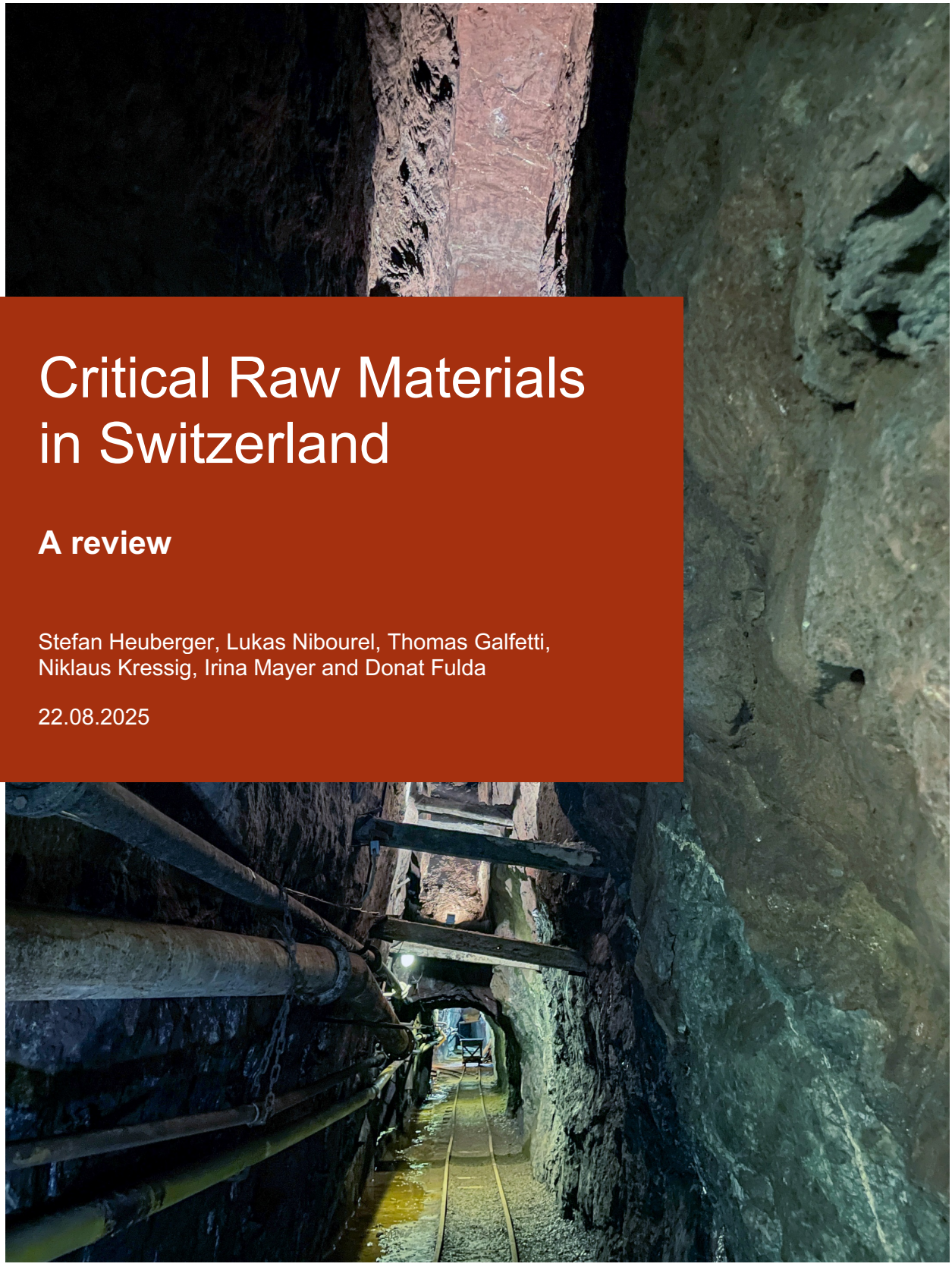
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Critical Raw Materials in Switzerland

A review

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1 Executive Summary

Critical raw materials (CRMs) such as copper (Cu), manganese (Mn), cobalt (Co), rare earth elements (REEs), lithium (Li), graphite (C), platinum group metals (PGMs), and others, are crucial for the energy transition and digital transformation. While the global demand for these materials is expected to increase, their supply is at risk due to the current geopolitical landscape. Although the direct demand for CRMs is negligible in Switzerland, the Swiss industry is heavily reliant on imports of semi-finished products and components containing CRMs, such as magnets, batteries, and computer chips. A domestic mining or processing industry for metallic ores or CRMs is absent in Switzerland.

According to the current geological knowledge, Switzerland has no significant CRM deposits that might be economically relevant in the near future. Some CRM-bearing, mostly smaller-sized metallic deposits were mined until the 1960s. Regional-scale geological investigations have localised and assessed occurrences in a patchy manner but the current understanding is limited by the fact that no country-wide exploration programmes have been carried out in the past in a coordinated way. A dedicated prospection programme for CRMs is currently not on the national agenda.

This report provides an overview of the geospatial distribution and the characteristics of hundreds of natural CRM-bearing occurrences in Switzerland with special emphasis on the CRMs that are currently regarded as most critical for the energy transition: Cu, Mn, Co, Ni, Ge, REEs, Li, graphite and PGMs. It is primarily based on a review of the Resource Information System (RIS), a database hosted by the Georesources Switzerland Group (FGS). A series of large-scale tectonic and lithological maps illustrate the relationship between geodynamics and the documented CRM occurrences. The report also documents the availability of CRMs from secondary sources including the ongoing efforts to recover them.

The documented CRM occurrences are numerous, but generally rather small in volume and, with some exceptions, low to moderate in grade (concentration of a given CRM). Many occurrences are associated with distinct rock types, tectonic domains or structures, highlighting areas with potentially favourable geological settings for CRM-bearing mineralisations.

Cu represents the most abundant CRM in the RIS database and occurs at 278 localities. It often occurs in or close to Permo-Carboniferous sedimentary and volcanic rocks, which deposited in intra-continental and normal fault-bounded troughs. Today, these rocks and the apparently associated Cu occurrences are locally exposed in the Helvetic, Penninic, Austroalpine and South Alpine tectonic domains, variably overprinted by Alpine deformation and metamorphism. The formation of these troughs, the associated magmatic and hydrothermal activity as well as the subsequent Mesozoic marine transgression providing saline fluids, apparently favoured the enrichment of Cu in occurrences showing characteristics of epithermal or Sediment-Hosted Stratiform Copper-type deposits (SSC). Ophiolite-hosted Cu commonly occurs in the Upper Penninics (Valais, Graubünden) and seems to be associated with Volcanogenic Massive Sulfide ore-type systems (VMS).

Many of the 40 documented Mn occurrences are associated with Mesozoic oceanic mafic-ultramafic rocks (e.g. associated with seafloor exhalative processes) or deep-sea sediments (e.g. Mn-rich radiolarites or shales) of the Upper Penninics and Lower Austroalpine in Valais and Graubünden.

Ni and Co occurrences (28 and 29 localities, respectively) are rare and typically associated with polymetallic hydrothermal vein systems hosted in the metamorphic basement, mafic-ultramafic rocks or in Permo-Carboniferous shales.

REE occurrences (Y, La, Ce or Nd) are reported from 22 localities, mostly hosted by high-grade metamorphic rocks or pegmatites, scattered and generally relatively small.

Minor graphite-bearing occurrences (15 localities) are primarily hosted in high-grade metamorphic rocks, particularly in the Penninic and Helvetic domains.

PGMs (2 localities containing Pt) and Li-bearing pegmatites (2 localities) are rarely documented and small-sized.

Li concentrations higher than 80 mg/l were detected in two deep wells in the Swiss Molasse basin. The potential of Li extraction from deep saline aquifers remains mostly unexplored.

Ge, Ga, Dy and Pr, which are also considered as most critical for the energy transition, are rarely or not documented in the RIS database.

There are currently no relevant secondary sources, such as historic mine tailings or industrial waste, that could represent a potential source of strategic raw materials in Switzerland in terms of quantity. However, the recovery of CRMs from electronic waste is increasing, with some Swiss companies expanding their production, particularly of Li, Co, Mn, C and Ni from car batteries.

Although Switzerland is less systematically explored and historically mined than other EU countries, our review shows that there is valuable data on naturally occurring CRMs indicating potentially favourable geology. This may guide future prospection efforts, especially for Cu, Mn and possibly Co, graphite and REEs. Most prominently, the Permo-Carboniferous sedimentary and volcanic rocks of the Helvetic, Penninic, Austroalpine and South Alpine tectonic units, as well as the Mesozoic oceanic rocks stand out as domains with higher prospectivity. These domains potentially host Cu-, Co-, Mn-bearing mineral systems while the high-grade metamorphic rocks (e.g. the Lepontic domain) could host graphite, REE or Li occurrences. Whether a reasonable prospect of economic extraction exists for some occurrences can only be established through detailed exploration programmes and dedicated feasibility investigations. In addition, most documented CRM occurrences are located in remote Alpine regions with limited infrastructure or in protected areas.

The current geological understanding of CRMs in Switzerland remains limited due to the absence of systematic and coordinated exploration in the past. A structured mineral prospection programme would be needed to confidently assess the potential for CRM occurrences. Future academic research should focus on better understanding the genetic mineral systems of the various types of CRM-bearing occurrences described in this report.

2 Introduction

2.1 Motivation

Critical raw materials (CRMs) are the basic building blocks for key technologies that are necessary to secure the energy transition by 2050 and enable the digital transformation, among other things. To achieve climate neutrality, the world society is faced with the immense task of transitioning from the current, CO_2-intensive, fossil fuel-based energy system to a renewable one. The manufacturing of a broad range of key technologies across all industries, especially computer chips, batteries, solar photovoltaics, wind turbines, traction motors, heat pumps, electrolysers and data transmission cabling, all rely heavily on the availability of certain CRMs (Fig. 1).

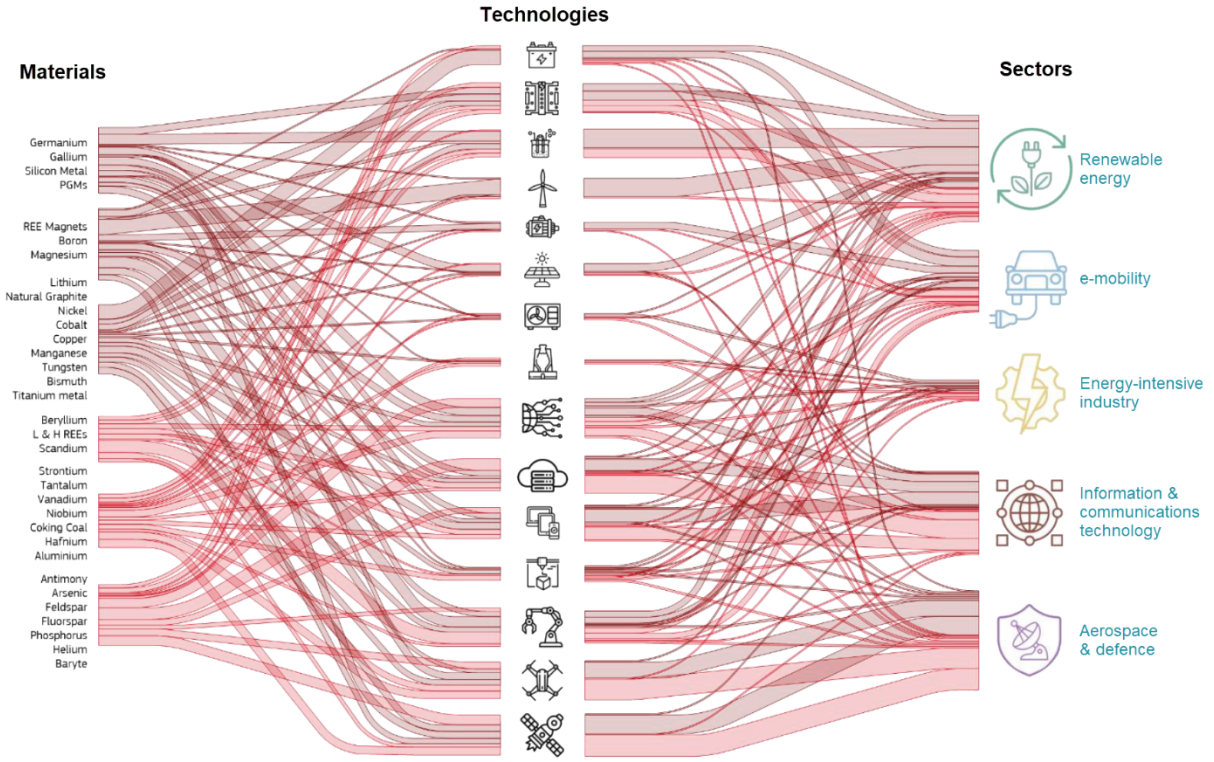


Fig. 1. Sankey diagram showing the share of raw materials used across the fifteen technologies and five sectors considered in the Joint Research Centre of the European Commission report (Carrara et al. 2023), focusing on the strategic (dark red) and critical materials (bright red). The renewable energy sector requires the biggest share of strategic raw materials. See Carrara et al. (2023) for more details on the technologies considered and the required raw materials.

The International Energy Agency (IEA 2024) indicates that the raw material demand for clean energy technologies is expected to double until 2030 in a scenario reflecting current policy settings. This demand would nearly triple by 2030 and quadruple by 2040 in a net-zero scenario. With the entry into force of the EU Critical Raw Material Act (EU 2024) on the 23 May 2024, the European Commission aims at ensuring the EU's access to a secure, resilient and sustainable supply of CRMs and, to significantly reducing the EU's dependence on single third-country suppliers, promoting circularity and establishing sustainable sourcing practices. In particular, the CRM Act sets that by 2030, the EU's primary extraction capacity will have to cover at least 10% of the EU's annual consumption of CRMs. It also sets that the EU should process 40% of its CRM needs and cover 25% of its needs through recycling. The EU should also diversify its imports of CRMs and, for each CRM, should not depend on a single third country for more than 65% of its supply by 2030.

As the EU is far from the target of 10% of domestic production for most raw materials (see Fig. 2 and the EU Raw Materials Monitoring Dashboard for a current overview of the CRMs flows), Article 19 of the CRM Act stipulates that each EU Member State has to draw up a national programme for general exploration of CRMs, including mineral mapping, geochemical and geophysical surveys and the development of predictive maps to locate promising mineral deposits. In order to assist policy makers, geological surveys and the mining industry in preparing relevant exploration programmes, EuroGeoSurveys recently published a first set of maps showing the occurrences of CRMs situated onshore (Fig. 3 and offshore).

To secure and diversify access to raw materials in the EU under the CRM Act, the EU Commission selected in March 2025 47 CRM strategic projects that involve extraction, processing, recycling and substitution of CRMs (Fig. 4).

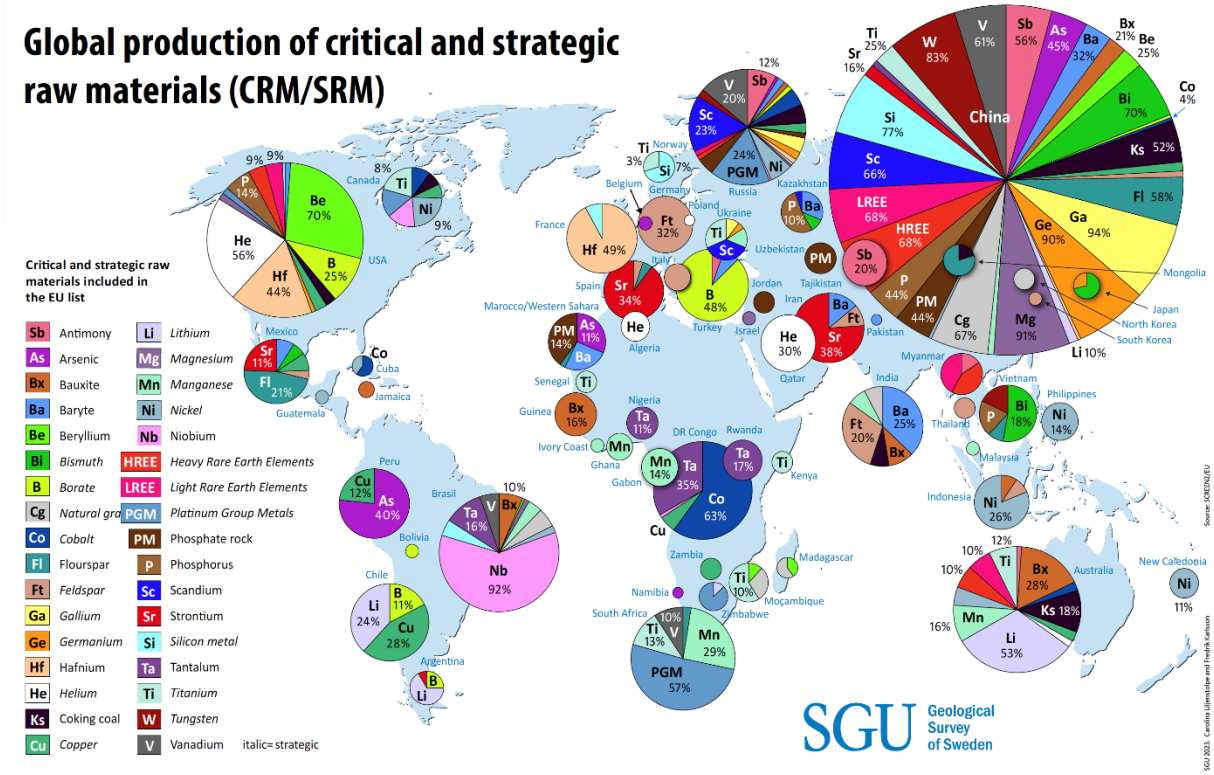


Fig. 2. Global production of critical and strategic raw materials (SGU 2023). Each circle shows estimates of a country's average production [weight %] of various CRMs between the 2016 and 2020. Production refers to primary production, which in most cases corresponds to ore or concentrate.

Switzerland has a relatively high per capita consumption of metals, non-metallic minerals and energy materials/carriers (Tab. 1). With the exception of most non-metallic minerals (such as gravel, sand, and hard rock aggregates, among others), which are produced domestically, all of the metals, metal-bearing components and energy materials/carriers are imported.

Tab. 1. Domestic material consumption of metals, non-metallic minerals and fossil energy materials/carriers in 2022 in Switzerland (from Federal Statistical Office - Material flow accounts - Direct input flows and their aggregates).

Domestic material consumption DMC in 2022 [tonnes per capita]	
Metals	0.307
Non-metalic minerals	6.258
Fossil energy materials/carriers	1.468

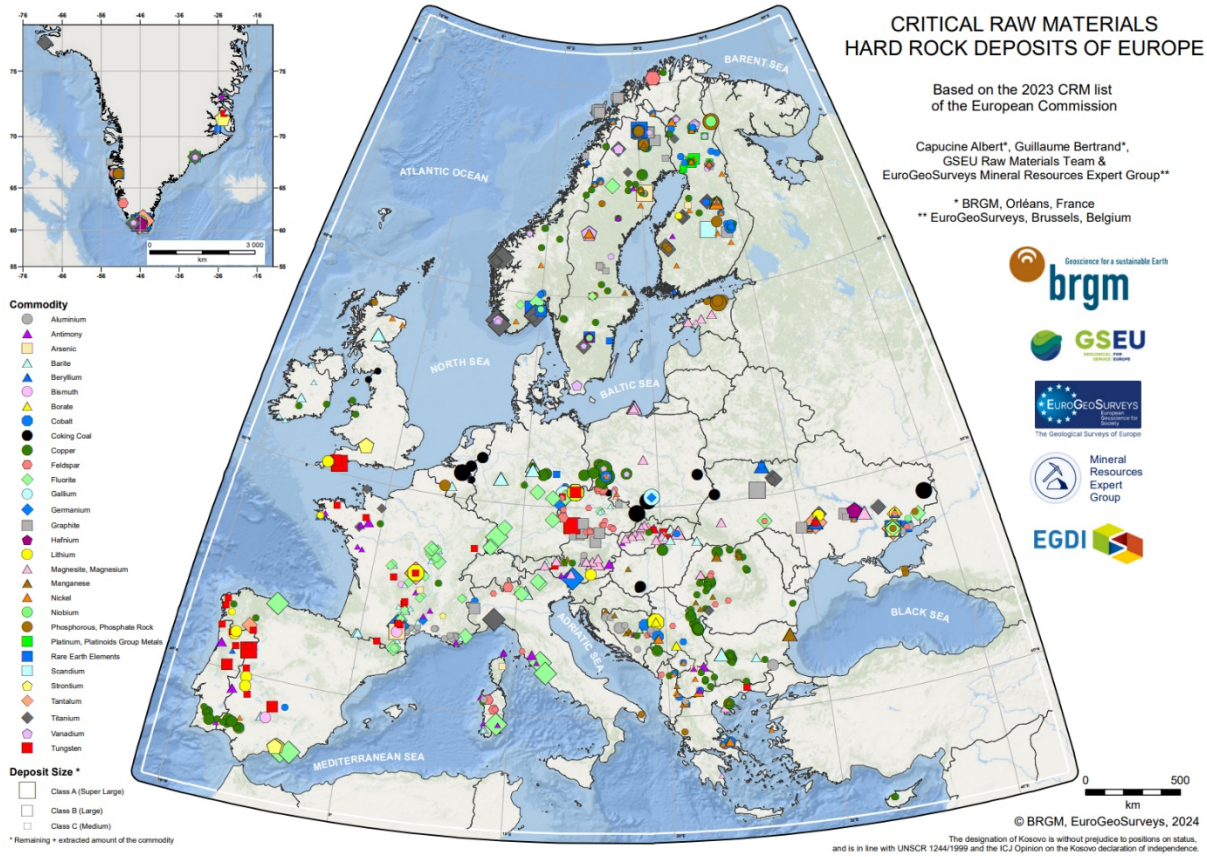


Fig. 3. Onshore critical raw materials hard rock deposits of Europe (Albert & Bertrand 2025). See here for an interactive GIS version of the map from the European Geological Data Infrastructure Portal (EGDI). The absence of data points in Switzerland is explained by the fact that only Class A/B/C deposits (A = Super Large, B = Large and C = Medium Size deposits) are considered economically important, while the occurrences in Switzerland are classified as Class D (small deposits).

