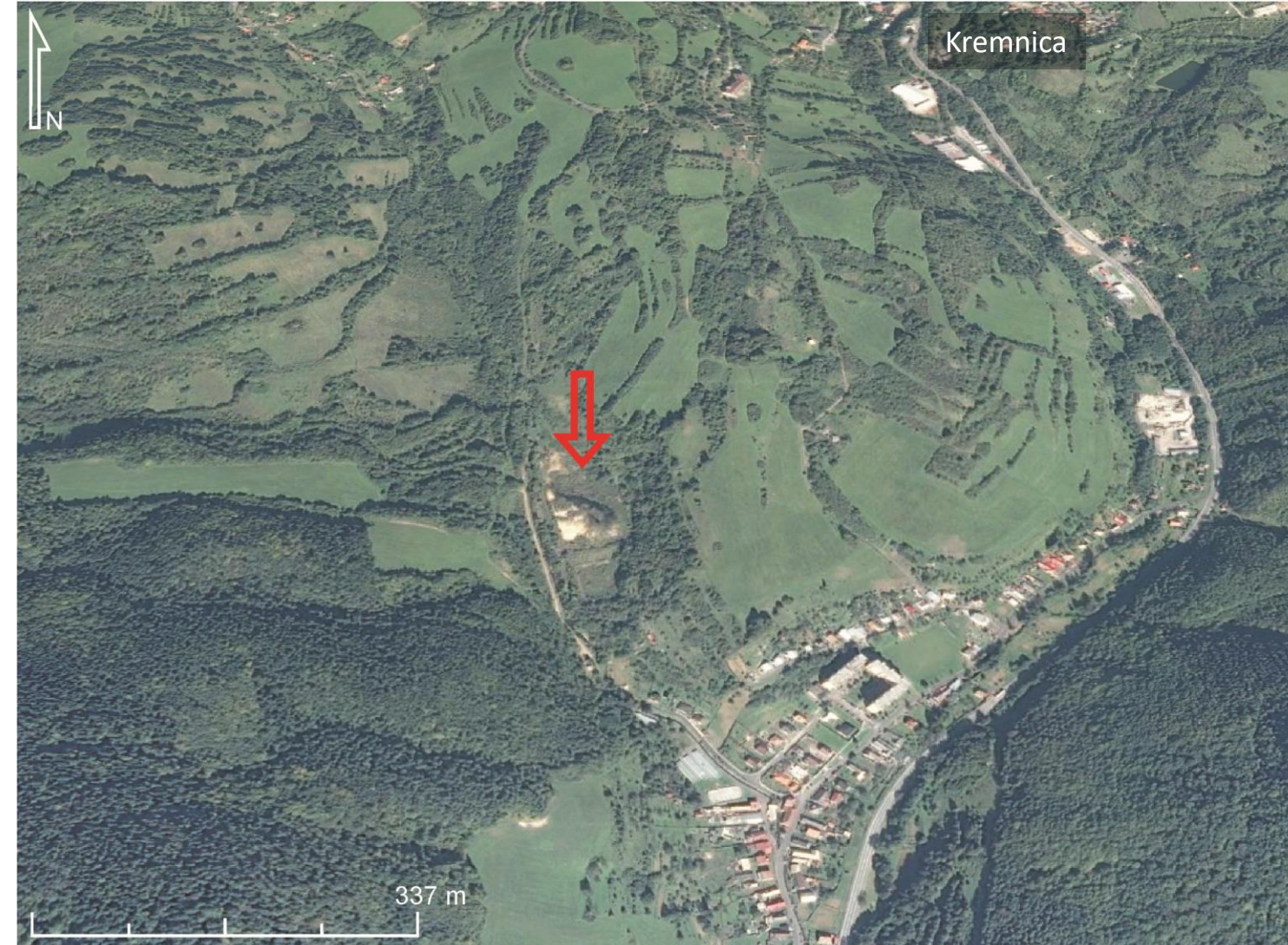


“Ochres”

mostly amorphous and partly crystalline forms of Fe and Al (e.g. ferrihydrite, goethite, lepidocrocite, schwertmannite), which precipitate/form at the bottoms of the creeks → they often act as sorbents for various risk elements (As, Sb,...)