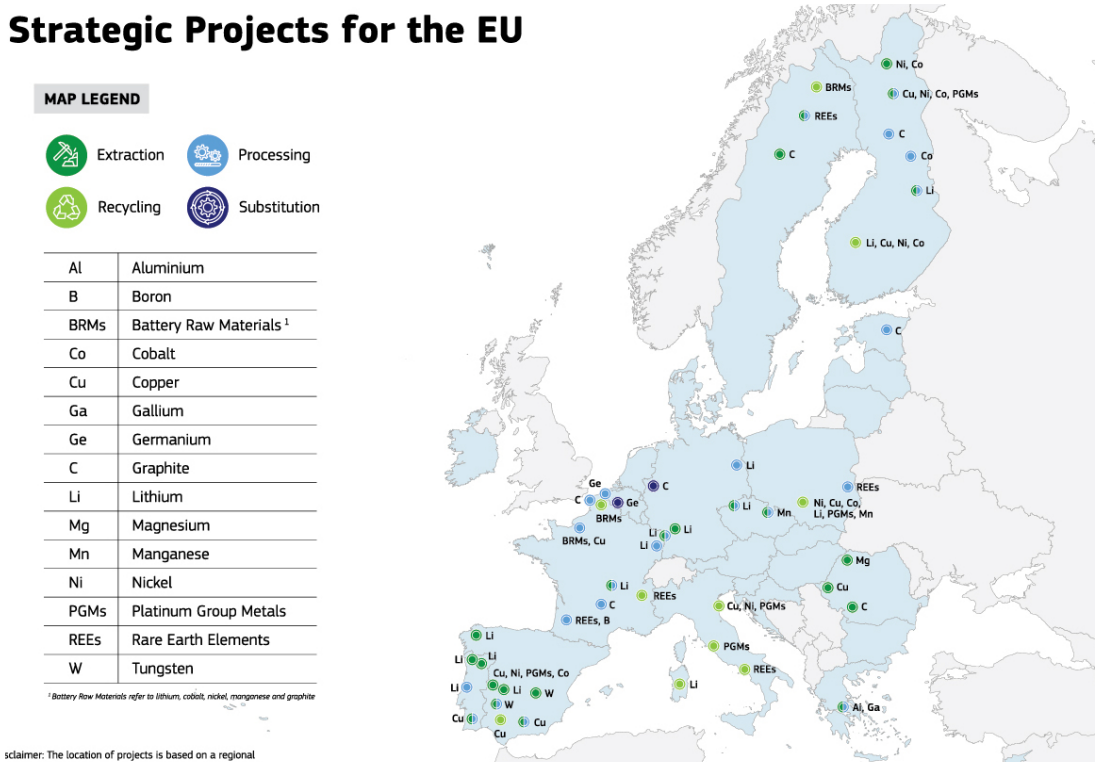


Fig. 4. The 47 strategic projects selected by the EU Commission on 25.03.2025 (European Commission 2025).

While Switzerland, as non-EU member state, is not directly confronted with the CRM Act or its obligations, there is a growing concern whether, and how far, the Swiss high-tech manufacturing industry is exposed to risks related to the supply of CRMs (see Postulate 20.3950 and the Interpellation 25.3155 submitted to the National Council) and the position of the Swiss Rare Metals Foundation ESM (Niklowitz 2024). In order to secure Switzerland's long-term economic resilience and industrial competitiveness through forward-looking trade policy instruments, the Motion 25.3947 asks the Federal Council ensure that supply security for strategically important raw materials and semi-finished products is a key part of any free trade agreement (FTA) and that the right provisions are included in the agreements.

In its report answering to the Postulate 20.3950, the Federal Council (2024), assisted, among others, by the State Secretariat of Economic Affairs SECO, the Federal Office for National Economic Supply FONES, the Federal Office for the Environment FOEN and the Swiss Geological Survey swisstopo), recognised that:

- the Swiss industry fully relies on imports of certain raw materials, but these materials are mostly bound to semi-finished products or components. The quantities of imported raw or refined metals/minerals, classified as CRM, are relatively small.
- Switzerland mainly imports refined copper (in the form of cables, plates and pipes) for its machinery industry (electronics, precision tools, etc.), phosphate for its pharmaceutical and agriculture industries, and magnesium and titanium for its high-tech, chemical, optical and biomedical industries. A large proportion of raw materials or semi-finished products are not imported directly from the producing countries, but mainly from EU countries. Depending on the materials' type, the EU can be heavily reliant on single third-country suppliers.
- a monitoring system would be required to anticipate and de-risk potential bottle necks in the supply of raw materials (and semi-finished products) important for the Swiss industry.
- according to the current state of geological knowledge, the Swiss subsurface does not offer economically relevant deposits of metals, rare earths, energy raw materials or industrial minerals that would be suitable for commercial development.
- except for steel industry, which sources its raw iron essentially from metal scrap, there are no metal ore refineries or concentrators in Switzerland.

2.2 Goal of this review

In the light of the growing importance of CRMs in the geopolitical landscape and considering the relevance of this topic also in Switzerland, the goal of this review is to inform the public and the relevant authorities about the country's CRM occurrences, with a special emphasis on those that are relevant for the energy transition.

Whether one or more CRM occurrences described in this report have a reasonable prospect of economic extraction can only be established through detailed exploration programmes and dedicated feasibility investigations. An assessment of the economic potential is not part of this investigation.

2.3 Structure of this report

Chapter 3 provides a broad definition of the term CRM. The investigation procedure used to screen the geological archives in Switzerland for CRMs is presented in Chapter 4.

Chapter 5 gives an overview of the known natural occurrences of CRMs in the Swiss subsurface.

Chapter 6 informs on the status quo regarding the recovery of CRMs from secondary sources, in particular from the recycling of electronic waste.

The conclusions of the assessment and an outlook are presented in Chapters 7 and 8, respectively.

3 Critical and strategic raw materials: a definition

There is no single, globally recognised definition of critical raw materials. Several organisations and governments have developed their definitions and criteria based on their specific needs, policies, and economic priorities. The following definition attempts to combine the various definitions into one.

Critical raw materials are materials that are strategically and economically important to a country's economy but have a high risk of supply disruptions. Used in environmental technologies, consumer electronics, health, steel-making, defence, space exploration, and aviation, these materials are not only "critical" for key industry sectors and future applications, but also for the sustainable functioning of a countries' economy.

The European Critical Raw Material Act additionally defines the sub-category "Strategic Raw Materials" (SRMs), a subset of CRMs (Fig. 5). These are considered as of high importance in strategic sectors such as renewable energy, digital, space and defence technologies and for those that are likely to create supply risks in the near future.

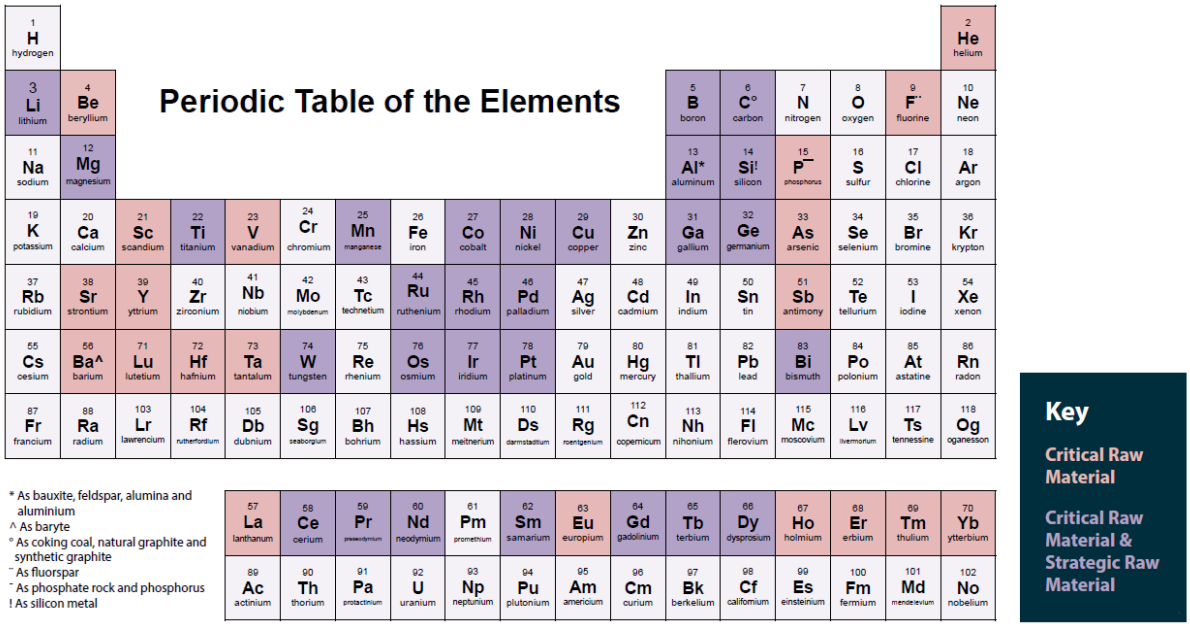


Fig. 5. The 34 CRMs as defined by the EU Commission, highlighted in the periodic table of elements. Note that there are more than 34 elements highlighted here. This is because the Heavy and Light rare earth elements are counted as a group each (IGI 2024).

4 Investigation procedure and data sources

4.1 List of the investigated CRMs

As part of this investigation, we have established a list of critical raw materials to be considered in the process of screening the geological archives (documented in Chapt. 5). At the time being, there is no globally-adopted list of CRMs and there is none officially recognised in Switzerland. Europe and the United States of America have defined lists (EU: Critical Raw Material Act; US: Energy Act), but these are tailored toward their economic interests and do not explicitly focus on the materials required for the energy transition technologies.

To fill this gap, the International Renewable Energy Agency (IRENA & NUPI 2024) recently produced a CRM list ranking the materials that are globally essential for renewable energy purposes (Fig. 6). In a two-step approach, CRMs are first compiled based on how frequently the materials are listed in international (non) governmental organisations as well as in academic publications. Then, a composite index of criticality is created based on six indicators according to Graedel et al. (2015): (1) trends in the listing of critical materials, (2) diversification of materials markets, (3) abundance of minerals in the Earth's crust, (4) demand scenarios, (5) recycling potential and (6) substitution potential. The combination of the two steps results in a list of CRMs needed for energy transition technologies (see the category "Most Critical" in Fig. 6).

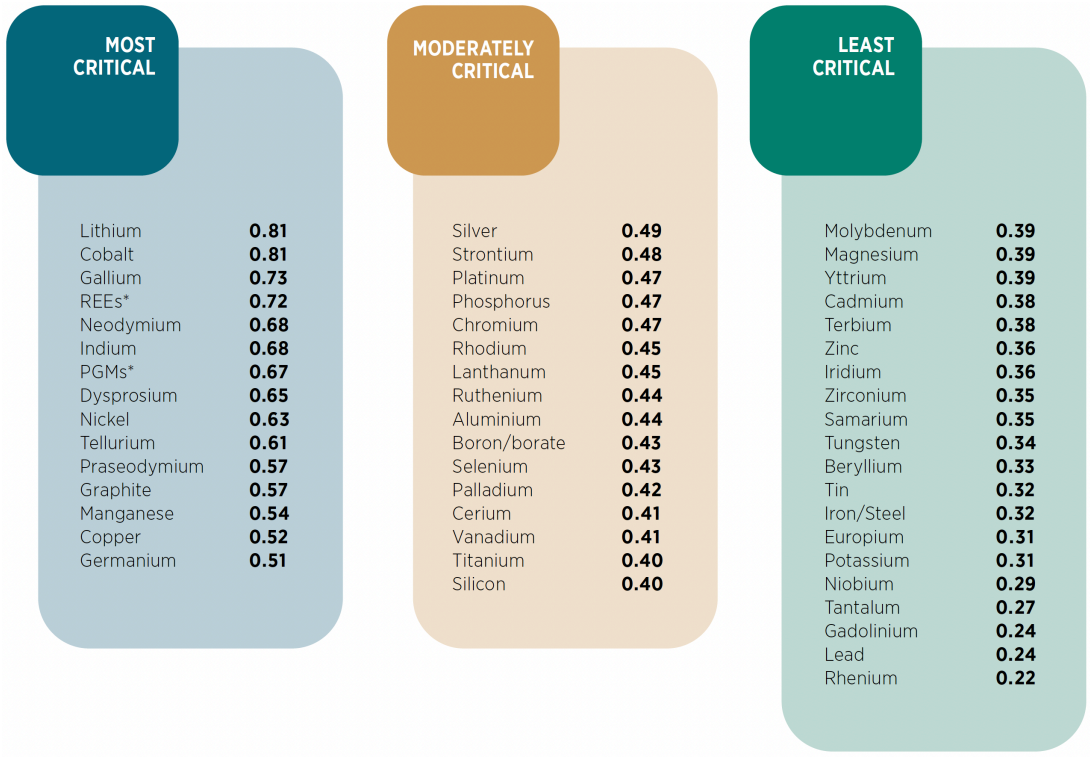


Fig. 6. Ranking of CRMs needed for the energy transition, i.e. renewable energy technologies (IRENA & NUPI 2024). Rankings are based on the criticality scores ranging from 0 to 1. *The mineral groups REEs (rare earth elements) and PGMs (platinum group metals) and the individual minerals that are part of those groups are treated separately.

The CRMs considered in this review are listed in Tab. 2, representing a hybrid combining the list of IRENA & NUPI (2024, Fig. 6) and the list of the European Critical Raw Material Act (EU 2024).

Our investigation prioritised the CRMs defined in the EU Critical Raw Material Act that are ranked by IRENA & NUPI (2024) as "most critical for the energy transition". The remaining CRMs were investigated as a second priority.

Tab. 2. List of CRMs considered in this review based on the Critical Raw Material Act (EU 2024) with criticality ranking according to IRENA & NUPI (2024). CRMs that are also listed as Strategic Raw Materials in the Critical Raw Material Act are highlighted in bold. In our review we addressed the CRMs that are "most critical for the energy transition" as a first priority.

CRM list according to the Critical Raw Material Act (EU 2024)	**Criticality ranking** (according to IRENA & NUPI 2024)
	Most critical
	Moderately critical
	Least critical
Antimony (Sb)	
Arsenic (As)	
Baryte	
Bauxite/Alumina/Aluminium (Al)	
Beryllium (Be)	
Bismuth (Bi)	
Boron (B)	
Cobalt (Co)	
Coking coal (C)	
Copper (Cu)	
Feldspar	
Fluorspar	
Gallium (Ga)	
Germanium (Ge)	
Graphite (C)	
Hafnium (Hf)	
Helium (He)	
Heavy rare earth elements (HREE)	
Dysprosium (Dy)	
Erbium (Er)	
Gadolinium (Gd)	
Holmium (Ho)	
Lutetium (Lu)	
Terbium (Tb)	
Thulium (Tm)	
Yttrium (Y)	
Ytterbium (Yb)	

CRM list according to the Critical Raw Material Act (EU 2024)	**Criticality ranking** (according to IRENA & NUPI 2024)
	Most critical
	Moderately critical
	Least critical
Light rare earth elements (LREE)	
Lanthanum (La)	
Cerium (Ce)	
Europium (Eu)	
Neodymium (Nd)	
Praseodymium (Pr)	
Samarium (Sm)	
Lithium (Li)	
Magnesium (Mg)	
Manganese (Mn)	
Nickel - battery grade (Ni)	
Niobium (Nb)	
Phosphate rock	
Phosphorus (P)	
Platinum group metals	
Iridium (Ir)	
Osmium (Os)	
Palladium (Pd)	
Platinum (Pt)	
Rhodium (Rh)	
Ruthenium (Ru)	
Scandium (Sc)	
Silicon metal (Si)	
Strontium (Sr)	
Tantalum (Ta)	
Titanium metal (Ti)	
Tungsten (W)	
Vanadium (V)	

4.2 Sources and quality of the data

The CRM occurrences compiled in this report originate from the Resource Information System (RIS), a geospatial database hosted by the Georesources Switzerland Group (FGS). The RIS contains information on occurrences and extraction sites of mineral resources in Switzerland. It results from an extensive compilation campaign conducted from the 1980's onward by the Schweizerische Geotechnische Kommission (SGTK, e.g. Wenger 1988, Fulda et al. 2018). It essentially contains historic data that was acquired mainly in the 19th and until mid-20th century during several exploration phases (e.g. Heuberger et al. 2022), with varying focus, level of detail and quality. The RIS data, and extracts thereof, are publicly available on the following geodata platforms:

- Resources Information System RIS (map.georessourcen.ethz.ch)
- Layers "Metallic raw materials", "Other industrial minerals" and "Energy raw materials" on the Federal Geoportal map.geo.admin.ch representing different extracts of the RIS
- Layer «Pan-European Mineral occurrence points (EGDI/MIN4EU)» on the European Geological Data Infrastructure (EGDI)

The results of the investigation presented in this report are based on data extracted from the RIS database in March 2025. At more than 650 of the sites listed in the RIS database, CRMs were reported as main or accessory components. Each data point includes a spatial reference and a not exhaustive list of bibliographic references. In the RIS database, accessory components are reported even if their concentration is low or in many cases unknown. In this investigation, we report and discuss the spatial and temporal distribution of the CRM occurrences with the goal to provide the basis to identify geological provinces with potentially favourable prospectivity. The RIS database is still under development and of variable precision and completeness. Therefore, the maps and tables presented below must be used with caution.

In close collaboration with, and financial support from swisstopo, the RIS database will undergo a periodic verification and actualisation process. FGS and swisstopo welcome any kind of feedback or provision of missing data.

5 CRM occurrences in Switzerland

5.1 Overview

Currently, there are no mining activities of CRM-bearing minerals in Switzerland and there is very limited exploration. However, certain metallic ores, industrial minerals and coal, some of which are considered today as CRMs (Tab. 2), were explored and mined in the past. These mining activities were modest in size. Metal mining (i.e. iron ores) ended in the second half of the 20th century (e.g. Kündig et al. 1997).

In contrast to several European countries, no systematic national-scale prospection or exploration programmes were carried out on metals or industrial minerals in Switzerland. This is due to the absence of a thriving metal mining industry. Additionally, subsurface resources are governed at the cantonal level, leading to regulatory fragmentation and inconsistent permitting procedures (Kündig et al. 1997, Kettiger 2016, Heuberger et al. 2022). Some geochemical prospection was carried out in selected regions such as the Valais (Woodtli et al. 1987), Graubünden (Hofmann 1985) and the Berner Oberland (Saheurs 1975) or around important historic mining sites (e.g. Wenger 1989). During the World Wars I and II and in the early post-war period, exploration mainly focussed on hydrocarbons (coal, peat, oil, gas, anthracite). During this period, a Federal Bureau for Mining and the Study Society for the Exploration of Swiss Ore Deposits was established (Heuberger et al. 2022). These organisations conducted mostly large data compilations, but only minor and local exploration projects (see more details in Heuberger et al. 2022 and references therein). More recent metal-focussed exploration has mainly focused on uranium occurrences in the Valais (e.g. Meisser 2012) or on gold occurrences in Graubünden (e.g. Jaffé 2010, Reichlin 2016), Valais (e.g. Kuehnbaum 2011) and Ticino (e.g. Rigaux 2022).

Many geological, political, environmental and technical factors influence whether the extraction of raw materials in a particular case has an economic potential. According to the current state of knowledge, most of the documented CRM occurrences must be considered indications or mineralisations that are, at the time being, most likely uneconomical. However, the availability of CRM-related data is patchy, and Switzerland remains partly underexplored. Many known occurrences remain poorly investigated and new discoveries cannot be excluded, especially if changes in the (geo) political-economic context, or increased requirements from the renewable energy or defence sectors stimulate a renewed interest in domestic exploration initiatives.

Among the localities reported in the RIS database, 678 list CRMs as the main or accessory component. Of these, 343 were mined in the past, but mostly not at an industrial scale. At 222 localities, the ore was mined underground. The remaining sites were exploited open pit or both underground and open pit. The type of deposit, volume, grade and age of the mineralisations are in many cases not or poorly documented. For five representative and relatively well-documented sites we compiled the available key information from the literature (Tab. 3). This table gives an overview of the size, type and mining history of the respective sites and the degree of knowledge in the literature.

At the **Gonzen** site (Fig. 7), iron and manganese ores were extracted at least since the 14th century and the site closed in 1966 (e.g. Epprecht 1946; Löpfe et al. 2018, Tab. 3). Between 1921 and 1966, about 2.8 mio. t of ore were extracted underground. The up to 2.5 m thick stratiform, but spatially limited sedimentary ore body contains up to 55% Fe and up to 50% Mn. The reserves were estimated to about 5.5 mio. t (Epprecht 1987). The ore body is locally folded and faulted due to Alpine deformation, which complicates the geometry.

Tinizong (Tab. 3, Fig. 7) hosts historically important manganese occurrences. At the sites **Parsettens** and **Falotta**, about 5'900 t of ore containing 31-36% Mn were extracted between 1919 and 1945 (Wenger 1989). The up to 4 m thick stratiform manganese ore is hosted by Late Jurassic radiolarites. The reserves for both sites together are estimated to approximately 110'000 t Mn-bearing ore (Suana 1984). The two sites are located in the Oberhalbstein region, the only location in Switzerland for which prehistoric copper mining has been documented (Reitmaier-Naef et al. 2020).

Tab. 3. List of selected CRM occurrences, including key information such as the size and the grade of the deposit, the tectonic and lithostratigraphic unit hosting the deposit. More information and references are given in the text. The localities are highlighted in Fig. 7. Important note: the term "reserves" does not follow the current mining reporting standards definition. The tonnages reported have not been specifically verified in the frame of our investigation.

Locality, community, region (Canton)	**Extracted commodities** (**main**, associated)	**Extracted tonnage, reserves**	**Extraction period**	**Grade** (wt %)	**Tectonic unit**	**Host lithology** (unit, age)
Gonzen, Sargans (SG)	**Fe, Mn**, Cu	2.8 mio. t ore, estimated reserves ca. 5.5 mio. t ore	14th century - 1966	48-59% Fe, up to 50% Mn	Helvetic nappes	Limestone (Quinten Formation, Upper Jurassic)
Falotta, Parsettens, Tinizong (GR)	**Mn**	5'931 t ore, estimated reserves 110'000 t ore (33'000 t Mn)	1916-1919	32-36% Mn	Upper Penninic	Radiolarite (Blais Formation, Upper Jurassic)
Herznach, Herznach (AG)	**Fe**, Mn, P	1.7 mio. t extracted ore (1937-1967), estimated reserves ca. 7 mio. t ore	1204-1840, mostly 1937-1967	30% Fe, 0.2-0.7% P, 0.2-0.4% Mn	Detached North Alpine Foreland	Iron Oolite (Herznach Member, Middle Jurassic)
Val Traversagna, Roveredo (GR)	**Graphite (C)**	Estimated reserves 660-5'600 t graphite	Explored around 1942-1943	9% C on average	Lepontic	Migmatite (Alpine metamorphic, age unknown)
Rousson, Gollyre, Grand Praz, Val d'Anniviers (VS)	**Ni, Co**, Cu, Bi and others	264 t extracted, estimated reserves ca. 100 t	1780-1858	14-20% Ni, 8-20% Co	Middle Penninic	Amphibolite, Gneiss (pre-Triassic)
Baicolliou, Val d'Anniviers (VS)	**Cu, Bi**, Ag and others	Ca. 2'540 t, estimated reserves ca. 1'000 t (à 3% Cu)	1836-1943	1.7-14.7% Cu, up to 3% Bi	Middle Penninic	Polycyclic metamorphic basement (Ergischhorn Complex, Proterozoic)

Between 1204 and 1967, an up to 5 m thick mostly Fe-bearing oolite was extracted during multiple phases at **Herznach** (Bodmer 1978, Diebold et al. 2006). In total, about 1.7 mio. t of ore were extracted between 1937 and 1967 with the extracted ore having a concentration of up to 30% Fe. In addition to iron, the oolites show concentrations of 0.2-0.7% P and 0.2-0.4% Mn (Fehlmann & Rickenbach 1962), both of which are listed as CRMs.

The **Val Traversagna** south of Roveredo hosts several graphite occurrences (Tab. 3, Fig. 7, Bianconi 1976). These were explored during World War II. The graphite-bearing band, which appears to be related to an Alpine fault zone, is up to 10 m thick and contains on average 9% C (graphite). Within this zone, the graphite occurs as lenses or nodules, locally relatively pure, in several cm to dm wide veins. Given the strongly discontinuous distribution of graphite in the mineralised fault zone, tonnage estimates are associated with a very high uncertainty and range between 660 t (Forster 1943) and 5.6 mio. t (von Moos 1942). According to Bianconi (1976), the potential for economic extraction of the graphite is relatively small.

Several smaller nickel and cobalt occurrences are known from the Val d'Anniviers and Turtmanntal (Tab. 3, Fig. 7). Around 264 t of ore, containing up to 20% Ni and Co, were extracted during the 19th century from the two underground mines **Grand Praz** and **Gollyre** (Woodtli et al. 1987). At the neighbouring **Pipjitälli** (Turtmanntal), a comparable vein mineralisation is up to 60 cm thick but laterally discontinuous. There, reserves were estimated to approximately 1 t of ore having a concentration of ca. 7% Co and 12% Ni, assuming a lateral continuity of the ore body of 100 m^2 (Woodtli et al. 1987). The Turtmanntal and Val d'Anniviers areas also host some copper and bismuth occurrences, which were exploited in the 19th and 20th centuries. At the site **Baicolliou** for example, an on average 10 cm thick vein hosting the ore contains up to 15% Co and 3% Bi. The occurrences in this area are generally thin and structurally complex.

Overall, many of the deposits listed in Tab. 3 show relatively high grades with some target element concentrations being higher than the cut-off values in present-day mining operations. However, the ore bodies are often small-sized with a thickness typically lower than 2 m and a limited lateral extent.

In the Alps, the tectonic evolution has led to a complex architecture of many mineral deposits (Kündig et al. 1997). Pre-Alpine deposits were thinned, faulted, folded or distributed over larger areas during the Alpine tectonic evolution. The Alpine metamorphic overprint and the associated recrystallisation have often led to dispersed mineralisations (Kündig et al. 1997). These factors, and the poor accessibility in the rugged Alpine terrain, make mining operations in the Alps challenging. The accessibility, environmental considerations and the region's ecological sensitivity, often limiting extensive mining operations are addressed in Chapt. 5.5.

5.2 Geological distribution of the CRM occurrences

Mineral occurrences are often associated with distinct host rock types, tectonic settings or structural features. In Chapt. 5.2 and 5.3, we map how the CRM occurrences are spatially and temporally distributed across different tectonic and lithostratigraphic units. This provides essential insights into the processes forming the mineralisations (e.g. magmatic, hydrothermal, sedimentary and others, see Chapt. 5.4) and may help to highlight areas with favourable geological and tectonic settings.

Please note that clusters of CRM occurrences (e.g. Val d'Anniviers VS; Malcantone TI, Fig. 7 - Fig. 10) do not necessarily imply that one area is richer in CRMs than another. They mostly indicate that a site/area has been investigated more intensively. Note also that our geospatial analysis does not take into account the volume and the grade of the CRM occurrences, as these are often unknown and hence not reported in the RIS database.

5.2.1 Tectonic setting of the CRM occurrences

We plotted the CRM occurrences documented in the RIS database (Tab. 2) onto a simplified Tectonic Map of Switzerland (swisstopo 2024, Fig. 7). The tectonic units shown on this map mainly reflect former paleogeographic domains which formed in response to Mesozoic extension, as schematically sketched in Fig. 8. Major faults and nappe boundaries, often places with more intense fluid circulation, are highlighted as blue lines. Each tectonic unit has its distinct stratigraphy and geodynamic evolution. This may have influenced the presence and type of mineral systems, the spatial and temporal distribution of CRM occurrences, which is discussed in Chapt. 5.4.

In this chapter we briefly introduce the different tectonic units considered in this study. For more details regarding the tectonic units, refer to Handy et al. (2010), swisstopo (2024) and references therein.

In the Early Cretaceous (Fig. 8), the future Helvetic and Lepontic domains were situated at the proximal and distal European continental margin, respectively. The Middle Penninics are derived from the Briançonnais continental fragment. This continental fragment was at that time separated by two oceanic domains: the Valais Ocean (Lower Penninics) in the NW and the Piemont-Ligurian Ocean (Upper Penninics) in the SE. The Austroalpine and the South Alpine units are derived from the Adriatic continental margin. The smaller Cervinia fragment, which separated from the Adriatic continent, is supposed to be the origin of the Salassic units (e.g. Gouffon 2024).

The Molasse basin formed as a foreland basin during the Alpine orogeny, when the load of the growing Alps caused the European crust to flex and subside, allowing sediments eroded from the Alps to accumulate. The detached North Alpine Foreland, including parts of the Molasse basin and the Folded Jura, formed during the late stages of the Alpine collision when thrusting also affected the more proximal European continental margin. In contrast, the autochthonous North Alpine Foreland was not significantly affected by the Alpine collision. On Fig. 8a, the approximate paleogeographic position of these tectonic units is indicated with an arrow.

The Periadriatic Line (highlighted as *PER* in Fig. 8) represents a major tectono-metamorphic boundary in the Alps separating the Helvetic, Penninic, Salassic and Austroalpine nappes from the South Alpine. During the Alpine orogeny, the Austroalpine, Salassic, Penninic and Helvetic nappes were, in descending order, accreted to form the present-day Alpine nappe stack. The tectonic units north of the

Periadriatic Line were overprinted to varying degrees by Alpine metamorphism. In contrast, the South Alpine was not involved in the Alpine nappe stack and was only weakly overprinted by Alpine tectonics and metamorphism (e.g. Pfiffner 2024).

The Folded Jura and the autochthonous North Alpine Foreland of northern Switzerland contain 14 CRM occurrences, which represents less than 2% of the total amount of occurrences. These include some manganese occurrences, but mostly phosphorous and arsenic, as well as silicon (e.g. cherts or pure sandstones). Arsenic and phosphorous are hosted in the iron oolite (Herznach Member, Middle Jurassic), silicium in chert layers of the Upper Jurassic (Balsthal Formation) or in sandstones of the Siderolithic Group residual deposits (see also Fig. 10a). In all cases, the concentrations of CRMs are rather low or unspecified. Elevated lithium concentrations are reported from geothermal fluids of two deep wells of the Swiss Molasse basin (see Chapt. 5.3.5).

More than 98% of the documented CRM occurrences, including all copper, cobalt, nickel, germanium, rare earth elements (REEs), platinum group metals (PGMs), graphite, anthracite and bituminous coal, as well as most manganese and many other occurrences are located in the Alps (Fig. 7, see also Chapters 5.3.1-5.3.6 for more details). These occurrences are heterogeneously distributed across different tectonic units (Fig. 7, Fig. 8). Clusters can be recognised in the Helvetics of central and eastern Switzerland, in the Valais south of the Rhône-Simplon fault zone (RSF), in the Penninic and Austroalpine nappes of Graubünden and in the South Alpine domain. Many of these clusters are aligned with the strike of major tectonic units or boundaries (Fig. 7). The largest number of occurrences are situated in the Helvetic (233) and Penninic (219) units. The Lepontic, Salassic, Austroalpine and the Autochthonous and the detached Mesozoic sediments of the North Alpine Foreland also contain each 11 to 54 CRM occurrences (Fig. 8b).

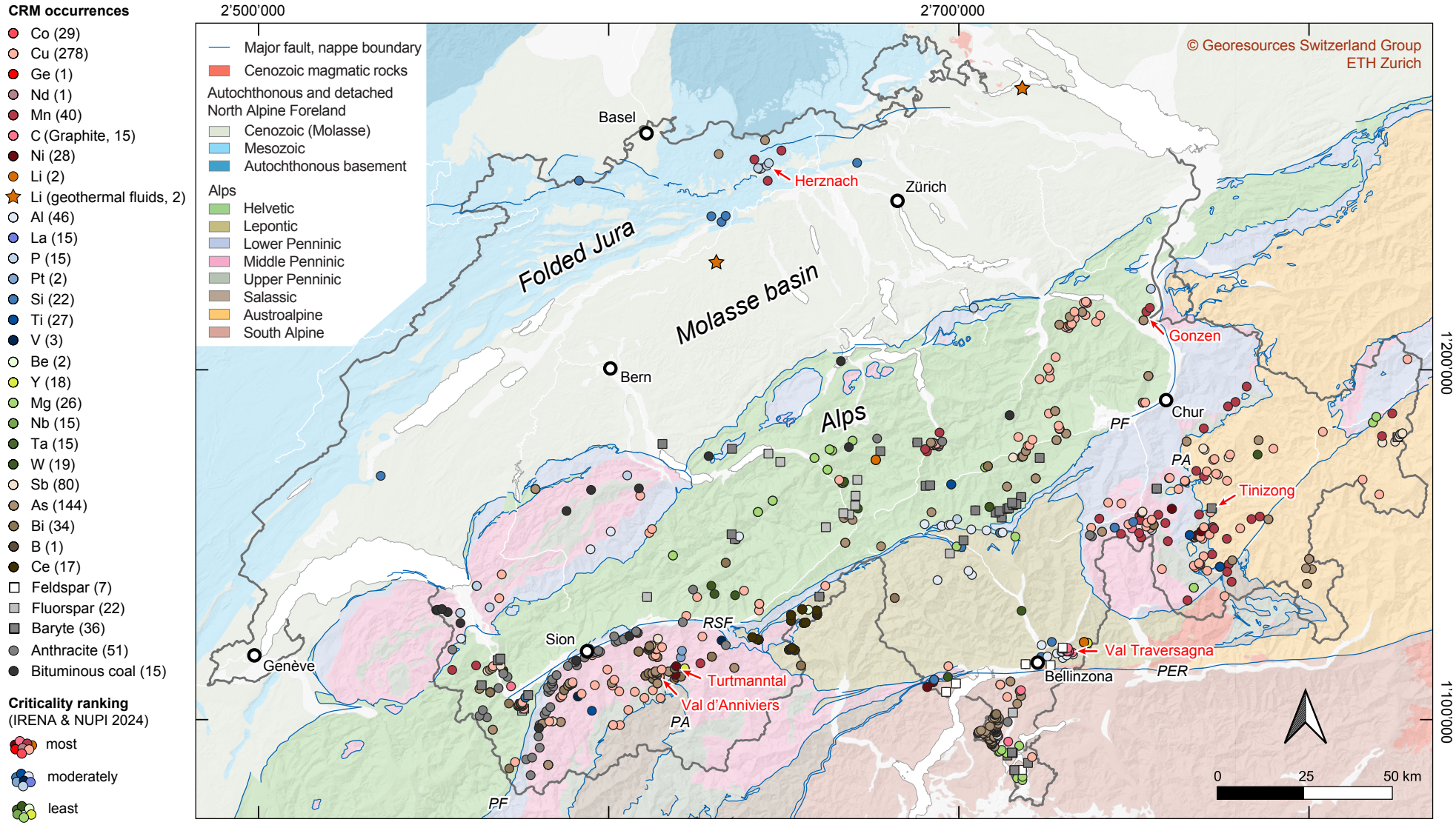

CRM occurrences
Co (29)
Cu (278)
Ge (1)
Nd (1)
Mn (40)
C (Graphite, 15)
Ni (28)
Li (2)
Li (geothermal fluids, 2)
Al (46)
La (15)
P (15)
Pt (2)
Si (22)
Ti (27)
V (3)
Be (2)
Y (18)
Mg (26)
Nb (15)
Ta (15)
W (19)
Sb (80)
As (144)
Bi (34)
B (1)
Ce (17)
Feldspar (7)
Fluorspar (22)
Baryte (36)
Anthracite (51)
Bituminous coal (15)
Criticality ranking
(IRENA & NUPI 2024)
most
moderately
least
2'500'000
2'700'000
1'200'000
1'100'000
Major fault, nappe boundary
Cenozoic magmatic rocks
Autochthonous and detached
North Alpine Foreland
Cenozoic (Molasse)
Mesozoic
Autochthonous basement
Alps
Helvetic
Lepontic
Lower Penninic
Middle Penninic
Upper Penninic
Salassic
Austroalpine
South Alpine
© Georesources Switzerland Group
ETH Zurich
Basel
Zürich
Bern
Genève
Sion
Chur
Bellinzona
Herznach
Gonzen
Tinizong
Turtmanntal
Val d'Anniviers
Val Traversagna
Folded Jura
Molasse basin
Alps
RSF
PF
PA
PER
0
25
50 km

Fig. 7. Map showing the distribution of CRM occurrences listed in the RIS database across different tectonic units (modified from swisstopo 2024). Circles represent metal occurrences whereas squares depict industrial minerals, coal or anthracite occurrences. Elevated lithium (Li) concentrations in deep geothermal fluids (well data) are marked with an asterisk (see also Chapt. 5.3.5). The number of occurrences is given in brackets. Criticality is assigned according to the global ranking of critical materials for renewable energy defined by IRENA & LUPI (2024). Major faults or nappe boundaries are indicated: *PF* = Penninic Front, *RSF* = Rhône–Simplon Fault System, *PA* = Penninic–Salassic/Austroalpine Boundary, *PER* = Periadriatic or Insubric Line. For many CRM occurrences shown on the map, the corresponding elements/minerals are present as accessory component (often with low or unspecified concentrations) and are not the main component. The number of occurrences may partly reflect the different level of detail of past exploration campaigns.

To highlight the tectonic units with the highest density of documented occurrences, we normalised the number of occurrences by the exposed area (km^2) of the corresponding tectonic units (Fig. 8c). Our density mapping shows that the South Alpine contains the highest number of documented occurrences per area (0.155/km^2), mostly copper as well as some nickel and graphite. In the Middle Penninic and in the adjacent oceanic Upper Penninic, CRM occurrences such as copper, manganese, nickel and cobalt are enriched with respect to the other tectonic units. The Helvetic, Lepontic, Lower Penninic, Salassic, Austroalpine, the folded Jura and the Molasse basin each contain less than 0.025 occurrences per km^2. The Helvetic domain contains mainly copper as well as some manganese, bituminous coal, anthracite, nickel, cobalt, graphite and lithium. The Lepontic is known for its REE occurrences but also hosts some graphite, lithium and copper. The Lower Penninic contains some copper and manganese occurrences but is mostly known for its many bituminous coal and anthracite occurrences, especially in the Valais area. The Salassic and Austroalpine contain some copper, nickel and cobalt occurrences.

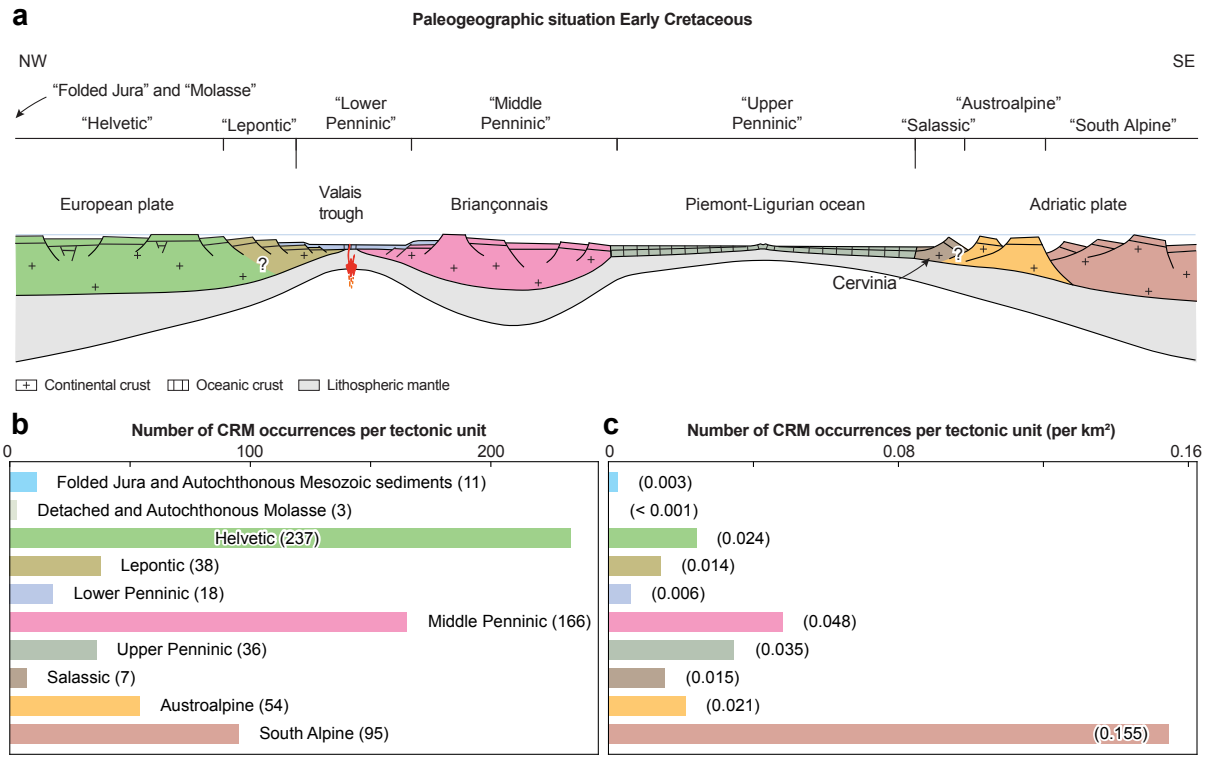


Fig. 8. (a) Schematic sketch showing the Early Cretaceous paleogeographic situation of the continental and oceanic crustal fragments which are today exposed in the Alps (not to scale). The European continental margin (Helvetic, Lepontic), the Briançonnais continental fragment (Middle Penninic) and the Adriatic plates / subplates (Salassic, Austroalpine and South Alpine) were separated by the Valais (Lower Penninic) and Piemont-Ligurian (Upper Penninic) oceanic domains. (b) Bar plot highlighting the number of the occurrences per tectonic unit. (c) Bar plot showing the number of occurrences per tectonic unit normalised by the area of the corresponding unit within Switzerland as shown in Fig. 7. The number of occurrences may partly reflect the different level of detail of past exploration campaigns.

5.2.2 Lithostratigraphic setting of the CRM occurrences

Understanding how CRM occurrences are distributed across different lithostratigraphic units is essential for identifying potential geological sources, tracing fluid pathways, and locating the final host rocks of the mineralisations. The lithostratigraphic context helps to link CRM occurrences to specific depositional, magmatic, metamorphic environments that control metal fertility and preservation (Müller et al. 2024). Fig. 9 and Fig. 10 map the distribution of CRM occurrences across seven lithostratigraphic units described below. Two representative stratigraphic profiles highlight the distribution of different lithologies typically found in a continental crust setting, for the examples of the Lower Helvetic (Fig. 10a, left, Nibourel et al. 2021) and the South Alpine (Fig. 10a, right, Lithostratigraphic Lexicon of Switzerland, www.strati.ch):

- Crystalline basement contains pre-Variscan polycyclic metamorphic basement including a variety of rock types and many pre- to post-Variscan magmatic intrusions of variable size, which are typically Permo-Carboniferous in age. Today, exposures of the crystalline basement are located in the Helvetics (i.e. Aiguilles Rouges, Mont Blanc and Aar Massifs as well as Gotthard nappe, see Fig. 9), the Lepontic, the Middle Penninic, the Salassic, the Austroalpine and the South Alpine.
- Permo-Carboniferous sedimentary and volcanic rocks were deposited in intra-continental and normal fault-bounded troughs. The volcanic rocks are related to the magmatic intrusions mentioned above. Today, exposures of these rocks are relatively scarce and mostly restricted to the Helvetics, the Middle Penninic, the Austroalpine and the South Alpine (Fig. 7 and Fig. 9).
- Mesozoic sediments: The Triassic units mainly consist of dolostones, limestones, and evaporites (anhydrite and gypsum), reflecting deposition in a shallow, warm, and periodically restricted marine environment. Jurassic to Cretaceous sediments are dominated by limestones and marls, with early carbonate platforms transitioning to deeper water sedimentation, especially in the more rapidly subsiding distal parts of the continental margins. Today, Mesozoic sediments are widely exposed across all tectonic units except for the Molasse basin (Fig. 7 and Fig. 9).
- Cenozoic sediments mainly consist of deep marine flysch sequences, composed of sandstones, marls, and shales, deposited in a foredeep basin ahead of the advancing Alpine orogen. Younger units in the North Alpine Foreland are dominated by Molasse sediments (conglomerates, sandstones and shales), representing fluvial to shallow marine environments as the Alps were uplifted and eroded. In the Helvetics and the North Alpine Foreland, residual sediments (Siderolithic Group, Menkveld-Gfeller et al. 2016, see “Siderolithic” in Fig. 10) formed through intense chemical weathering of crystalline and sedimentary rocks during the Late Jurassic to early Paleogene. These highly weathered soils and paleosols were later redeposited and preserved in karst systems and topographic lows of the underlying Mesozoic carbonates.