Example of extremely acidic mining waste (pH≈2), originating from mixed sulfidic metal ores, that contains high amounts of Pb, Zn, Cu (near Kremnica, Slovakia)



Example of alkali waste from bauxite (Al ore) processing near former aluminum factory (Žiar nad Hronom, Slovakia)

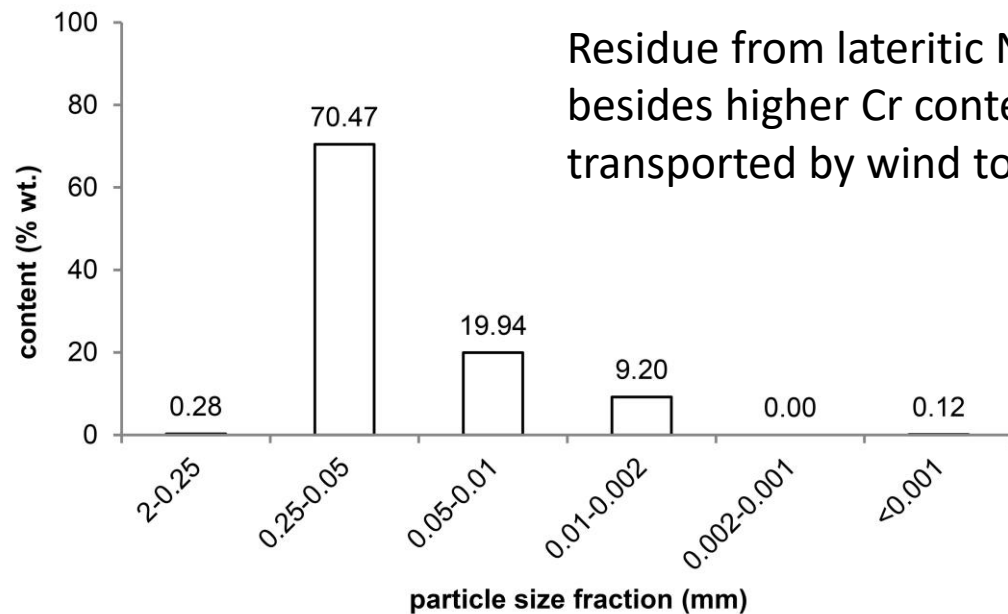


the negative consequences of Al ore processing include strong alkalization of near-by environment, contamination with F, As, and polycyclic aromatic hydrocarbons