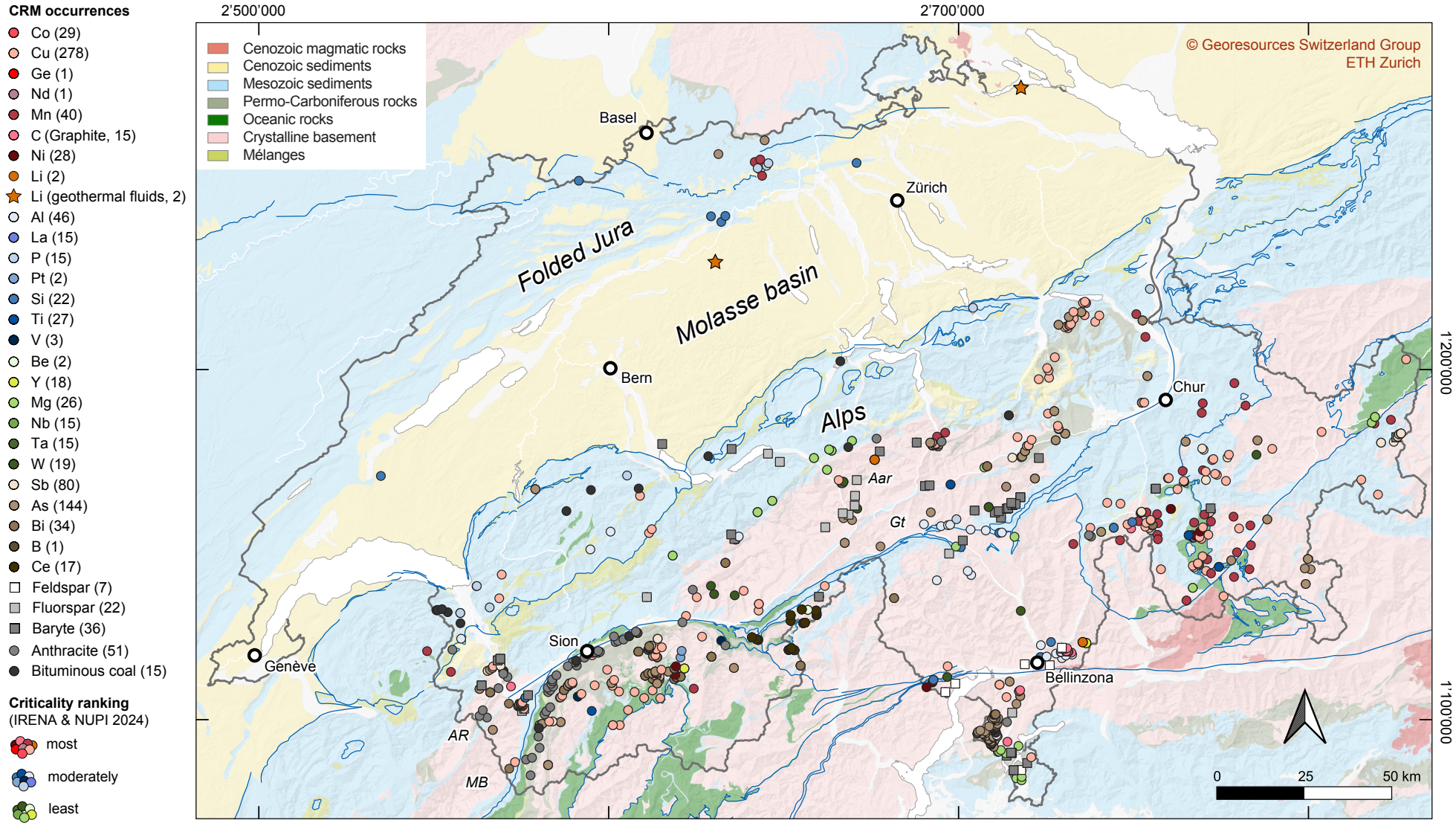

CRM occurrences
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Ti (27)
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Mg (26)
Nb (15)
Ta (15)
W (19)
Sb (80)
As (144)
Bi (34)
B (1)
Ce (17)
Feldspar (7)
Fluorspar (22)
Baryte (36)
Anthracite (51)
Bituminous coal (15)
Criticality ranking
(IRENA & NUPI 2024)
most
moderately
least
2'500'000
2'700'000
1'200'000
1'100'000
Cenozoic magmatic rocks
Cenozoic sediments
Mesozoic sediments
Permo-Carboniferous rocks
Oceanic rocks
Crystalline basement
Mélanges
© Georesources Switzerland Group
ETH Zurich
Basel
Zürich
Bern
Chur
Genève
Sion
Bellinzona
Folded Jura
Molasse basin
Alps
Aar
Gt
AR
MB
0
25
50 km

Fig. 9. Map showing the distribution of CRM occurrences listed in the RIS database across different lithologic units (modified from swisstopo 2024). Circles represent metal occurrences whereas squares depict the industrial mineral, coal or anthracite occurrences. Elevated lithium (Li) concentrations in deep geothermal fluids (well data) are marked with an asterisk (see also Chapt. 5.3.5). The number of occurrences is given in brackets. Criticality is assigned according to the global ranking of critical materials for renewable energy defined by IRENA & LUPI (2024). Important litho-tectonic subunits are indicated: *Aar* = Aar Massif, *Gt* = Gotthard nappe, *AR* = Aiguilles-Rouges Massif, *MB* = Mont Blanc Massif. For many CRM occurrences shown on the map, the corresponding elements/minerals are present as accessory component (often with low or unspecified concentrations) and are not the main component. The distribution of occurrences may partly reflect the different level of detail of past exploration campaigns. Note that on this map, the Lower Penninic containing only smaller fragments of mafic and ultramafic rocks, is not attributed to the oceanic rocks, but to the Mesozoic to Cenozoic sediments.

Fig. 10a (centre) shows the lithologies which are in this investigation summarised as oceanic rocks. These represent an example of an oceanic crust associated with slow spreading-rates (e.g. Upper Penninic, Platta nappe, Pfiffner 2024; Manatschal & Nievergelt 1997).

- Oceanic rocks represent remnants of the Valais and Piemont-Ligurian oceans which existed during the Mesozoic. The basal ophiolitic rocks typically consist of serpentinised peridotites, gabbros and pillow basalts, formed at a mid-ocean ridge. These are followed by deep-sea sediments such as radiolarites (siliceous deep-sea sediments) and pelagic limestones, reflecting slow sedimentation in a deep, open marine setting. Younger deposits mainly consist of marls and limestones, indicating continued deep marine conditions. Finally, Paleogene flysch sediments were deposited as the oceanic basin was progressively deformed and incorporated into the Alpine orogen. Today, oceanic rocks are commonly exposed in the Upper Penninic (Fig. 7). In the Valais trough (Lower Penninic), mafic and ultramafic rocks and radiolarites are less abundant (Pfiffner 2024). In this report, parts of the Lower Penninic are, therefore, not attributed to the oceanic rocks (Fig. 9).
- Mélanges are described as a deformed rock unit composed of a mixture of various rock types, often occurring in subduction zones, accretionary wedges, or ophiolitic settings. They typically consist of large, randomly distributed blocks of different lithologies embedded in a shale- or mud-dominated and sheared matrix.

In the Alps, the lithostratigraphic units defined above occur with variable Alpine metamorphic and tectonic overprint.

- Finally, Cenozoic magmatic rocks summarise the Alpine magmatic rocks which formed during the Cenozoic, mostly around the Periadriatic line in the Bergell area. Many pegmatites are related to these magmatic rocks which follow a several kilometre wide belt north of the Periadriatic line.

More than half of the CRM occurrences (345 out of 665), in particular copper, cobalt, nickel, REEs and PGMs, are hosted by the crystalline basement of the Helvetic, Lepontic, Middle Penninic or South Alpine (Fig. 9, Fig. 10b). About 25% of the CRM occurrences are hosted by Mesozoic sediments. For example, most manganese occurrences are hosted by Middle-Upper Jurassic radiolarites while some copper, nickel and cobalt occurrences are hosted by carbonate-dominated Mesozoic sediments or shales. Especially the Triassic carbonates of the Austroalpine and the Jurassic carbonates of the Helvetic contain some copper occurrences. Many (86) occurrences are located in Permo-Carboniferous sedimentary or volcanic rocks. These host in particular copper, bituminous coal, anthracite as well as some cobalt and graphite. Manganese, copper and nickel are often occur in oceanic rocks, mostly in Valais and Graubünden.

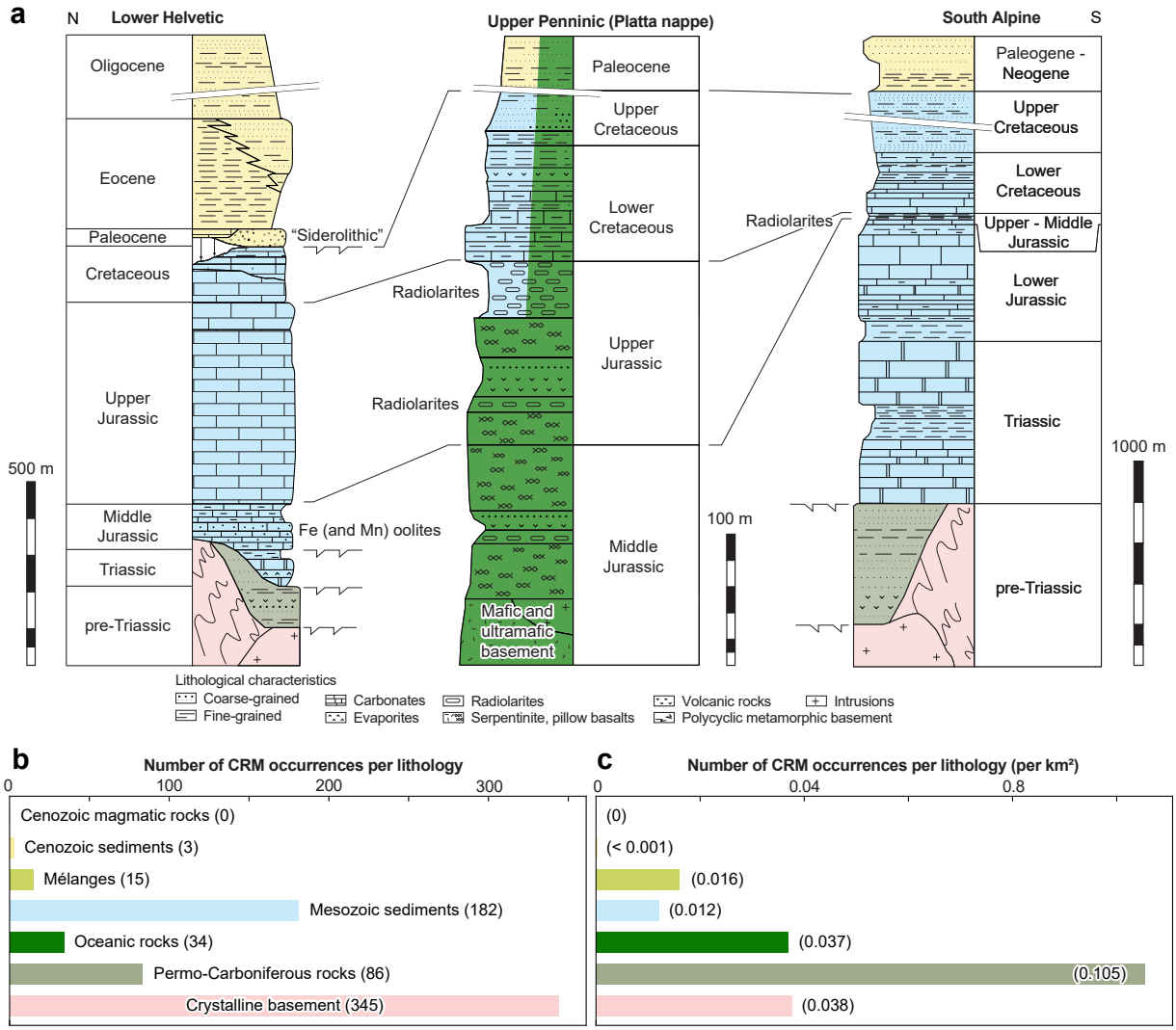


Fig. 10. (a) Generalised lithostratigraphic profiles of the Helvetic (left, modified from Nibourel et al. 2021), the Upper Penninic oceanic rocks (Platta nappe, modified from Pfiffner 2024) and South Alpine (right, modified from Lithostratigraphic Lexicon of Switzerland, www.strati.ch) tectonic units showing the lithological groups used to classify the CRM occurrences highlighted in Fig. 9. Mélanges, occurring along tectonic boundaries or in an accretionary prism, are not shown in subfigure a. In the Lower Penninic (Valais trough), mafic and ultramafic rocks and radiolarites are less abundant. In our analyses, parts of the Lower Penninic rocks are, therefore, not attributed to the oceanic rocks. Note that the lithostratigraphic profiles are scaled differently. (b) Bar plot highlighting the number of occurrences per lithological group (host rock). (c) Bar plot showing the number of occurrences per lithology (host rock) normalised by the area of the corresponding lithology within Switzerland as shown in Fig. 8. The number of occurrences may partly reflect the different level of detail of past exploration campaigns.

To visualise which lithostratigraphic units contain the highest density of occurrences, we normalised the number of occurrences by the exposed area (km^2) of the corresponding unit (Fig. 10c). The Permo-Carboniferous rocks host more than 0.1 occurrence per km^2, which is by far the highest value across all investigated lithostratigraphic units. Similarly, many copper or cobalt occurrences hosted by crystalline basement or Mesozoic sediment appear to be aligned with the trend of these Permo-Carboniferous troughs.

The crystalline basement and oceanic rocks each host more than 0.037 occurrences/km^2. The oceanic rocks are exposed in the Upper Penninic of the Graubünden and Valais areas along strongly tectonised suture zones. The widely exposed Mesozoic sediments and the locally exposed Mélanges host less than 0.02 occurrences/km^2.

5.3 Most critical CRMs for the energy transition

In this chapter, the spatial and temporal distribution of the CRMs that are considered as most critical for the energy transition (see Chapt. 4.1) are discussed in more detail, individually for each element or group. The characteristics of the most important deposits or occurrences are summarised. These are deposits or occurrences that have either been exploited over a longer period, contain supposedly larger reserves, have historically been of greater importance or their exploitation could be reactivated relatively quickly.

5.3.1 Copper (Cu)

Copper (Cu) is essential for the development of renewable energy technologies, electrification, and digital infrastructure. It represents the backbone of the global energy transition (scrreen.eu/crms-2023/).

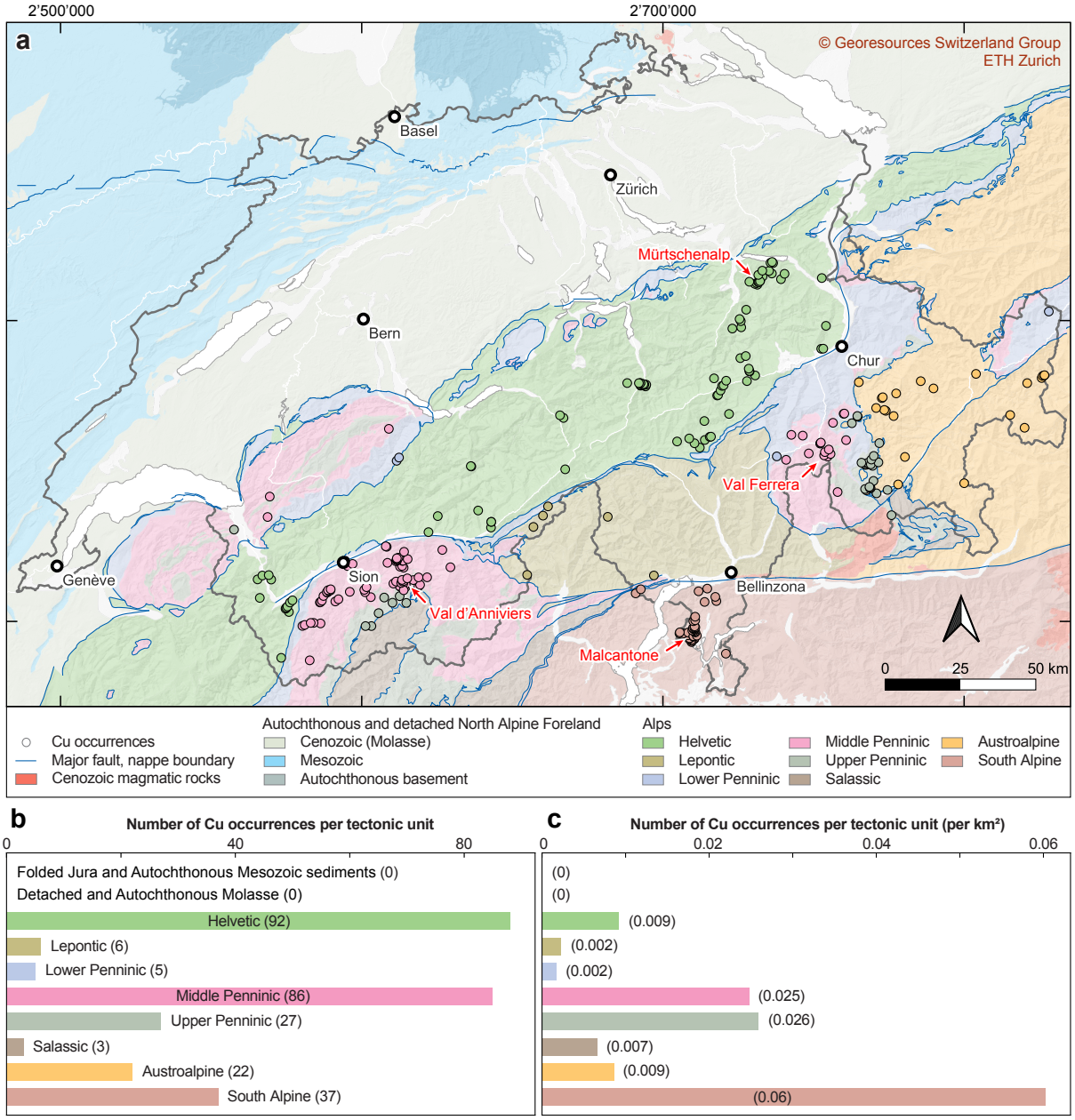


Fig. 11. (a) Map showing the tectonic units hosting the 278 copper (Cu) occurrences listed in the RIS database. (b) Bar plot highlighting the number of occurrences per tectonic unit. (c) Bar plot showing the number of occurrences per tectonic unit normalised by the area of the corresponding unit as shown in (a). For 97 occurrences shown on the map, Cu is the main component. For the remaining 181 occurrences, Cu is present as accessory component (often with low or unspecified concentration). The distribution of occurrences may partly reflect the different level of detail of past exploration campaigns.

In Switzerland, Cu deposits that would be likely suitable for an eventual extraction are rare. Historically, there has been little Cu mining activity (Kündig et al. 1997). However, Cu is mentioned at 278 localities in the RIS database. At 97 localities, it represents the main component.

Four clusters occur in the Penninics, south of Sion (Valais) and south of Chur (Graubünden), in the central and eastern Helvetics and in the South Alpine (Fig. 11a, b). The Helvetic and the Middle Penninic each host more than 85 Cu occurrences. 22 to 37 occurrences are situated in the South Alpine, Upper Penninic and the Austroalpine domains. The Lepontic, Lower Penninic and Salassic domains each contain less than 5 occurrences.

The South Alpine contains the highest density of Cu occurrences (0.06 Cu occurrences per km^2), the Upper and Middle Penninic nappes host around 0.025 Cu occurrences per km^2 (Fig. 11c). In the Helvetics, Salassic and Austroalpine units, we observe a much lower density of occurrences (around 0.01 occurrences per km^2).

About half of the Cu occurrences (150) are located in the crystalline basement, mostly in hydrothermal veins or lenses. Mesozoic sediments, mostly Triassic carbonates and shales host 62 mostly vein-type or stratiform occurrences. Oceanic rocks (mostly serpentinites) host 27 Cu occurrences. These Cu occurrences are clearly associated with the Mesozoic serpentinites of the Upper Penninic (Valais and Graubünden) and with the Penninic-Salassic-Austroalpine boundary (Fig. 11, Fig. 12), showing some characteristics of Volcanogenic Massive Sulfide (VMS)-type deposits.

35 occurrences are within Permo-Carboniferous sediments and volcanic rocks, mostly in veins but some stratiform occurrences are also reported. These rocks have the highest per area density of Cu occurrences among all investigated lithostratigraphic groups (>0.04/km^2). Oceanic rocks contain almost 0.03 Cu occurrences per km^2, the crystalline basement around 0.016. The Mesozoic sediments and Mélanges contain 0.004 occurrences per km^2.

In summary, the South Alpine stands out as the tectonic unit with the highest per area density of occurrences, with a high concentration of occurrences especially in the crystalline basement of the “Malcantone” (Fig. 11). However, a closer look at the geochemical data (Koeppel 1966) reveals that Cu often represents an accessory component in polymetallic veins that also contain Au, As and Sb. The corresponding Cu concentrations are mostly lower than 1%. Relative age constraints (Köppel 1966) and U-Pb dating of syn-genetic rutiles (Rigaux 2022, Müller 2023) in the alteration zone suggest that most of these fault-related ore-bearing vein mineralisations are of Permian age, which points to an epithermal genesis.

Cu occurs across all Alpine tectonic units and most lithostratigraphic groups, which makes it challenging to recognise clear groups, spatial or temporal patterns. The most important historic extraction sites in terms of grade and volume are the sites at “Val d’Anniviers”, with Cu concentrations of 1.5-15% (Woodtli et al. 1987, see also Tab. 3), "Mürtschenalp", with 1.3-13.5% Cu (Bächtiger 1963) and “Val Ferrera” (Fig. 11, Fig. 12). The "Mürtschenalp" site is particularly interesting because it comprises both, stratiform and fault-related vein mineralisations up to several metres thick. The occurrences are distributed across red Permian terrestric sediments and the overlying Triassic dolomites. Between 1608 and 1918, Cu was periodically extracted and exported (Kündig et al. 1997). However, structural complexities and the strong lateral variability of the deposits made the mining operation difficult and not profitable (Bächtiger 1963).

The "Mürtschenalp" deposits belong to a group of occurrences that are clearly aligned with the inverted N-S-trending Glarner Verrucano trough, containing Permo-Carboniferous sediments and volcanic rocks (Fig. 12a).

Cu generally seems to be enriched around Permo-Carboniferous sediments and volcanic rocks, in the carbonates overlying these rocks or in the nearby crystalline basement. Similarly, many Aar Massif-hosted Cu occurrences appear to be aligned with thin ENE-trending wedges containing Permo-Carboniferous sedimentary and volcanic rocks (Fig. 12a). The Cu occurrences of the Middle Penninic south of Sion, and around “Val Ferrera” are also aligned with exposures of Permo-Carboniferous sedimentary and volcanic rocks. Some stratiform occurrences, which are hosted in shales or carbonates show characteristics of Sediment-hosted Stratiform Cu (SSC) deposits. Other vein-hosted occurrences show some characteristics of hydrothermal vein-type, epithermal or VMS-style deposits. Potential links between Permo-Carboniferous transtension, magmatism and the formation of Cu occurrences will be discussed in Chapt. 5.4.

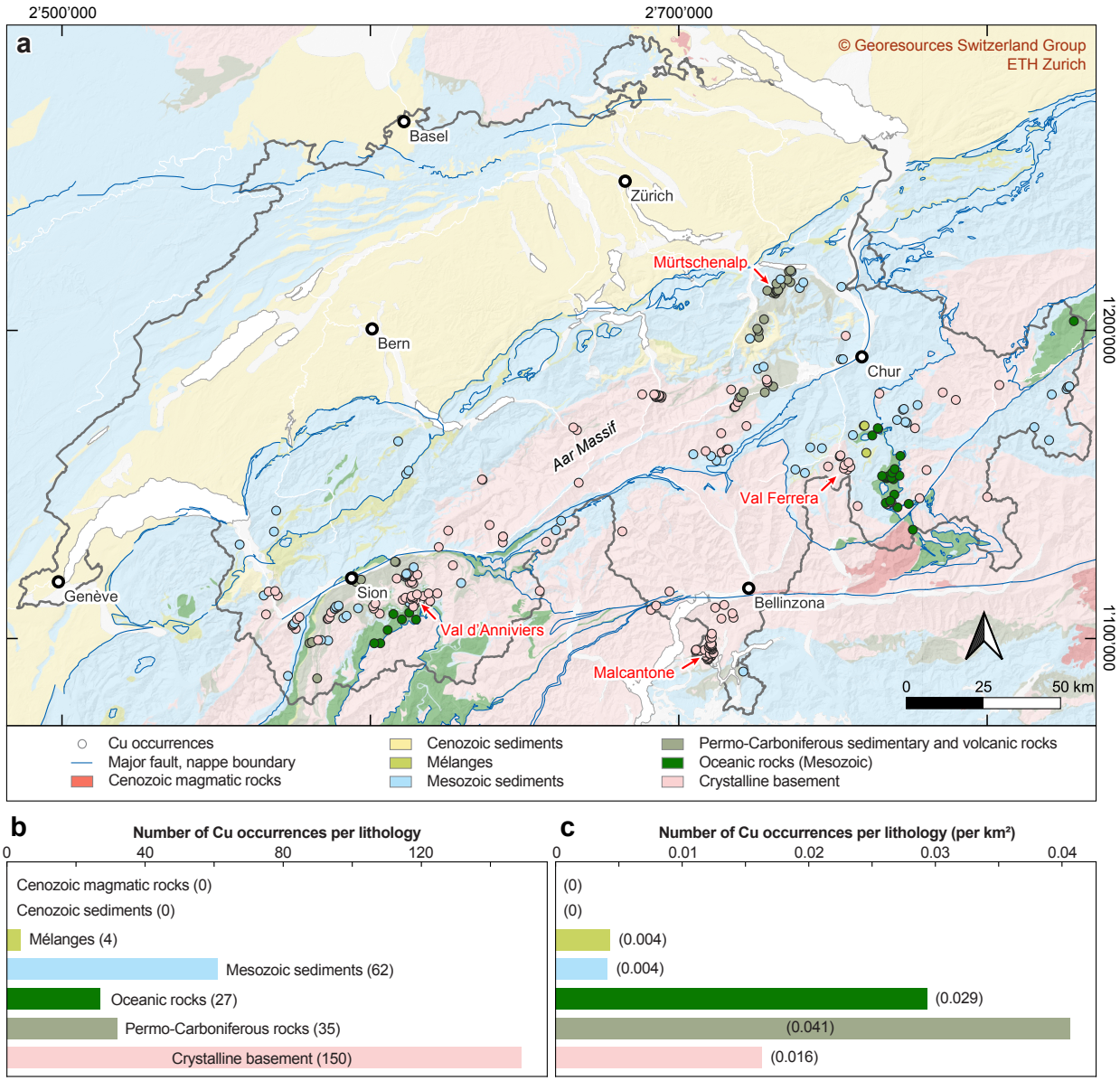


Fig. 12. (a) Map showing five lithological groups hosting the 278 copper (Cu) occurrences listed in the RIS database. (b) Bar plot highlighting the number of occurrences per lithological group. (c) Bar plot showing the number of occurrences per lithology normalised by the area of the corresponding lithology within Switzerland as shown in (a). For 97 occurrences shown on the map, Cu is the main component. For the remaining 181 occurrences, Cu is present as accessory component (often with low or unspecified concentration). The number of occurrences may partly reflect the different level of detail of past exploration campaigns.