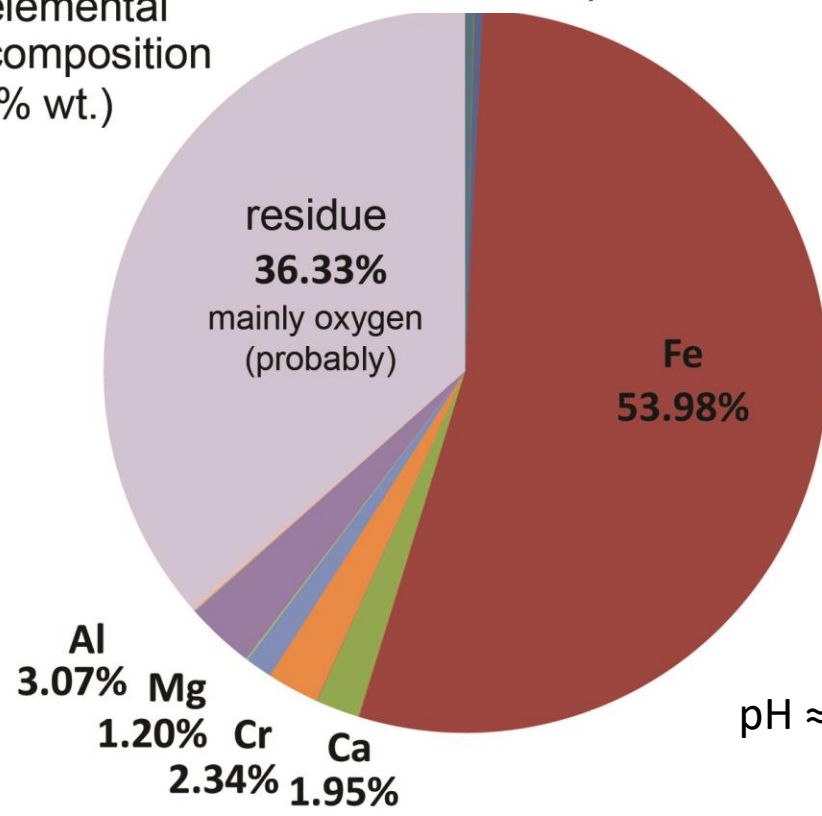


the heap was covered by geotextile to prevent further leaching and particle transport by wind erosion in dry conditions

Residue from lateritic Ni ore processing (Sereď, Slovakia, app. 55 km north-east from BA):
besides higher Cr content, the problem is that the silt/fine sand particles are being
transported by wind to near-by environment when material is dry



elemental
composition
(% wt.)



pH $\approx$ 8 (slightly alkalic)

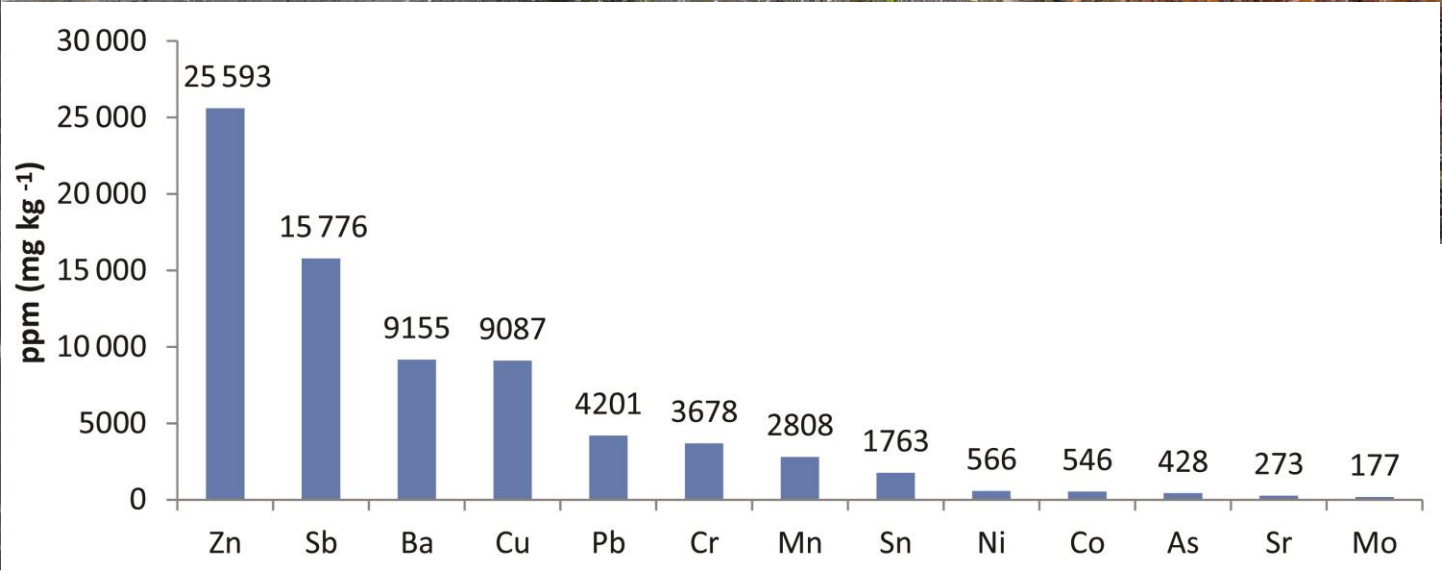
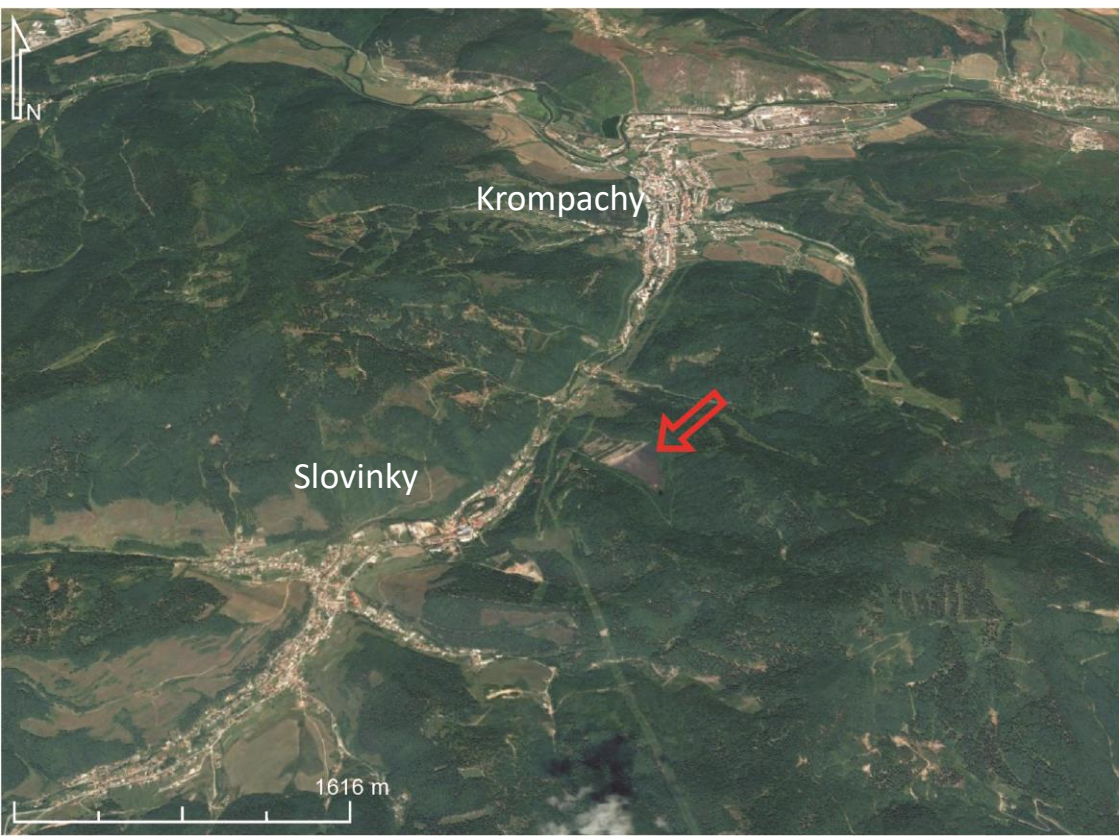