5.3.2 Manganese (Mn)

Manganese (Mn) is particularly important in steel production, where it serves as an alloying element to improve strength, hardness, and resistance to wear. It is also vital for battery technologies, particularly in lithium-ion and sodium-ion batteries (scrreen.eu/crms-2023). The economic importance of Swiss Mn deposits is considered very low (Kündig et al. 1997).

The most relevant historic Mn extraction sites are the “Gonzen” and “Tinizong” sites (see also Chapt. 5.1, Fig. 13, Fig. 14). In the RIS database, Mn occurrences are reported as main or accessory component at 40 sites (Fig. 13a). Most of these sites are situated in the Middle (10) and Upper Penninic (8) as well as in the Austroalpine (9) units south of Chur (Fig. 13b). The Folded Jura, the Helvetic, the Lower Penninic and the Salassic also host a few occurrences.

Fig. 13c highlights the tectonic units with the highest abundance of Mn occurrences, relative to the exposed area (km^2). The oceanic Upper Penninic hosts 0.008 Mn occurrences per km^2. The Middle Penninic, Austroalpine and South Alpine units contain around 0.004 occurrences per km^2, the remaining units less than 0.001 occurrences per km^2.

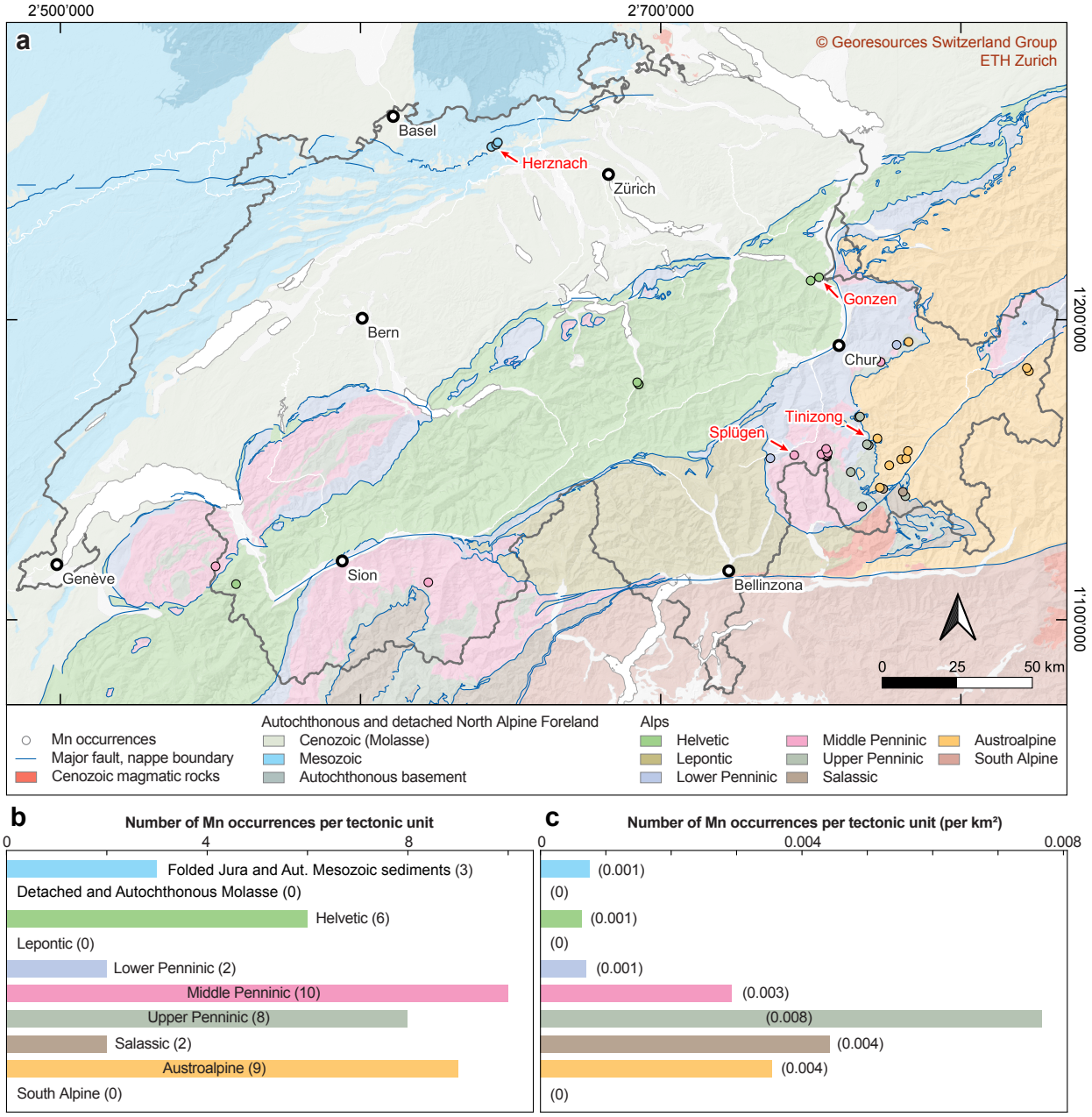


Fig. 13. (a) Map showing the tectonic units hosting the 40 manganese (Mn) occurrences listed in the RIS database. (b) Bar plot highlighting the number of occurrences per tectonic unit. (c) Bar plot showing the number of occurrences per tectonic unit normalised by the area of the corresponding unit within Switzerland as shown in (a). For many occurrences shown on the map, Mn is present as accessory component (often with low or unspecified concentration) and is not the main component. The number of occurrences may partly reflect the different level of detail of past exploration campaigns.

Fig. 14a shows how the Mn occurrences are distributed across different lithostratigraphic units. More than 75% of the Mn occurrences, including the sites at “Tinizong”, are hosted by Middle-Upper Jurassic radiolarites, representing siliceous deep-sea sediments (Fig. 14b). These radiolarites occur in the oceanic rocks of the Upper Penninic, but also in the Salassic, the lower Austroalpine nappes and the South Alpine. However, most of the radiolarite-hosted Mn occurrences are located close to the Penninic-Salassic/Austroalpine boundary (Fehlmann 1947, Geiger 1948, Fig. 14). The occurrences are located in structurally complex settings and are characterised by a strong lateral variability. Mn concentrations

are reported for a few sites and typically vary between 2 and 36 % (Baumberger et al. 1923, Glauser 1946, Suana 1984). As mentioned in Chapt. 5.1, reserves of approximately 33'000 t of Mn are estimated for the sites "Falotta" and "Parsettens" near "Tinizong" (Suana 1984, Kündig et al. 1997). The deep-sea sediment-hosted Mn occurrences show many characteristics of modern oceanic Mn deposits. Oceanic rocks contain the highest per area density of Mn occurrences (0.007 occurrences/km^2, Fig. 14c).

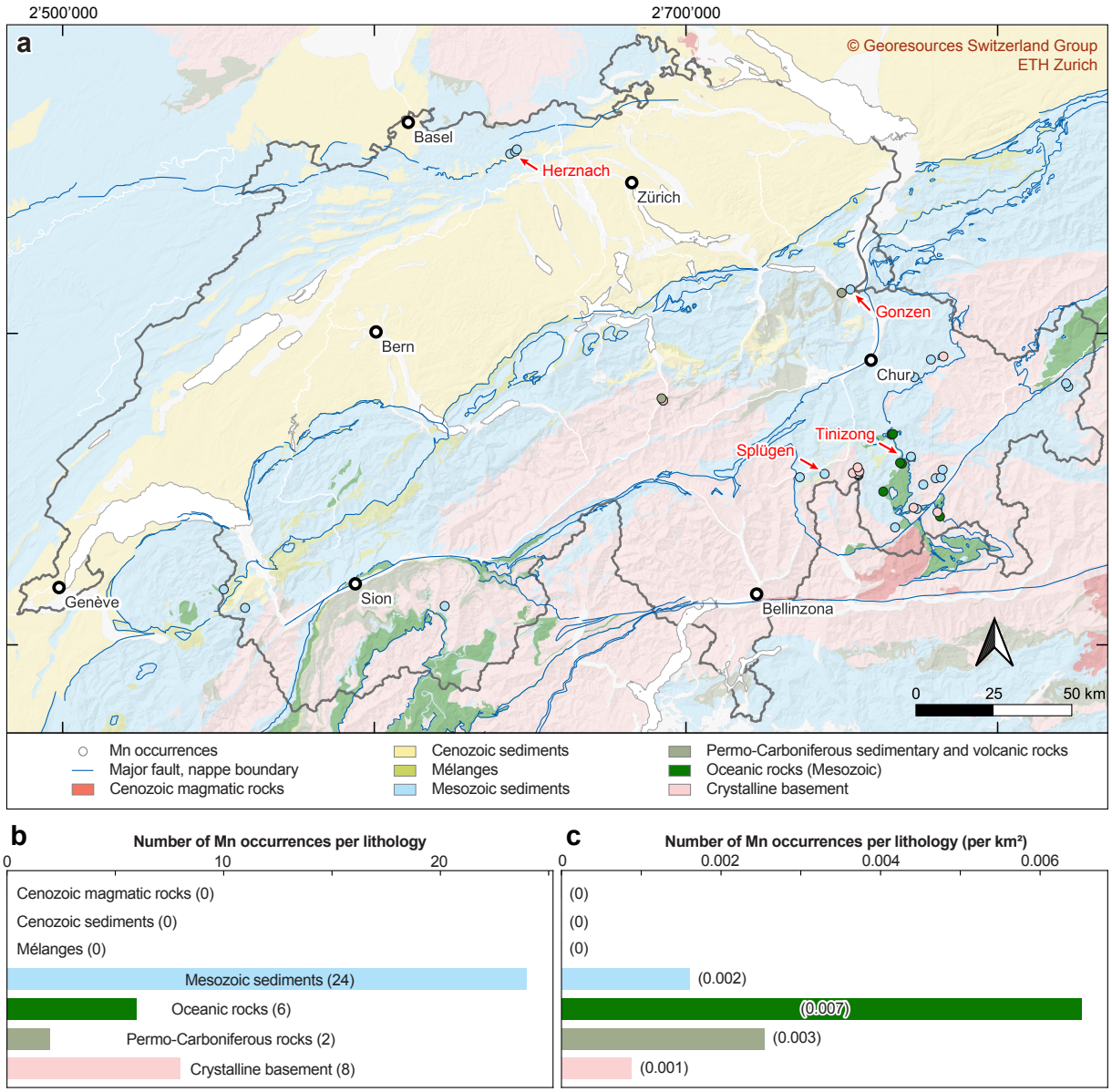


Fig. 14. (a) Map showing four lithological groups hosting the 40 manganese (Mn) occurrences listed in the RIS database. (b) Bar plot highlighting the number of occurrences per lithological group. (c) Bar plot showing the number of occurrences per lithology normalised by the area of the corresponding lithology within Switzerland as shown in (a). For many occurrences shown on the map, Mn is present as accessory component (often with low or unspecified concentration) and is not the main component. The number of occurrences may partly reflect the different level of detail of past exploration campaigns.

About 25% of the Mn occurrences are hosted in Triassic carbonates or in the underlying crystalline basement of the Austroalpine or Penninic, containing Mn at concentrations mostly lower than 10% (Grünenfelder 1956, Stucky 1960, Baumberger et al. 1923), but locally up to 16% (e.g. "Splügen", Grenouillet 1920). The "Gonzen" site (Tab. 3) is quite unique with respect to the relatively high Mn concentrations (up to 50% Mn of the mineralisation) and the presumably combined sedimentary-hydrothermal genesis of the Fe-Mn ore.

At the historically important Middle Jurassic iron oolite deposits around “Herznach”, Mn occurs at relatively low concentrations (0.2-0.4%). In the Helvetics, the corresponding iron oolites documented in the RIS contain even less or no Mn (Fehlmann & Rickenbach 1962).

5.3.3 Cobalt (Co), Nickel (Ni) and Germanium (Ge)

Cobalt (Co) is essential for lithium-ion batteries, particularly in electric vehicles and energy storage systems. It enhances battery stability and energy density. Nickel (Ni) represents a key component in stainless steel and high-performance batteries, especially in Ni-rich lithium-ion battery cathodes. Germanium (Ge) is a rare semiconductor material used in fibre and infrared optics, high-efficiency solar cells, as well as in military applications and advanced electronics (scrreen.eu/crms-2023/).

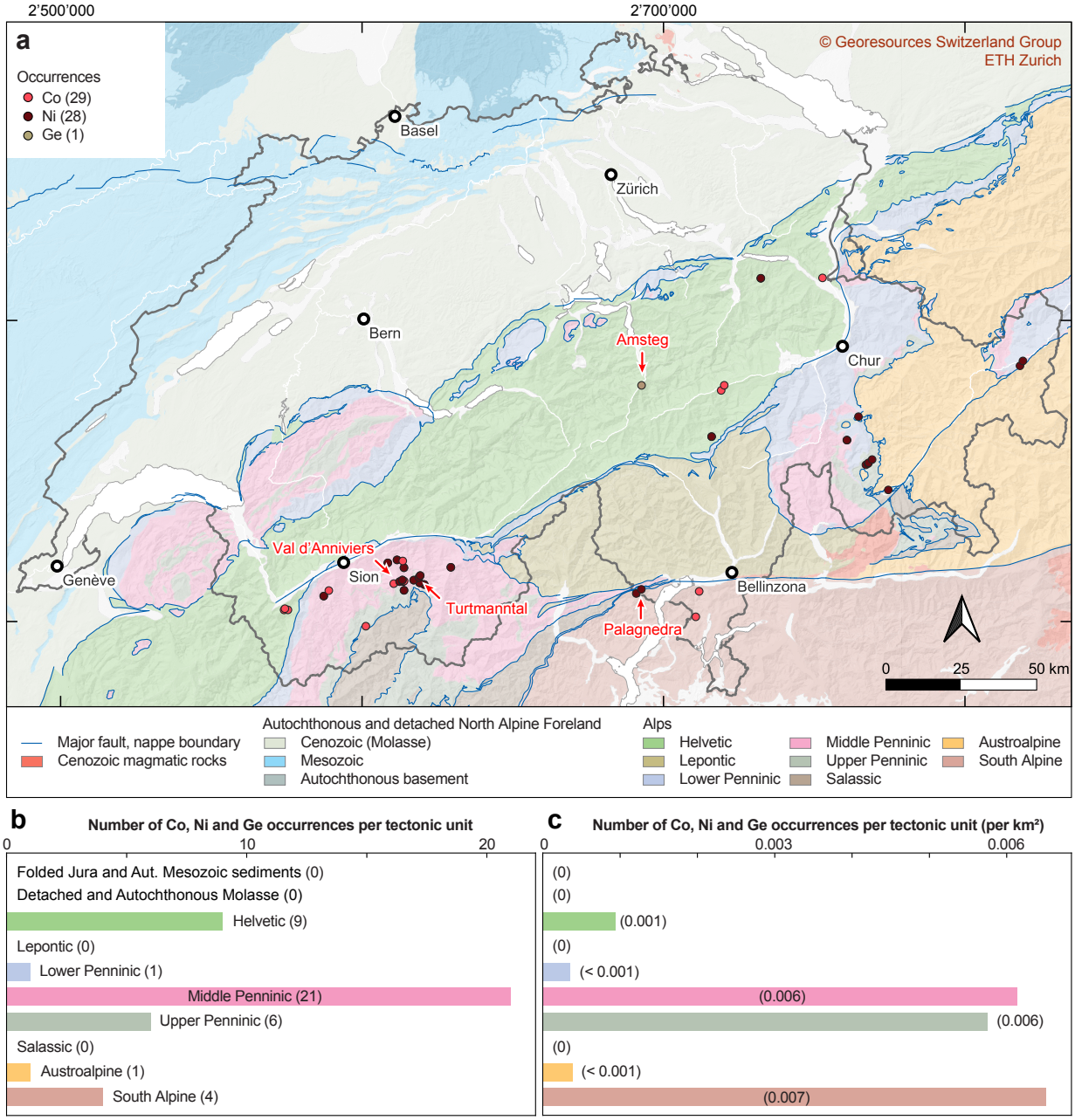


Fig. 15. (a) Map showing the tectonic units hosting the cobalt (Co), nickel (Ni) and germanium (Ge) occurrences listed in the RIS database. The number of occurrences per element are given in brackets. (b) Bar plot highlighting the number of occurrences per tectonic unit. (c) Bar plot showing the number of occurrences per tectonic unit normalised by the area of the corresponding unit within Switzerland as shown in (a). For many occurrences shown on the map, Co, Ni or Ge are present as accessory components (often with low or unspecified concentration) and are not the main component. The number of occurrences may partly reflect the different level of detail of past exploration campaigns.

In the RIS database, Co, Ni or Ge are mentioned 58 times as a main or accessory component at 42 sites (Fig. 15a, b). About half of these sites are in the Middle Penninic nappes of the Valais and to a lesser extent also in Graubünden (Fig. 15b). The remaining occurrences are in the Helvetic (9), Upper Penninic (6) and South Alpine domains (4). A few sites are found in the Lower Penninic and Austroalpine domains.

The South Alpine, Middle and Upper Penninic domains show densities of approximately 0.006 to 0.008 occurrences per km^2 (Fig. 15c). In the remaining tectonic units, Co or Ni occur at much lower per area densities.

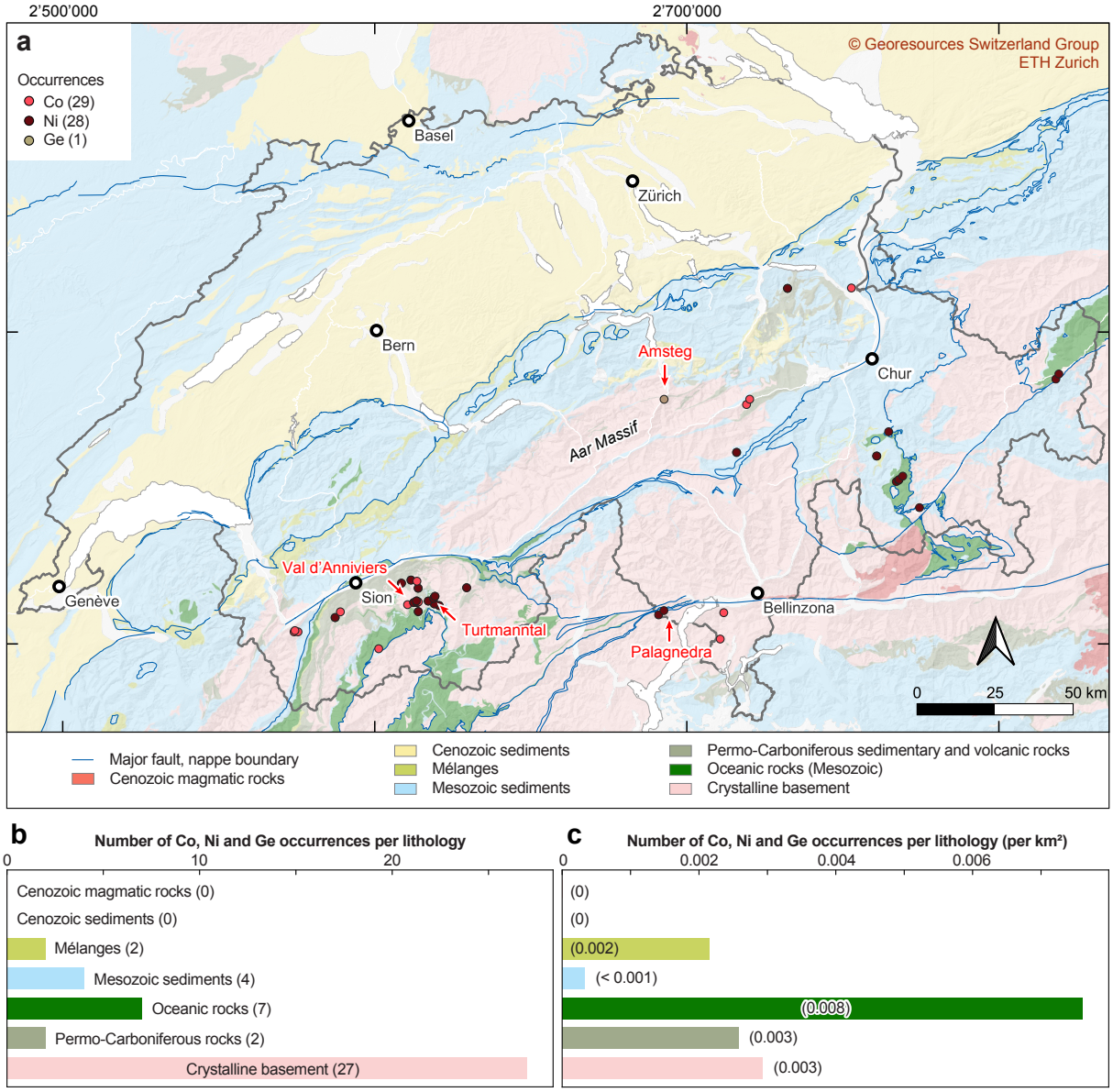


Fig. 16. (a) Map showing five lithological groups hosting the cobalt (Co), nickel (Ni) and germanium (Ge) occurrences listed in the RIS database. The number of occurrences per element are given in brackets. (b) Bar plot highlighting the number of occurrences per lithological group. (c) Bar plot showing the number of occurrences per lithology normalised by the area of the corresponding lithology within Switzerland as shown in (a). For many occurrences shown on the map, Co, Ni or Ge are present as accessory components (often with low or unspecified concentration) and are not the main component. The number of occurrences may partly reflect the different level of detail of past exploration campaigns.

More than half (27) of the Co and Ni occurrences are hosted in crystalline basement (Fig. 16a), 7 occurrences are hosted by oceanic rocks. The remaining occurrences are hosted by Mesozoic sediments, Permo-Carboniferous sedimentary and volcanic rocks or by Mélanges (Fig. 16b). Relative to the exposed area, oceanic rocks clearly host the highest density of Co and Ni occurrences (Fig. 16c),

followed by crystalline basement and Permo-Carboniferous rocks. In the other tectonic units, Co and Ni occurrences are rarely reported.