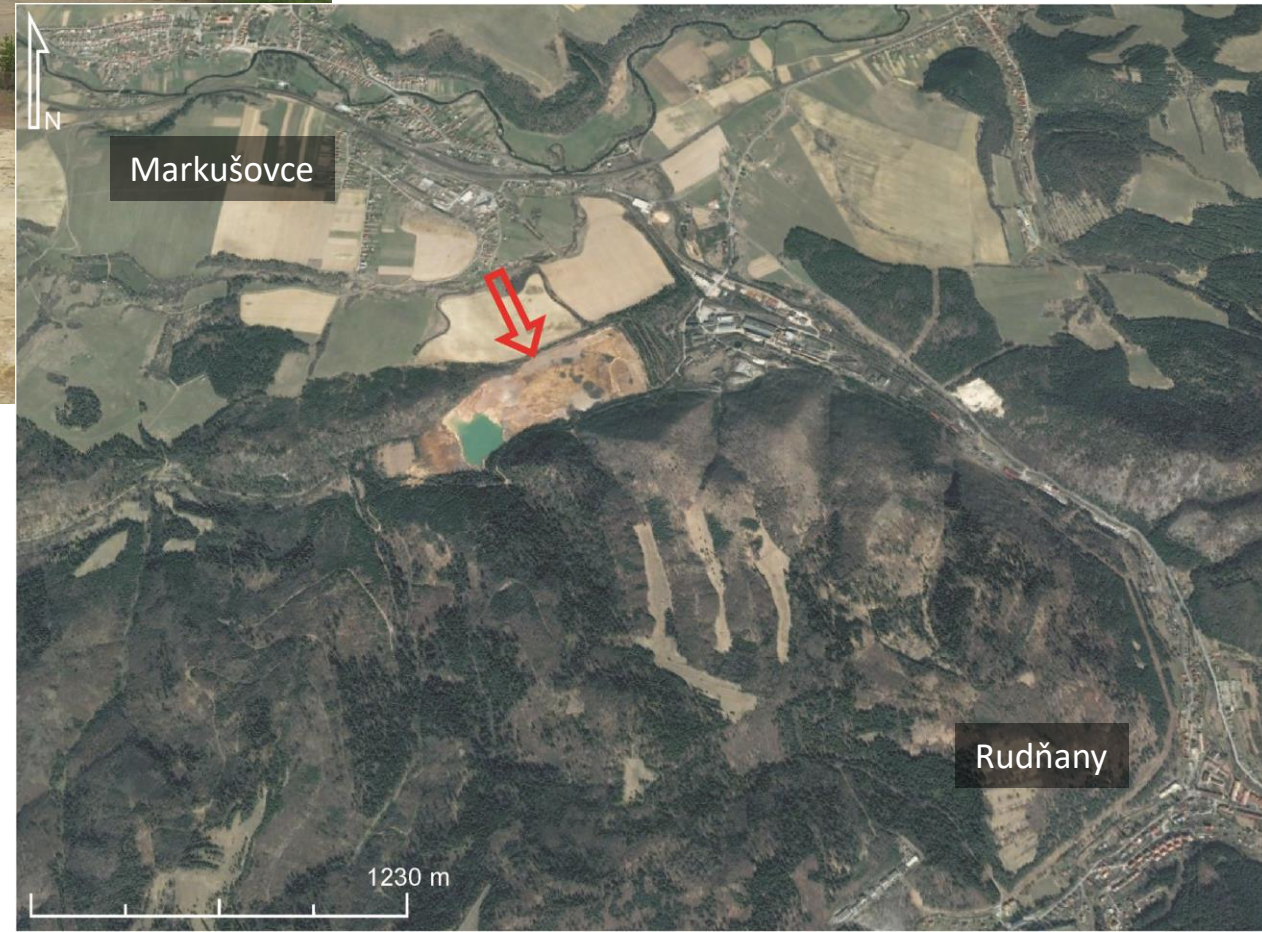
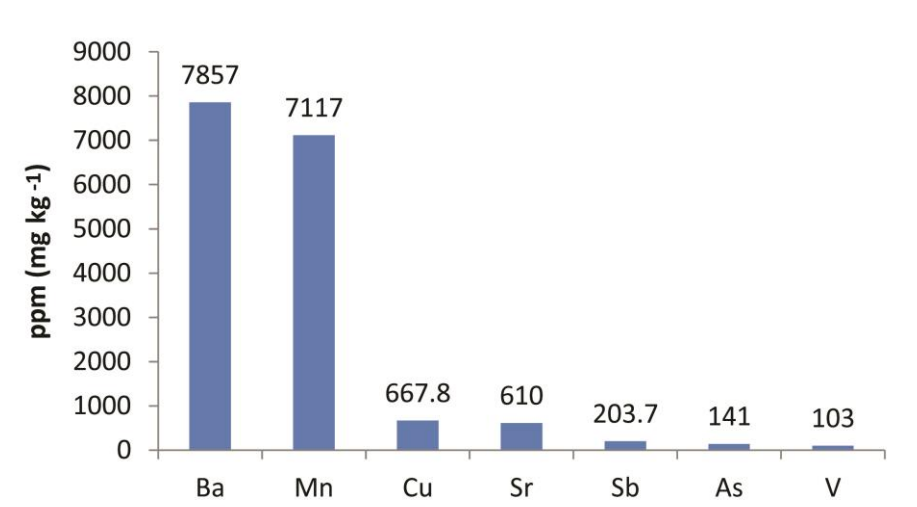