The historically most important Co and Ni ores are associated with basic or ultrabasic rocks of the Middle and Upper Penninic nappes in the Valais and Graubünden areas as well as in the Ivrea zone ("Palagnedra" site in Fig. 15 and Fig. 16, Kündig et al. 1997).

As already mentioned in Chapt. 5.1, some Co and Ni mining took place in the 18th and 19th centuries at the sites "Grand Praz" and "Gollyre" (see "Val d'Anniviers", Fig. 15 & Fig. 16) and in the late 19th century at "Kaltenberg" (see "Turtmanntal" in Fig. 15 & Fig. 16, Woodtli et al. 1987). No further mining was carried out during the World Wars I and II, mostly for economic reasons. Co and Ni occur in concentrations of 8-20 and 2-20%, respectively, but the fault and vein-related mineralisations are structurally complex and typically less than 0.5 m thick.

The Co and Ni mineralisations of the Ivrea zone are associated with an up to 30 m thick and complex fault zone. In contrast to the "Val d'Anniviers" and "Turtmanntal" sites, the concentrations of Co and Ni are generally lower than 0.05% and 2.5%, respectively (Bianconi et al. 1976).

In summary, the documented Co and Ni bearing occurrences are structurally very complex and laterally discontinuous. Co and Ni concentrations and associated reserve estimates are not available for most of the sites.

Germanium is mentioned as accessory component at one site close to "Amsteg" (UR) in the crystalline basement of the Aar Massif (Helvetics, Fig. 15 & Fig. 16). Huttenlocher (1936) described Ge-bearing minerals, which are part of a lead-iron-zinc-copper ore. However, a subsequent geochemical investigation could not detect any Ge (Jenni 1973).

5.3.4 Rare earth elements (REEs) and platinum group metals (PGMs)

REEs are essential for high-tech industries, renewable energy (especially wind turbines) and defence applications due to their unique magnetic, optical, and catalytic properties (scrreen.eu/crms-2023/).

In Switzerland, several REE-bearing minerals such as allanite, titanite or monazite are well-documented in the literature (e.g. Cuchet et al. 2022a,b). In these minerals, yttrium (Y), lanthanum (La), cerium (Ce) and neodymium (Nd) have been identified, mostly by mineral collectors (e.g. Cuchet et al. 2022a, b) or in academic studies (e.g. Guastoni et al. 2016). Gallium (Ga), dysprosium (Dy), praseodymium (Pr) are not mentioned in the RIS database.

15 out of 22 REE occurrences shown in Fig. 17 are located in amphibolite-facies gneisses of the Monte Leone nappe, representing one of the uppermost Lepontic nappes (e.g. "Binntal" site). Further sites are known across the border with Italy (e.g. Cuchet et al. 2022a, b). At most of these sites, Y, La and Ce-bearing minerals have been reported. The gneiss units with elevated REE concentrations are up to 50 m thick (Cuchet et al. 2014). However, Y, La and Ce concentrations are generally thought to be lower than the REEs mined today.

The 15 documented REE occurrences of the "Binntal" area are hosted by Alpine-metamorphic amphibolite facies gneisses (Fig. 18). Carbonate phases in the associated rocks point to a sedimentary protolith, at least for some of these gneisses (Crumbach et al. 2014).

The remaining occurrences of REEs are situated in the Helvetics, Middle Penninics, the southernmost Lepontic or in the South Alpine domains (Fig. 17, Fig. 18). All occurrences are hosted by crystalline basement.

Some REE-bearing pegmatites are documented in the mineral-collecting literature or on platforms such as www.mindat.org. For example, the migmatite belt, representing the southernmost part of the Lepontic contains some Y (see "Val Leggia", e.g. Guastoni 2012, Guastoni et al. 2016). These references were not systematically screened for this review but may provide interesting indications for follow-up studies.

PGMs have catalytic properties, essential in catalytic converters, industrial catalysts, hydrogen technologies (i.e. hydrogen production), and in electronic components. They are highly concentrated in a few countries (especially South Africa), making their supply economically and strategically vulnerable (scrreen.eu/crms-2023/).

Platinum is reported as accessory component at one historic gold extraction site at the “Turtmanntal” (Fig. 17, Fig. 18, Woodtli et al. 1987). Analyses of the down-valley Turtmänna river deposits (Marthaler et al. 2008) also revealed elevated platinum concentrations. However, no bedrock ore concentrations are reported in the corresponding literature.

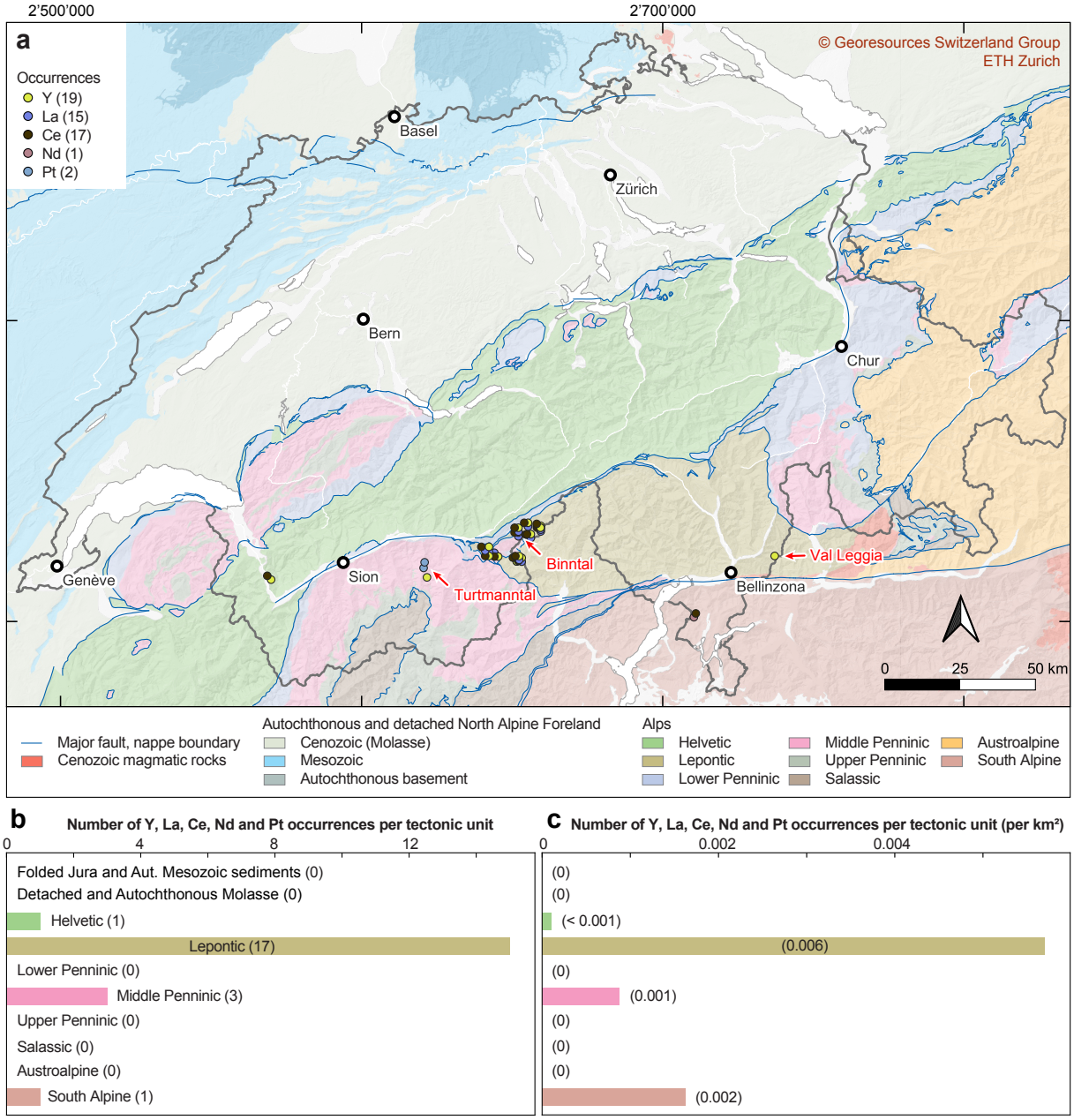


Fig. 17. (a) Map showing the tectonic units hosting occurrences of the rare earth elements (REEs) yttrium (Y), lanthanum (La), cerium (Ce) and neodymium (Nd) as well as platinum (Pt) listed in the RIS database. The number of occurrences per element are given in brackets. (b) Bar plot highlighting the number of occurrences per tectonic unit. (c) Bar plot showing the number of occurrences per tectonic unit normalised by the area of the corresponding unit within Switzerland as shown in (a). For many occurrences shown on the map, Y, La, Ce, Nd or Pt are present as accessory components (often with low or unspecified concentration) and are not the main component. The number of occurrences may partly reflect the different level of detail of past exploration campaigns.

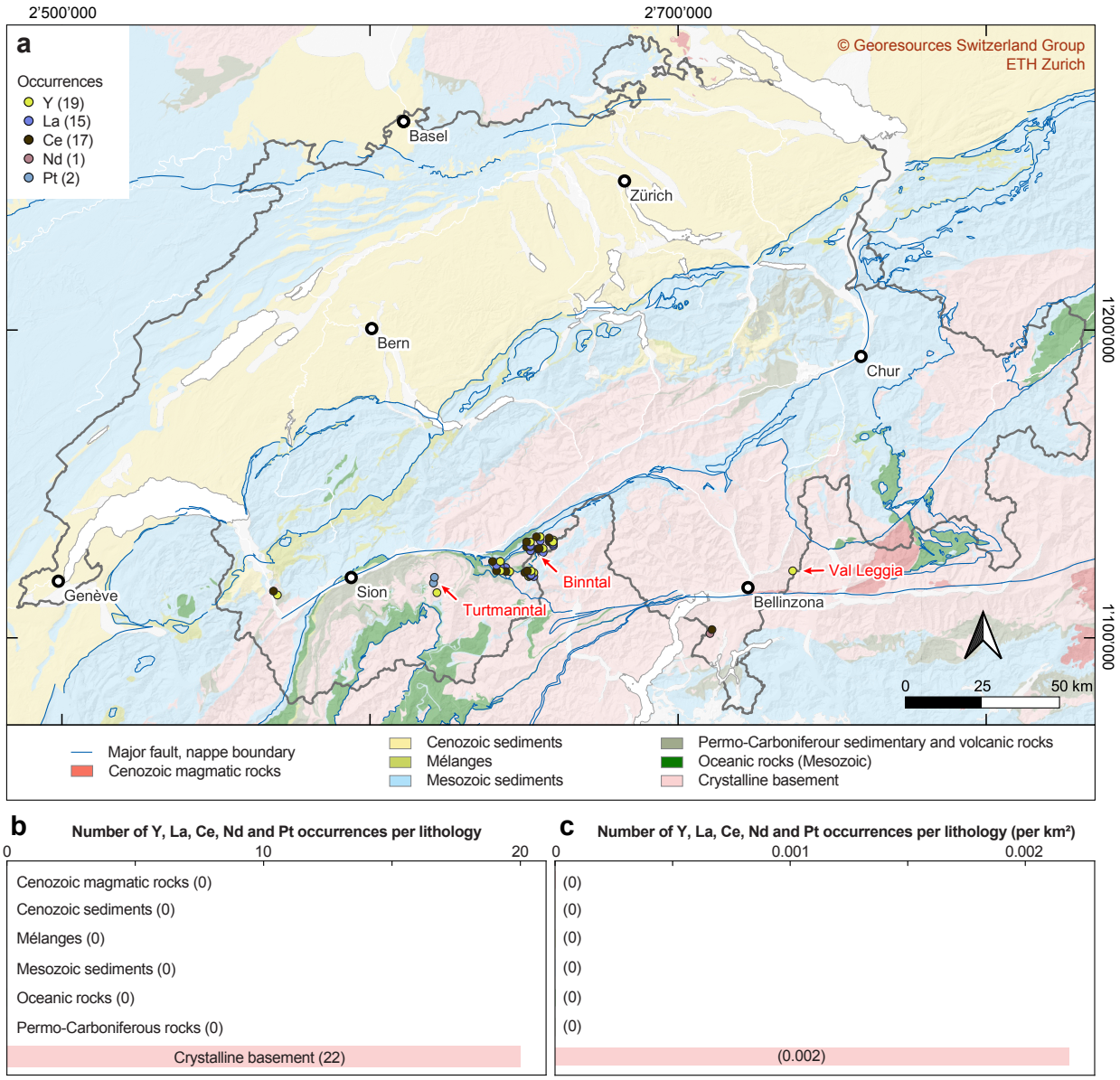


Fig. 18. (a) Map showing the only lithology (i.e. crystalline basement) hosting occurrences of the rare earth elements (REEs) yttrium (Y), lanthanum (La), cerium (Ce) and neodymium (Nd) as well as platinum (Pt) listed in the RIS database. The number of occurrences per element are given in brackets. (b) Bar plot highlighting the number of occurrences per lithology. (c) Bar plot showing the number of occurrences per lithology normalised by the area of the corresponding unit within Switzerland as shown in (a). For many occurrences shown on the map, Y, La, Ce, Nd or Pt are present as accessory components (often with low or unspecified concentration) and are not the main component. The number of occurrences may partly reflect the different level of detail of past exploration campaigns.

5.3.5 Lithium (Li) in pegmatites and from deep geothermal fluids

Lithium (Li) is the key component in Li-ion batteries, which power electric vehicles, renewable energy storage systems, and wide range of consumer electronics (scrreen.eu/crms-2023/).

Two Li-bearing pegmatites, both relatively small-sized and low-grade, are mentioned in the RIS database. One pegmatite is situated close to the “Steingletscher” in the Helvetic (Barcikowski 2010, Schmidlin & Loretz 2014), the other is in the southernmost Lepontic (“Val Leggia”, see Fig. 19, Guastoni 2012). Guastoni et al. (2016) report on other potentially lithium-bearing pegmatites, mostly in Italy close to the Bergell intrusion.

In recent years, Li exploration programmes are increasingly focusing on geothermal brines, as an alternative to conventional exploitation of bedrock deposits or salar brines (e.g. Heuberger & Morgenthaler 2023, Reich et al. 2023). Depending on the geological setting, deep geothermal aquifers

may contain elevated Li concentrations, for example in the Upper Rhine graben (Germany/France), north of Basel (Sanjuan et al. 2016, Frey et al. 2022) and in other parts of Europe (Sanjuan et al. 2022). Von Ungern-Sternberg Schwark et al. (2025) pointed out that Li extraction from geothermal brines is becoming technologically feasible and would have the potential to become a central component of the European raw materials strategy.

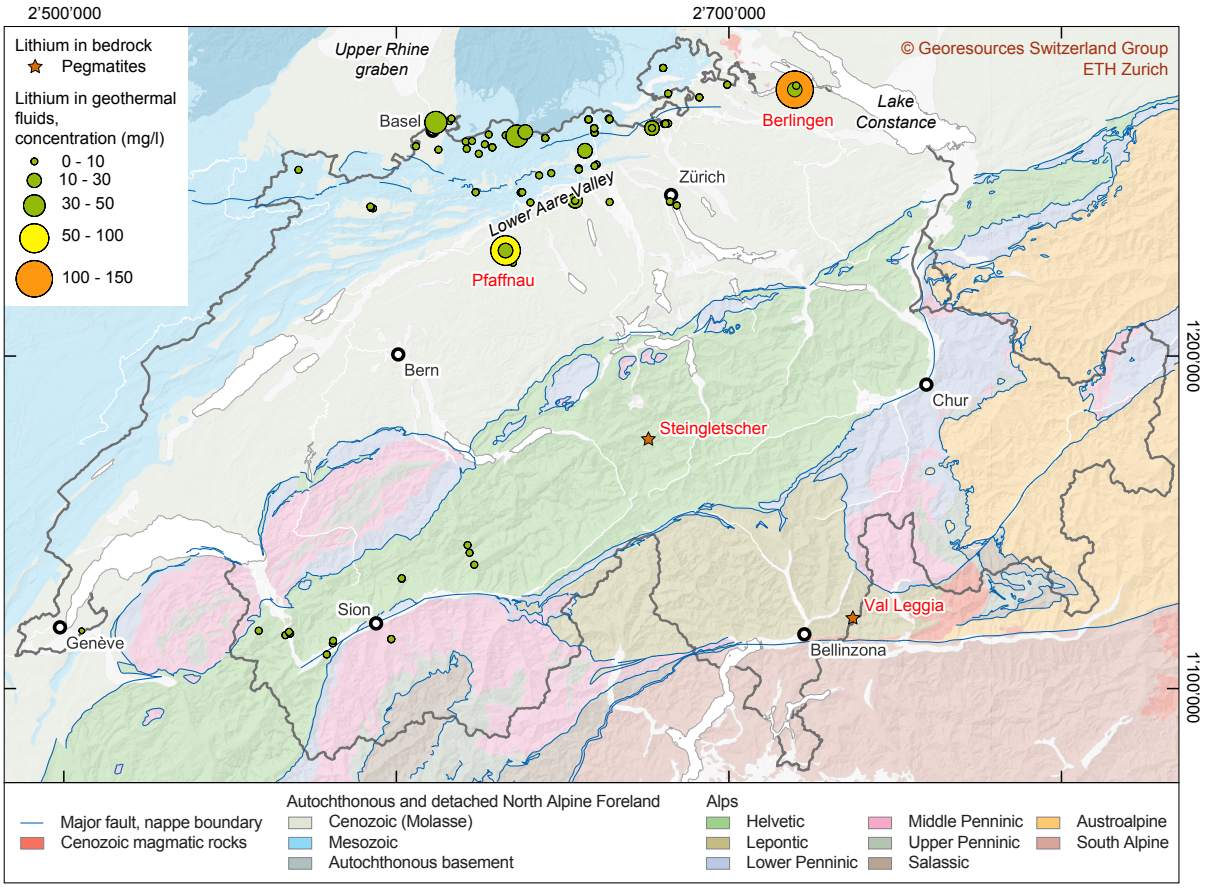


Fig. 19. Map highlighting the documented lithium (Li) occurrences in bedrock (asterisk) and deep saline aquifers in Switzerland (circles, modified from Heuberger & Morgenthaler 2023). Note that there are more wells with Li measurements, but their access is restricted. See above cited report and Fig. 22 there for further details.

Heuberger & Morgenthaler (2023) reported 79 Li concentrations from deeper (>100 m) wells in Switzerland. In 77 out of these wells, Li occurred at concentrations lower than 33 mg/l (Fig. 19). Elevated Li concentrations were detected in the aquifer of the Upper Muschelkalk in two wells of the Swiss Molasse basin (82 mg/l at “Pfaffnau”, 144 mg/l at “Berlingen”, Heuberger & Morgenthaler 2023 for further details). By comparison, the highest concentrations recorded in the Upper Rhine graben or in Italy are 100-210 mg/l (Sanjuan et al. 2016) and up to 480 mg/l (Dini et al. 2022), respectively. The industry considers concentrations above 100 mg/l to be of economic interest, assuming a suitable flow rate. It is worth to be noted that the “Berlingen” (Berlingen-1) and “Pfaffnau” (Pfaffnau-1) wells were drilled for hydrocarbon exploration in 1963 and 1964 and the reliability of the corresponding hydrochemical measurements should be considered with caution (Waber et al. 2014).

The genesis and enrichment of Li in deep geothermal fluid systems is being debated. Elevated Li concentrations preferentially occur in geothermal fluids with high total dissolved solids and appear to coincide with areas with high geothermal heat flow (Heuberger & Morgenthaler 2023, Frings et al. 2024). Based on the currently available data, further investigations in Switzerland should focus on the northern Molasse Basin, more specifically on the area close to Lake Constance, the Basel region and the Lower Aare Valley (Heuberger & Morgenthaler 2023, Stober et al. 2023). Fig. 19 also shows that hydrochemical well data are not available for most of the western part of the Molasse basin, which is mainly due to data access restrictions (see Fig. 22 in Heuberger & Morgenthaler 2023).

In order to fill the data gap and to support the relevant cantonal authorities and project developers in ensuring that future geothermal exploration projects will consider sampling and analysing the fluids encountered using state-of-the-art techniques, the Swiss Geological Survey and the Swiss Federal Office of Energy (SFOE) recently published a sampling and analysis Guideline for the hydrochemical characterisation of geothermal fluids (Stopelli et al. 2024).

5.3.6 Carbon-based CRMs (graphite, bituminous coal and anthracite)

Graphite is important due to its unique combination of properties. It conducts electricity, withstands high temperatures, and resists chemical corrosion. It is essential for Li-ion batteries, steelmaking, lubricants, and fuel cells, making it a key critical raw material in the transition to green and digital technologies (scrreen.eu/crms-2023/).

A few sites in Switzerland document the presence of graphite. At "Val Traversagna" (see also Chapt. 5.1), the presence of some graphite has been documented from a prospection campaign (e.g. Bianconi 1976), but detailed information regarding the extent of these deposits and their quality is limited. Further investigations would be necessary to assess if there is potential for graphite mining. Other graphite occurrences highlighted in Fig. 20 and Fig. 21 are distributed across the crystalline basement of the Helvetic, the Middle Penninic, and the South Alpine domains. They are typically hosted by high-grade metamorphic rocks and the presence of graphite is often related to faults or hydrothermal veins. The documented occurrences are rather small-scale, low-grade and are currently considered to have no economic potential.

Bituminous coal, anthracite and graphite, in the following referred to as carbon-based CRMs, are important raw materials necessary for the renewable energy infrastructure and energy storage technologies. Despite the significant climate impact resulting from its combustion, coking coal (or metallurgical coal) is still widely used for steel production worldwide. Wind turbines and electrical transmission towers require important amounts of steel as static construction material. High-purity anthracite is required for the manufacturing of Li-ion battery anodes and hydrogen storage. Additionally, anthracite serves as a precursor for synthetic graphite, a component employed by the electric vehicle and energy storage sectors (scrreen.eu/crms-2023/).

In Switzerland, bituminous coal and anthracite occur in Carboniferous, Mesozoic or Cenozoic sediments. The lignite occurrences of the Swiss Molasse Basin are not discussed in this report as lignite has a comparably lower embodied energy, a high moisture content and an excessively high impact on climate.

Swiss coal was first used in the Middle Ages, and then during the 18th and 19th centuries when it was mined under state control. However, it was during the World Wars I and II that it was most extensively exploited (Kündig et al. 1997; Heuberger et al. 2022). Between 1940 and 1947, around 500’000 t of anthracite was mined in Switzerland. Together with 410’000 t of lignite and 275’000 t of slate coal, this covered 28% of the country's coal demand during World War II (Kündig et al. 1997). With the resumption of coal imports after the war, Swiss coal production was no longer economically viable.