One of the most mined minerals in Slovakia has been **magnesite** (MgCO_3). It is used for MgO production, which subsequently used for making of heat-resistant materials, such as blast furnaces used in metallurgy. Although this type of ore-processing do not impose significant risk of producing toxic substances, it generates lot of dust.



Heap deposited between Krompachy and Slovinky (eastern Slovakia):
mining waste from the processing of mainly copper and iron ores (carbonates, sulfides, sulfates); the material is characterized by an alkaline pH (8.81) and higher content of various risk elements





Mining waste deposit with similar characteristics is located between Markušovce and Rudňany (the same region as previous site Slovinky). Although the contents of risk elements plotted in the figure on the right are not very high, the results of different studies showed higher values. The material deposited on the site is not homogenous and its chemical properties change over the time due to the chemical reactions that take place in the heap and in near-by environment.

Rare earth elements (REE) / rare earth metals mining

- Scandium, Yttrium, Lanthanum, Cerium, Praseodymium, Neodymium, Samarium, Europium, Gadolinium, Terbium, Dysprosium, Holmium, Erbium, Thulium, Ytterbium, Lutetium
- demand is growing, as the usage of electronics is increasing; REE are used in aerospace components, aircraft engines, lasers, car batteries, computer hard drives, cell phones, LED light bulbs, optical electronics, photovoltaics, wind turbines, magnets, x-ray machines, fiber optics, ceramics, catalysis, modern medical devices, such as MRI, etc.
- vast majority of REE (> 80 %) has been mined/produced in China, with minor contributions from USA, Australia and India; perspective mining areas are located also in the other states (Russia, Brazil, Central and South Africa, Thailand, Myanmar, Vietnam, Laos, Sweden, Canada, Greenland) but mining in these areas has been very limited or none
- since REE deposits, that have been mined recently, are relatively shallow, the ore is excavated through the open pit method (surface mining) → relatively large area is affected/disturbed
- the process of obtaining REE in concentrated form from the ore is relatively complicated and hazardous (from environmental viewpoint); environmental impacts differ based on specific ore/mineral types and applied processing

Rare earth elements (REE) / rare earth metals mining – ore minerals

- typical mineral deposit only contains up to five REE at higher concentrations (Ce, La, Nd, Pr, Sm) and the most abundant elements are usually the least expensive; REE content in ore material is often < 10 % of weight
- although there are > 200 minerals that contain REE, amongst most common are **monazite** and **bastnäsite**; monazite exists as a group of arsenates, phosphates, and silicates, but the primary REE bearing monazite is a complex phosphate $(\text{Ce,La,Nd,Th,Y})\text{PO}_4$; bastnäsite, also known as bastnaesite and bastnasite, is a fluorocarbonate $(\text{Y,Ce})\text{CO}_3\text{F}$
- example of mineral containing REE is **eudialyte**, which is a complex cyclosilicate with zeolite like structure and formula $\text{Na}_4(\text{Ca,Ln})_2(\text{Fe}^{2+},\text{Mn}^{2+},\text{Y})\text{ZrSi}_8\text{O}_{22}(\text{OH,Cl})_2$;
- REE are present in “**ion adsorption clays**” (e.g. in kaolinite) as ionic species in exchangeable positions; typically, these clays are enriched in Y, La, Nd, Gd, Er, and Yb