The most important occurrences of anthracite and bituminous coal are situated in the Middle Penninic south of Sion (Fig. 20). There, almost 30 occurrences, hosted by Permo-Carboniferous sediments, are found within the “Zone Houillère”, a structure trending SSW-NNE (e.g. Wehrli 1925, Fehlmann 1947). The most important historic extraction sites in this zone are “Bramois”, “Chandoline”, “Collonges”, “Dorénaz”, “Ferden”, “Grône”, “Isérables” and “Nendaz” (Fig. 20). In some areas, coal and anthracite seams can have a thickness of up to 2-3 m, but economically significant accumulations are rare. Furthermore, the occurrences are highly deformed, which limits their lateral continuity (e.g. Wehrli 1925, Fehlmann 1947). According to Kündig et al. (1997), the anthracites and coals from the Zone Houillère are difficult to ignite, burn slowly and have a high ash content. Further Carboniferous anthracite and coal occurrences are situated in the Helvetics, following the NNW-SSE trending “Dorénaz” syncline in the Aiguilles-Rouges Massif and in several relatively thin zones containing Permo-Carboniferous sediments in the Aar Massif (see for example site “Lötschental” in Fig. 20).

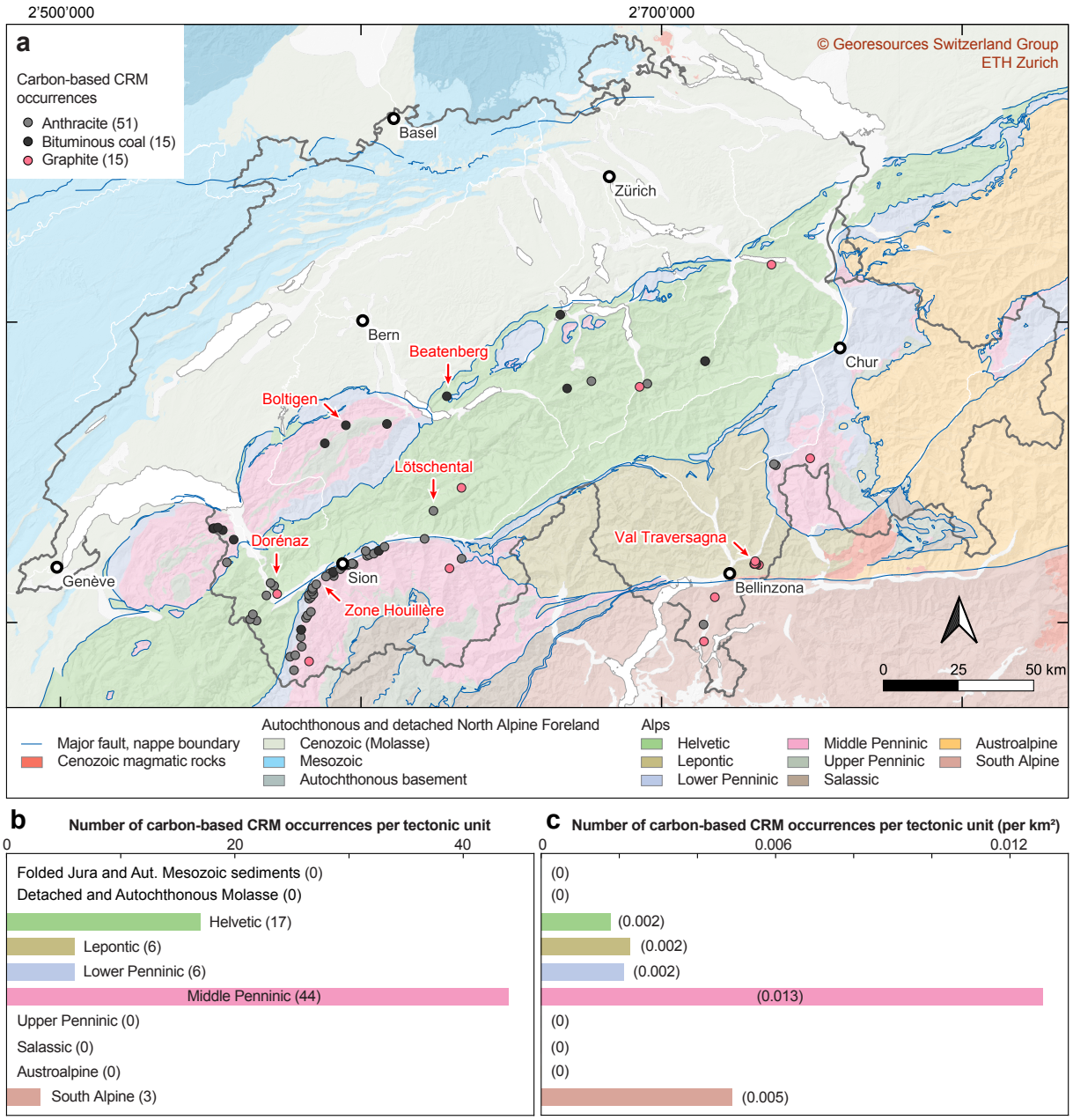


Fig. 20. (a) Map showing the tectonic units hosting occurrences of anthracite, bituminous coal and graphite, summarised as carbon-based CRMs. Bituminous coal and anthracite occurrences can be regarded as indicators for the presence of coal that could be used in metallurgy (coking coal, a material classified as a CRM). The number of occurrences per commodity are given in brackets. (b) Bar plot highlighting the number of occurrences per tectonic unit. (c) Bar plot showing the number of occurrences per tectonic unit normalised by the area of the corresponding unit within Switzerland as shown in (a). For many occurrences shown on the map, graphite is present as accessory component (often with low or unspecified concentration) and is not the main component. The number of all occurrences may partly reflect the different level of detail of past exploration campaigns. The occurrences of lignite are not displayed.

Most of the Mesozoic and Cenozoic coals (in Fig. 21b and c highlighted as Mélange-hosted) are structurally complex or poorly accessible (Kündig et al. 1997). The most important occurrences are the Eocene coals of “Beatenberg” and the Middle Jurassic coals of “Boltigen” (Fig. 20a). These are situated in the Helvetic nappes and in the Préalpes Médianes (Middle Penninic), respectively.

Fig. 21 highlights, that most bituminous coal and anthracite occurrences are situated in Permo-Carboniferous sediments. Mesozoic sediments and Mélanges host some occurrences, too. The mélange-hosted coals shown in Fig. 21b and Fig. 21c are of Cenozoic age. The Permo-Carboniferous sediments contain by far the largest per area density of anthracite and coal occurrences. Mesozoic and Cenozoic coals are much less abundant, relative to the exposed area of these lithostratigraphic units.

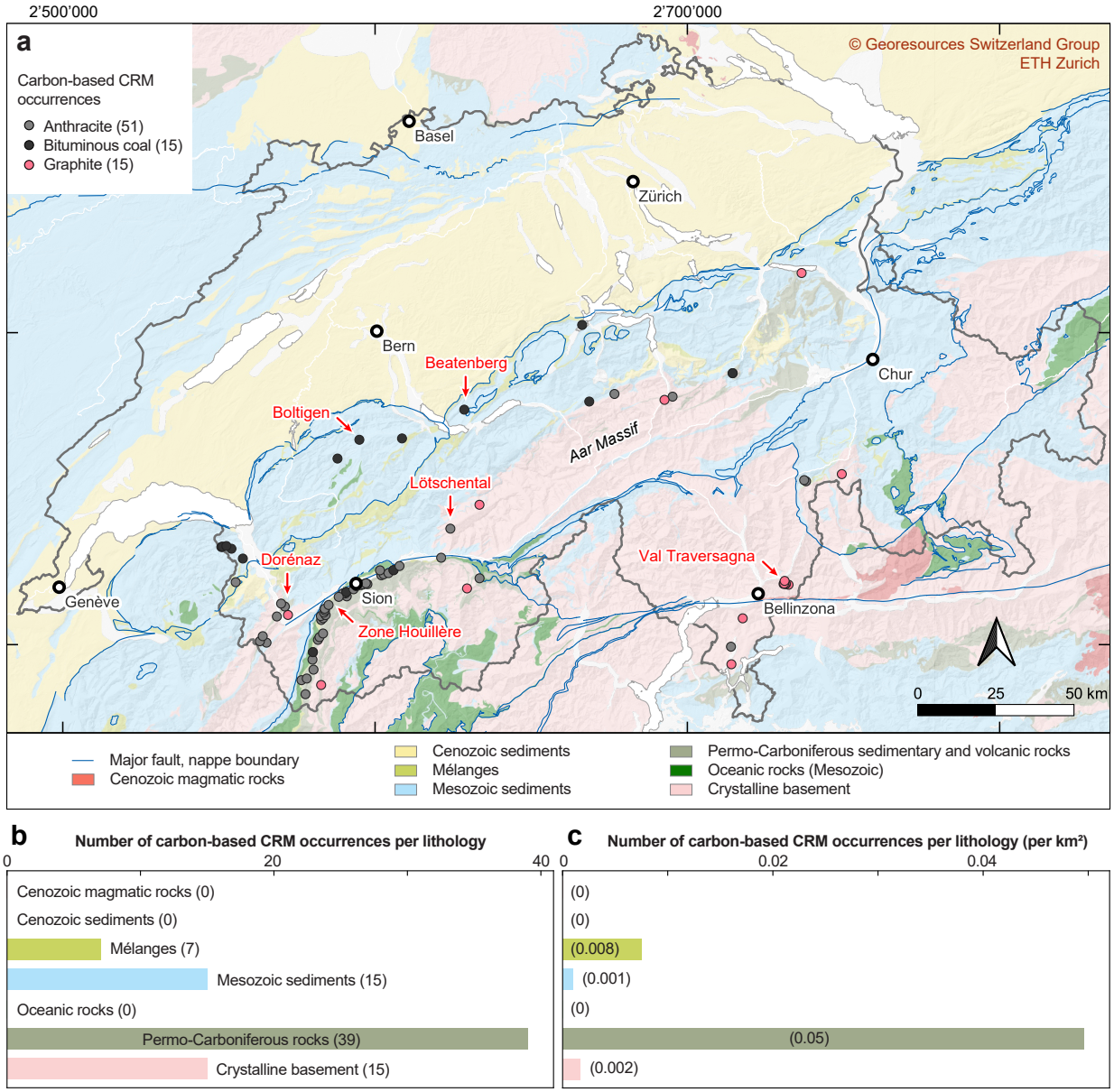


Fig. 21. (a) Map showing the lithostratigraphic units hosting occurrences of anthracite, bituminous coal and graphite, summarised as carbon-based CRMs. Bituminous coal and anthracite occurrences can be regarded as indicators for the presence of coal that could be used in metallurgy (coking coal, a material classified as a CRM). The number of occurrences per commodity are given in brackets. (b) Bar plot highlighting the number of occurrences per lithology. (c) Bar plot showing the number of occurrences per lithology normalised by the area of the corresponding unit within Switzerland as shown in (a). For many occurrences shown on the map, graphite is present as accessory component (often with low or unspecified concentration) and is not the main component. The number of all occurrences may partly reflect the different level of detail of past exploration campaigns. The occurrences of lignite are not displayed.

5.4 Regional geological and geodynamic context of the CRM occurrences

The aim of this investigation was not to interpret the genesis of the CRM occurrences. However, based on the outcome of our geospatial analysis and literature review, we present hereafter a preliminary attempt to categorise the CRM occurrences (in particular copper and manganese) within a genetic scheme of the geodynamic context. This initial interpretation should be regarded as a starting point for future, more in-depth investigations.

The formation of a mineral deposit requires a source, a transport mechanism and geological trap where the mineralisation can concentrate (Müller et al. 2024). Based on the spatial-temporal distribution of the CRM occurrences, this chapter attempts to identify the most important ore-forming processes.

5.4.1 General classification of the ore-forming processes

In this chapter, the processes contributing to the formation of CRM occurrences are outlined using the (limited amount of) data available in the RIS database. The RIS contains some basic and unsystematic information regarding the genesis of the CRM occurrences. Note that the formation of many occurrences may have required more than one of the processes listed below. Therefore, the numbers (in %) given below must be considered with caution.

A preliminary analysis of the RIS data suggests that:

- 50% of all CRM occurrences are associated with **hydrothermal, metasomatic or exhalative** processes. Typical examples are many of the ophiolite-hosted copper occurrences, which are related to the cooling of the newly formed oceanic crust near mid-ocean ridges. There, cold seawater infiltrated young, hot oceanic crust, became heated and chemically reactive. Fluids percolating along faults and fractures underwent intense rock-water interaction, potentially becoming enriched in metals like copper. These metals precipitated upon mixing with cold seawater at the sea floor, forming Volcanogenic Massive Sulfide (VMS)-like occurrences. Note that in such settings, faults and fractures (see below) often represent pathways channelling fluids rich in dissolved metals from the source rocks to the sites where these fluids can precipitate.
- 30% of the CRM occurrences are **sediment-hosted, diagenetic or represent residual sediments**. Some Sediment-hosted Stratiform Copper (SSC-like) occurrences of the “Mürtschenalp” area represent typical sediment-hosted examples. These may have formed when saline and metal-bearing fluids migrated through permeable sedimentary rocks, such as the Permian sandstones and conglomerates or along faults and fractures. These copper-rich fluids precipitated under reducing conditions, for example in shales or carbonates.

  The radiolarite-hosted manganese occurrences near “Tinizong” represent typical examples of sediment-hosted deposits. Such oceanic, manganese-rich deposits form primarily through the slow precipitation of manganese and iron oxides from seawater onto the sea floor, often forming nodules or crusts. This process occurs in deep-sea settings where low sedimentation rates and oxygen-rich waters promote the accumulation of metal-rich coatings.
- 10% of the CRM occurrences are associated with **magmatic activity** including pegmatites. For example, the polymetallic copper-bearing occurrences of the “Malcantone” area show strong evidence for an epithermal formation. Such epithermal deposits are closely associated with volcanic and subvolcanic activity. The magmatic heat drives hydrothermal circulation. Hot, metal-bearing fluids ascend from magmatic intrusions and precipitate minerals at shallow crustal levels, typically at less than 1.5 km depth. Many occurrences that are associated with magmatic activity may also be linked with hydrothermal processes (see above) or faults and fractures (see below).
- 5% of the CRM occurrences are associated with **faults and fractures**. Fault-hosted graphite occurrences, such as the “Val Traversagna” example, form when carbon-rich fluids migrate along larger faults and precipitate graphite under high temperature and pressure conditions. In this setting, graphite commonly occurs as disseminations or massive lenses within mylonitic or schistose rocks, reflecting intense deformation and metamorphism.

Faults and fractures may play an important role for many occurrences that are in the RIS database assigned to hydrothermal, sediment-hosted, magmatic or metamorphic processes (see above and below).

- 5% off the CRM occurrences are related to **metamorphic processes**. The Alpine copper-bearing occurrences (veins, hosted in Alpine metamorphic rocks) at "Val Ferrera" can be regarded as typical examples. Mineral reactions due to changing metamorphic conditions (pressure and temperature) during the Alpine orogeny are interpreted to be the source of the fluids, which mobilised and locally precipitated copper-bearing minerals. Metamorphic processes may play an important role for many occurrences that are in the RIS database assigned to hydrothermal, sediment-hosted or magmatic processes as well as faults and fractures (see above).

At a larger scale and over time, the processes listed above are controlled by the regional geodynamic and tectonic setting.

5.4.2 Copper and manganese ore-forming processes and geodynamic context

In this chapter, we focus exclusively on copper and manganese occurrences and discuss how the regional geodynamic evolution has led to very contrasting spatial-temporal distributions of these occurrences.

For most of the copper and manganese occurrences documented in the RIS database, there is little or no information regarding the age of the occurrences. Therefore, we have used the host rock age (defined in the GeoCover geological map dataset) to infer the minimum age of all copper and manganese occurrences in Switzerland (Fig. 22). The age of the host rock can often be regarded as a minimum age for an occurrence (i.e. an occurrence cannot be older than the bedrock hosting it).

Fig. 22 shows the large-scale geodynamic setting and the geological processes, which may have influenced the genesis of the occurrences. The geological sketches illustrate the paleogeographic distribution of continental and oceanic domains over the past 500 million years. These were created or modified by regional tectonic events, such as continent-continent collision, rifting and sea floor spreading. The duration of key processes such as hydrothermal, magmatic activity or the presence and circulation of hypersaline brines, is also indicated. The temporal distribution (host rock age) of the copper and manganese occurrences is shown and can be linked to potentially ore-forming processes.

The oldest copper and manganese occurrences may have formed during pre-Variscan orogenic cycles by a variety of hydrothermal, magmatic, sedimentary processes and/or weathering (Fig. 22, process a). Such occurrences have a small potential to be preserved due to intense deformation during subsequent orogenic cycles, so that no specific examples can be named.

The Variscan orogeny was associated with intense magmatic, metamorphic and hydrothermal activity, which has likely led to the formation of some Carboniferous copper and manganese occurrences (process b in Fig. 22). However, no specific examples are reported in the RIS database.

In the Late Paleozoic (mostly Carboniferous to Permian), post-Variscan transtension led to the formation of ENE-WSW and N-S trending troughs (e.g. rift graben and half grabens, Fig. 22, process c). This early continental rifting phase was associated with intense plutonic, volcanic and hydrothermal activity. These troughs were filled with terrestrial and volcanic sediments. Many vein-hosted and fault-related copper occurrences in the Helvetic, Penninic and South Alpine basement show some characteristics of epithermal or VMS-type deposits and are interpreted to be linked to post-Variscan transtension and the associated magmatic activity. For example, Rigaux (2022) and Müller (2023) propose a Permian age and epithermal formation for some occurrences of the “Malcantone” area. Bächtiger (1964) relates the genesis of some occurrences at the “Mürtschenalp” site to magmatic activity during the Permian (see Chapt. 5.3.1). Manganese occurrences are not significantly enriched in the Late Paleozoic (Fig. 22).

The Permian-Triassic boundary is marked by a sharp decrease in the number of copper occurrences per host rock age, while the manganese occurrences remain relatively stable. The Triassic is marked by a marine transgression and by sedimentation under epicontinental and sometimes evaporitic conditions (see process d on Fig. 22). Stratiform copper occurrences may have formed during this period by metal-leaching of the evaporitic sea water, especially where such fluids circulated through the

underlying permeable Permo-Carboniferous terrestrial sediments or the major basin-bounding fault zones (see for example the Sediment-hosted Stratiform Copper (SSC)-like occurrences of the “Mürtschenalp”, Chapt. 5.3.1).

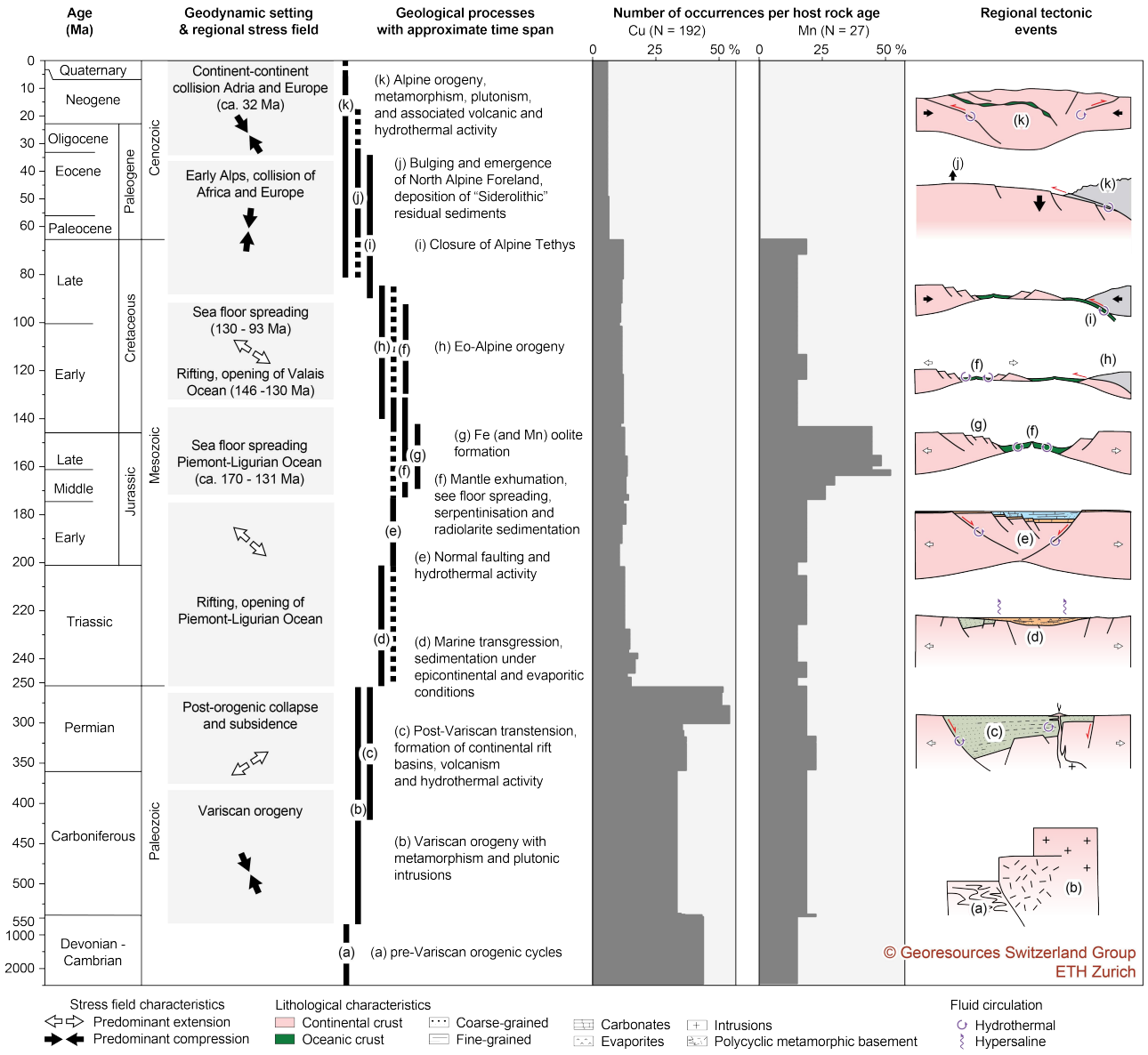


Fig. 22. Temporal distribution of the copper (Cu) and manganese (Mn) occurrences, based on the age information of the host rock, which can be regarded as a maximum age of the occurrence. N = total number of occurrences with known host rock age. Simplified regional geological and geodynamic evolution and geological processes, which are possibly controlling the heterogeneous distribution of occurrences in space and time (modified from Müller et al. 2002). The timing of geological processes is modified from Handy et al. 2010. The temporal distribution of occurrences may partly reflect the different level of detail of past exploration campaigns.

Rifting and the associated opening of the Piemont-Ligurian ocean was active though the Triassic, especially in the future South Alpine, Austroalpine and Penninic domains (Fig. 22, process e: Handy et al. 2010). This may have led to the formation of some Triassic, fault-related hydrothermal copper and manganese occurrences in these tectonic units (see for example some of the vein-hosted copper deposits in the Triassic dolomites of the Austroalpine).

During the Lower Jurassic, intense normal faulting is reported at the European (Helvetic, Lepontic) and Adriatic (Austroalpine, South Alpine) continental margins (Fig. 22, process e). Locally, copper or manganese occurrences may have formed due to the circulation of hydrothermal fluids along these faults, but no specific examples can be mentioned.

In the Middle Jurassic, sea floor spreading took place in the Piemont-Ligurian Ocean (Handy et al. 2010, Fig. 22, process f). The cooling of the newly formed basic and ultrabasic oceanic rocks has produced many CRM occurrences through exhalative processes (see also Fig. 10). The overlying deep-sea sediments, such as radiolarites, host many manganese occurrences. These occurrences are restricted to the Upper Penninic, Salassic and the Austroalpine nappes (Fig. 22). Sea floor spreading has not significantly affected the temporal distribution of the copper occurrences, although some ophiolite-hosted copper occurrences are known from the Upper Penninic.