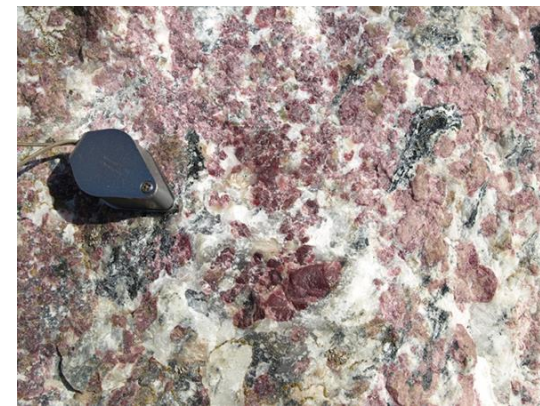
bastnaesite



monazite



IA clays



← eudialyte

Rare earth elements (REE) / rare earth metals mining – environmental impacts

- environmental implications usually follow from the ore type and associated processing
- As indicated waste from REE ore processing often contains certain portion of **radioactive elements**. Among the REE minerals, monazite is the primary source of Thorium. Monazite from the Kerala deposits (India) contains 7.96 % of thorium oxide.
- advantage of eudialyte compared to other minerals is low concentration of ThO_2 and U_3O_8 and hence lower amounts of radioactive elements (^{232}Th , ^{238}U)
- REE extraction from IAC (ion adsorption clays) → a wastewater is produced with high concentrations of ammonium sulfate and **heavy metals**
- additionally, the waste contains the **acids** and **organic solvents**
- besides **polluting water** and **soil**, left unmitigated, waste from REE ore processing can pose human health risks directly, for example, through **breathing** of contaminated dusts

Bayan Obo, China

ore bodies

tailings dams

Bayan Obo Mining District

Image © 2024 CNES / Airbus

3.40 km

Google Earth



Rare earth elements (REE) / rare earth metals mining

- The Bayan Obo (China) is perhaps most significant REE mining site in world.
- The production started in 1959. It is an open-cast mining surface that is estimated to release 62 tons of mine dust into the environment annually. The ore is mined and transported to milling facilities in Baotou where 90% of the material is deposited in a tailing dam covering an area of 11.5 km². When the water from the dam evaporates, this site becomes a major source of mineral dust.
- the area and soils at Baotou City are contaminated with heavy metals and radioactive ²³²Th
(<http://dx.doi.org/10.1016/j.jenvrad.2015.10.027>)
- REE mine dust may pose a health risk to people through inhalation by mechanisms of reactive oxygen species production in human lung cells
(<https://doi.org/10.1016/j.scitotenv.2020.139759>)



Reclamation / remediation of mining-affected sites

- remediation techniques for contaminated areas are a subject on its own and they will not be discussed here in detail
- when it comes to mining waste treatment, the measures should be aimed to protect the groundwater; general rule / aim → **to limit the mobility of risk substance**
- usually, the contaminants are being spread by water; to prevent it, some sort of **water treatment should be applied** (directly on site); this could be achieved (for example) by adding a chemical reagent that will cause oxidation or reduction, and subsequent precipitation of risk elements/substance
- use of **permeable reactive barriers** (PRB) for in situ water treatment; PRB is a subsurface emplacement of reactive materials through which a dissolved contaminant plume flows; usually there is a sequence of processes (1. filtration, 2. sedimentation, 3. oxidation,..), which cause the removal of the contaminants
- if waste material contains significant concentration of some valuable element, it can serve as a **source of secondary mining**
- often the mining waste (or waste from ore processing) is accumulated in huge amounts and there is practically no other (economical) option than to **encapsulate the whole heap with impermeable** (geotextile) **material** to prevent the spread of the hazardous substances