During the same period, iron (and manganese) oolites were deposited onto the proximal European continental margin (Helvetics, Folded Jura and Autochthonous North Alpine Foreland). However, the manganese concentration in these oolites is rather low (see also Chapt. 5.3.2). The stratiform “Gonzen” manganese deposit formed during the Late Jurassic, indicating that faulting and hydrothermal activity on the passive European margin persisted also during this period.

The Early Cretaceous was characterised by contemporaneous compression (the Eo-Alpine orogeny in the Austroalpine/South Alpine domains, process h in Fig. 22) and extension, including some sea floor spreading in the Valais domain (process f, Fig. 22). Both processes did not have a major impact on the temporal distribution of the copper and manganese occurrences.

The Mesozoic-Cenozoic boundary is characterised by a sharp drop in the number of manganese and copper occurrences. This period is dominated by the closure of the Piemont-Ligurian and the Valais oceanic domains (Fig. 22, process i). Bulging of the European plate (Fig. 22j) in response to the underthrusting of the European continental margin during the Alpine orogeny (Fig. 22k) has led to the emergence of the North Alpine Foreland for more than 60 Myrs. The “Siderolithic” residual deposits formed during this period. They are strongly enriched in iron and can contain low concentrations of manganese or phosphorous.

Finally, metamorphic and hydrothermal fluids associated with the Alpine orogeny have produced a significant number of copper and manganese occurrences in the Alps. Some polymetallic vein mineralisations, for example in the “Val Ferrera” or in the Helvetics, contain some copper and are often interpreted to be of Alpine origin (Cenozoic formation age). The Alpine deformation has also overprinted and segregated preexisting deposits into complex geometries.

Overall, the copper and manganese examples demonstrate how a better understanding of the geological settings associated with the formation of the mineralisations could help identify domains that could potentially host specific types of deposits, enabling more targeted and effective future prospection programmes.

5.5 Accessibility of the CRM occurrences

Many CRM occurrences are situated in remote Alpine regions at high elevations with limited infrastructure and difficult access. Fig. 23a shows all CRM occurrences in Switzerland.

To visualise the accessibility as a first approximation, we assume arbitrarily that only occurrences situated at a ground elevation lower than 1300 m are reasonably accessible from a logistical point of view (green area in Fig. 23a). Fig. 23b shows that about 65% of the CRM occurrences are situated at ground elevations higher than 1300 m (grey bars in histogram plot) whereas the remaining are situated close to the valley floor in “potentially accessible” areas.

Modern mining operations, either open-pit or underground, have a large territorial footprint resulting from the accomodation of their extraction, mineral processing and waste management infrastructure. Due to Switzerland’s relatively small size, morphology, densely built-up environment, numerous protected areas and important tourism, as well as other land use interests, a conventional mining operation of CRMs appears unlikely. As an example, Fig. 23a shows the extent of the Federal Inventory of Landscapes and Natural Monuments (ILNM), protecting nature and cultural heritage. As displayed in Fig. 23c, more than 20% of the CRM occurrences are in conflict with the ILNM, representing just one example of the many conservation inventories at the federal, cantonal and community levels.

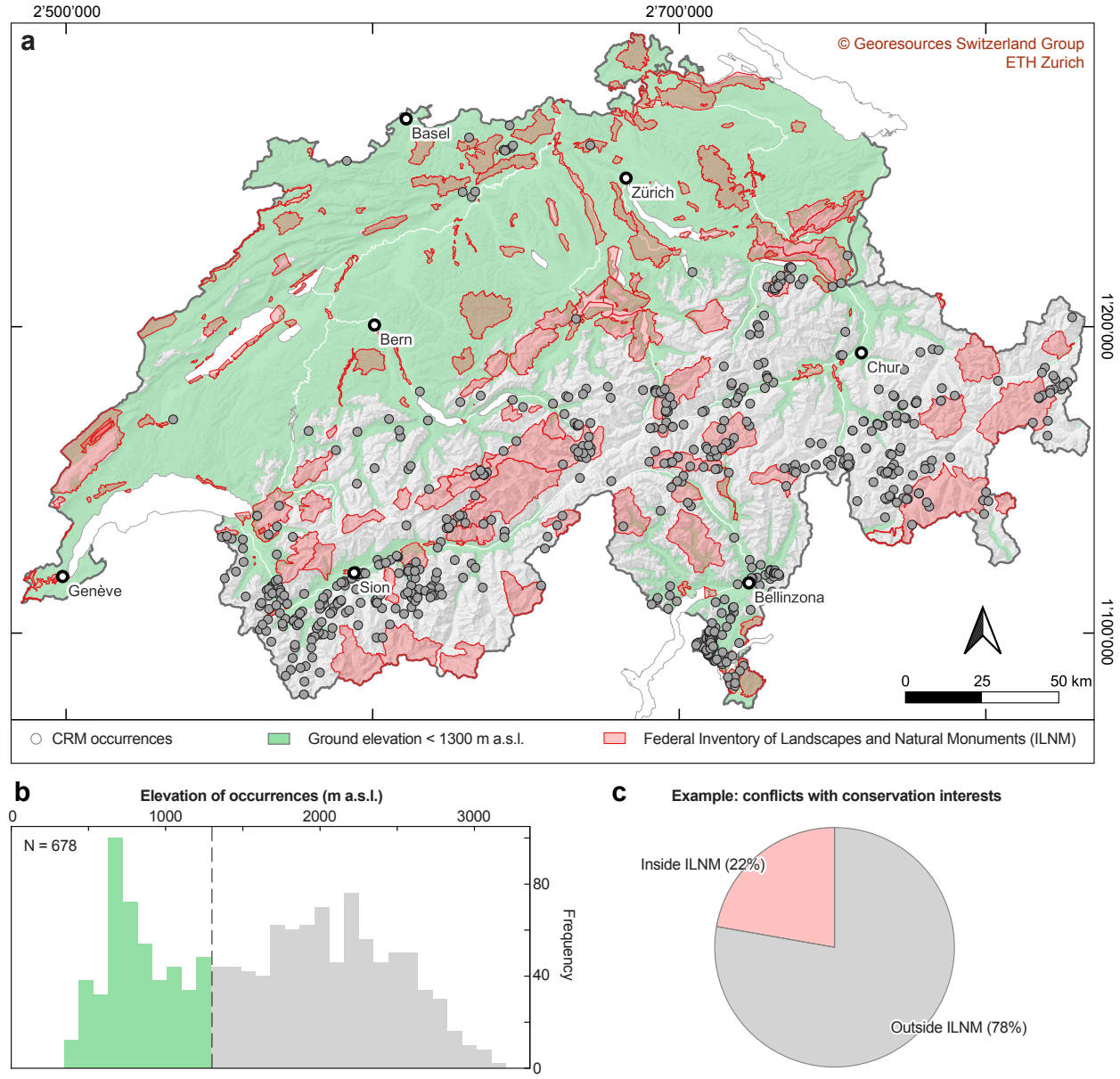


Fig. 23. (a) Map showing the CRM, bituminous coal and anthracite occurrences in Switzerland, as documented in the RIS. The area at ground elevations lower than 1300 m a.s.l. is highlighted in green. The Federal Inventory of Landscapes and Natural Monuments (ILNM) conservation areas is displayed in red. (b) Elevation distribution of occurrences shown in (a). The 1300 m upper elevation limit indicating, as a first approximation, proximity to the valley floor and associated basic infrastructure, is shown as a dashed black line. (c) Proportion of occurrences situated within an ILNM conservation area. Note that the ILNM represents one out of many conservation inventories.

6 Extraction of CRMs from secondary sources

6.1 Introduction

Municipal or industrial waste is known to contain valuable raw materials. The EU-funded FutuRaM project, in which the Technology & Society Laboratory of EMPA is involved, aims to investigate six major waste streams (batteries, electrical and electronic equipment, vehicles, mining, slags and ashes, and construction and demolition materials) that may represent an important source of CRMs.

This chapter briefly addresses the situation regarding the recovery of CRMs from the recycling of electronic waste and from the processing of historic mine tailings or industrial waste in Switzerland.

6.2 CRMs from e-waste

The recycling of most of the CRMs from electronic waste (e-waste) is complex for various reasons. Health and safety issues, as well as technical challenges make the disassembly of these materials difficult (Wäger et al. 2011). Often, batteries or monitors contain hazardous chemical substances such as mercury, which must be separated to further process these materials. Additionally, for certain CRMs, the technology to extract them does not exist yet or is not economically viable.

The EU Critical Raw Materials Act stipulates that, by 2030, the EU recycling capacity is capable of producing at least 25% of the EU's annual consumption of strategic raw materials (SRMs) and is capable of recycling significantly increasing amounts of each strategic raw material from waste (EU 2024). For some SRMs, like copper, tungsten and aluminium, the benchmark of 25% has already been reached or exceeded, with cobalt and nickel well underway (Fig. 24). However, for the majority of the SRMs that are especially needed in renewable energy technologies or high-tech applications, such as REEs, gallium or graphite, are not recycled yet or their recycling input rate is well below the 25% target.

Efforts to boost the recycling input rate of CRMs include (1) the development of new or more efficient technologies/processes and (2) to increase the collection rate of electronic waste. Currently, the collection rate of e-waste in the EU is 46% but varies across member states (Righetti & Rizos 2023 and references therein).

Switzerland is known for its good waste management (e.g. Morf et al. 2013) and high recycling rates. The most important waste streams that are collected, except municipal waste, are glass, aluminium, iron and steel, paper, PET and electronic waste (including batteries). The introduction of the "Ordinance on the Return, Taking Back and Disposal of Electrical and Electronic Equipment" (VREG, SR 814.620) in 1998 has resulted in one of the highest electronic recycling rates in Europe with over 90% of the devices being returned to recycling companies (Kamasa 2023). Switzerland has two recycling organisations for electronic waste, the SENS eRecycling and Swico, which together collected more than 132'000 tonnes of electronic waste in 2023, from which 75% has been reused as secondary raw materials (Sens eRecycling & SWICO 2024). The remaining 25% has been disposed as polluted waste or incinerated. The major fraction of the reused materials are metals (61%), followed by metal-plastic composites (21%) and plastics (7%). Printed circuit boards contribute with 1.5%. Printed circuit boards typically contain precious metals (Au, Ag, Au, Pd) but also CRMs, such as silicon and PGMs, in concentrations that can exceed those found in natural ores (e.g. Meng et al. 2018).

Metals that are easy to separate and recycle like iron, copper and aluminium are recycled by specialized companies in Switzerland or in the EU. The recycled fraction remaining in Switzerland is about 75%. The remaining 25% contains components that are difficult to process, such as printed circuit boards or batteries. Of these, most are exported for further processing and recycled exclusively in the EU (Sens eRecycling & SWICO 2024).

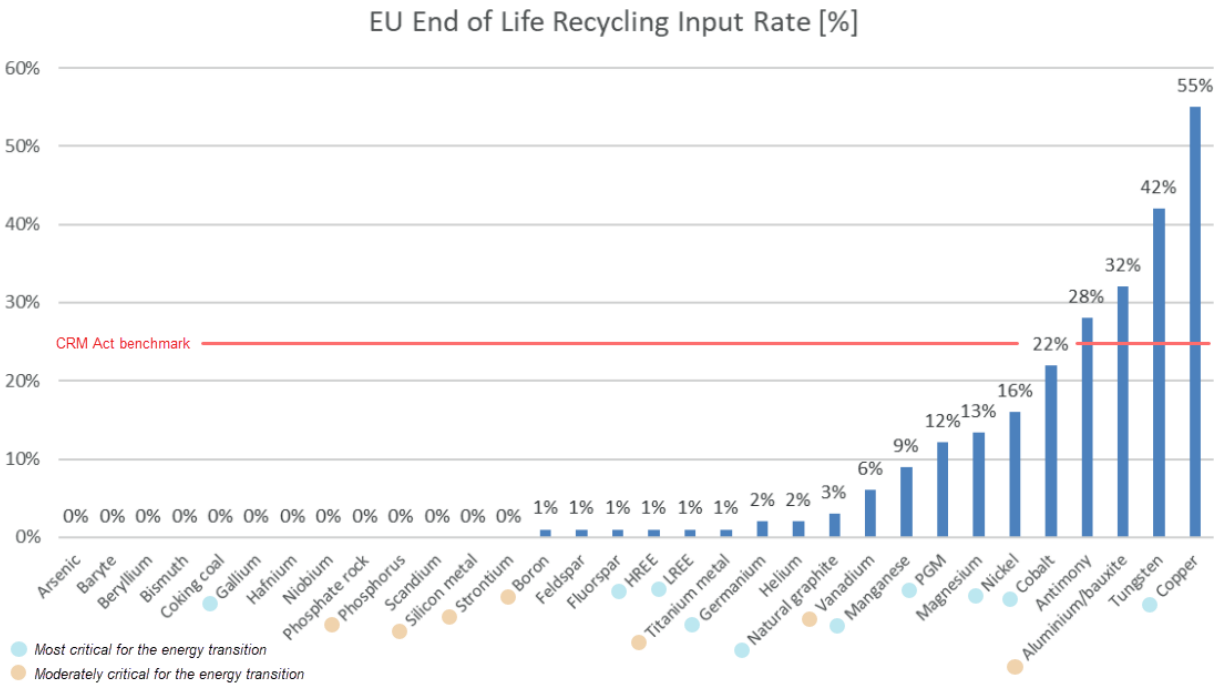


Fig. 24. Contribution of recycling in the EU (End of Life Recycling Input Rate) to meeting materials demand (modified from Grohol & Veeh 2023). The Recycling Input Rate (RIR) is the percentage of the overall demand that can be met through secondary raw materials. The coloured dots indicate the critical raw materials for the energy transition (classification after IRENA & NUPI 2024, see Fig. 6). Note that the RIR of lithium, one of the most critical raw materials for the manufacturing of batteries (not presented in this chart), is currently 0% (according to the EU Raw Materials Information System RMIS, accessed in May 2025).

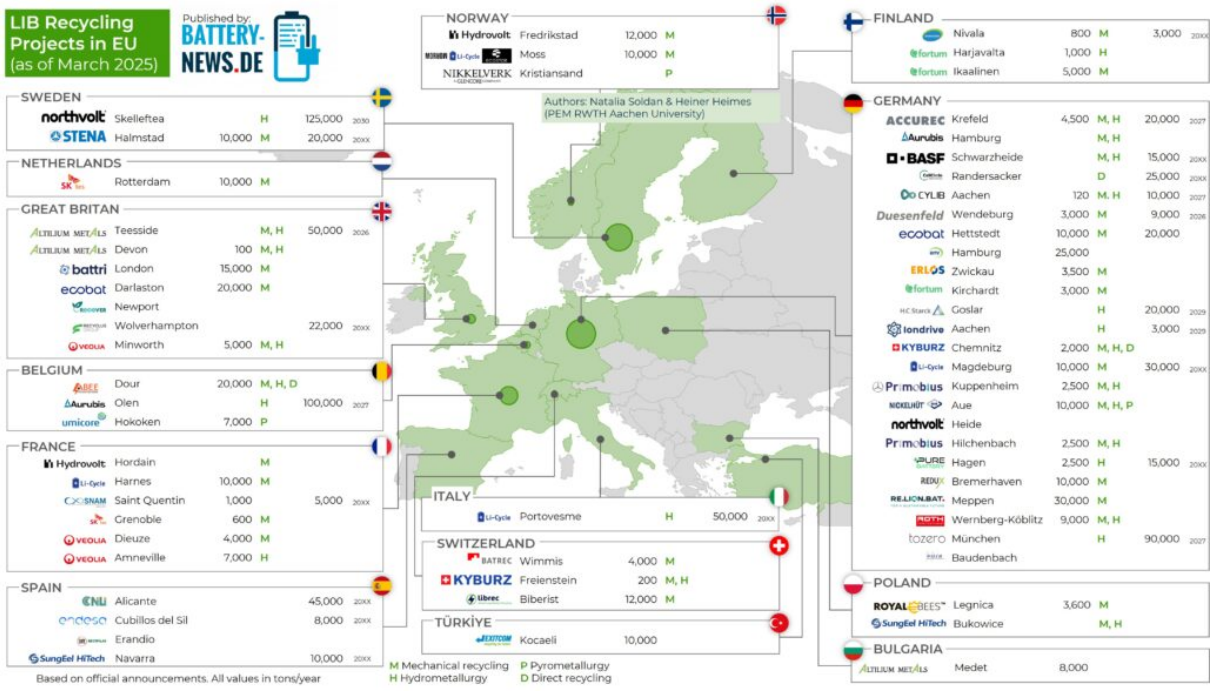


Fig. 25. Map of Europe showing the ongoing or planned installations to extract lithium (and other CRMs) from lithium-ion battery cells by means of mechanical, hydrometallurgical, pyrometallurgical or direct recycling processes (Battery News 2025).

With the modification of the VREG Ordinance (SR 814.620) in 2022, Swiss recyclers are required to specifically separate “rare technology metals” like indium, gallium, germanium, neodymium and tantalum whenever technologically and economically feasible (VREG, SR 814.620). The development of these recycling technologies is under investigation (for example the recycling of REEs, see e.g. Perrin et al. 2024) or, for some few CRMs (cobalt, neodymium, lithium) the solutions are being implemented (e.g. www.sorec.ch). Also to note that the Paul Scherrer Institute (PSI) and the start-up company RemReTech have developed a process for recovering REEs from the powder of spent fluorescent lamps, in particular yttrium, europium, lanthanum, cerium terbium and indium (Patil et al. 2021).

Regarding the recovery of lithium (and other CRMs) from lithium-ion battery cells, three Swiss companies, along with several other European companies (Fig. 25), are ramping up their operations. The company Librec AG recently inaugurated its new site in Biberist (SO) with an expected processing capacity of 12’000 t/a of car batteries and a recovery rate of 97% for cobalt, lithium, manganese and nickel.

6.3 CRMs from historic mine tailings or industrial waste

Some mine tailings (depending on the ore processed) are known to host CRMs (e.g. Mancini et al. 2024). Residual ash from coal-fired power plants is also known to contain CRMs including REEs (e.g. Klupa 2024).

In the frame of the FutuRaM project, the Swiss geological survey swisstopo was requested in 2024 to provide information on active or historic mine tailings in Switzerland. Based on the information provided by the Swiss Society for Historical Mining Research (SGHB) and given the small-sized ore mining history in Switzerland (see Chapt. 5.1) there are no relevant mine tailings sites that could represent a potential for CRM extraction in Switzerland in terms of volume.

The situation is similar with regard to the potential recovery of CRMs from residual ash of coal-fired power plants. First off, there are no active coal-fired power plants in Switzerland. Coal remained an important fuel in the country until about 1960, then was quickly replaced by oil and hydropower (Ferraro 2023). Based on our knowledge there are no historic tailings of coal ashes.

Slags from waste incineration plants represent another potential source of secondary (critical) raw materials. In Switzerland, 800'000 t of waste incineration slags are produced every year. These slags are deposited in dedicated landfills. A recent study on non-iron metals recovery from slags of four Swiss waste incineration plants has shown that the recovery rate varies significantly depending on the plant and the type of slag (Eggenberger 2023). The analysed slags contain the following CRMs: silicon metal, aluminium, copper, manganese, magnesium, nickel and vanadium. Aluminium is most frequent with 1.5-2.6 weight % Al recovered from the slags. The other CRM fractions are in the order of 0.5 weight % and lower (Eggenberger 2023).

7 Conclusions

- Critical raw materials (CRMs) are crucial to enable the energy transition and the digital transformation.
- Switzerland has a comparatively high per capita consumption of metals, non-metallic minerals and energy materials/carriers. Apart from most non-metallic minerals (such as gravel, sand, clay, cement raw materials, hard rock aggregates, salt and gypsum), Switzerland fully relies on imports of metal-bearing components and energy materials/carriers.
- There is no mining of metal ores or CRMs in Switzerland today and a state-driven exploration programme for CRMs is currently not on the national agenda. In contrast to many other EU countries, no nation-wide coordinated exploration programmes have been carried out in the past.
- Many documented CRM occurrences are generally rather small in volume and, with some exceptions, low to moderate in grade (i.e. concentration of a given CRM). However, most of these are not sufficiently investigated. The quality of the data is heterogeneous and unconclusive regarding a potential economic extraction of CRMs in Switzerland.
- This review particularly focussed on the CRMs that are most critical for the energy transition: copper, manganese, cobalt, nickel, germanium, rare earth elements (REEs), platinum group metals (PGMs), lithium and graphite. We produced a series of large-scale tectonic and lithological maps illustrating the relationship between geodynamics and the CRM occurrences documented in the Resources Information System (RIS). An attempt to assign some CRM occurrences to known metallogenic processes is provided, but this preliminary interpretation requires further in-depth analyses and validation.
- Our findings show that many CRMs, especially copper, occur in or close to Permo-Carboniferous sediments and volcanic rocks. Oceanic domains (ultramafic rocks and radiolarites) also contain a higher number of CRM occurrences, especially manganese and nickel. Future prospecting efforts should concentrate on these areas.
- REEs, including yttrium, lanthanum, cerium and neodymium are documented only at a few localities. These are primarily located within high-grade metamorphic rocks or associated with pegmatites, generally small-sized and scattered. Occurrences of PGMs in polymetallic veins and lithium-bearing pegmatites are very rare and the documented examples are small-sized.
- Germanium, gallium, dysprosium and praseodymium, which are also considered as most critical for the energy transition, are rarely or not documented in the RIS database.
- Due to Switzerland's relatively small size, morphology, densely built-up environment, numerous protected areas, important tourism and other land use interests, a conventional mining operation of CRMs with its large infrastructure currently appears unlikely. With its smaller territorial footprint, the recovery of lithium (among other CRMs) from geothermal fluids appears environmentally and socially more acceptable than conventional mining. This under the assumption that the fluids are sufficiently enriched in CRMs and the flow rate at the geothermal well(s) is sufficiently high.
- Switzerland has a very high recycling rate of electronic waste (up to 90%). Every year, 130'000 tonnes of electronic waste are collected and 75% of these are reused as secondary raw materials.
- Only few CRMs (e.g. copper or aluminium) are effectively separated and recycled in Switzerland. Most of the separated fractions are exported in particular to the EU and further processed and recycled there. New recycling technologies and processes will allow to increase the volume of recycled CRMs from electronic waste. Some Swiss companies are ramping up efforts to process lithium-ion car batteries to extract cobalt, lithium, manganese and nickel.
- There are no known (historic) mine tailings that could contain economic amounts of CRMs and the recovery of CRMs from slags from waste incineration plants is minor.

8 Outlook

- To support decision-making processes at national level and to define the scope of future academic- or industry-based investigations on CRMs in Switzerland, we consider it essential to further update, maintain and harmonise the RIS database. The RIS could be updated and refined using deep AI search techniques on existing literature and open geodata (e.g. assets.swissgeol.ch, GeoCover). Data from more recent scientific publications and theses, CRM data from Italy, France, Germany, Austria and Liechtenstein, the mineral collectors literature (e.g. Schweizer Strahler, the open databases of minerals, rocks, meteorites, www.mindat.org) or the open database of geochemical, petrological, mineralogical data (www.earthchem.org) could also be reviewed and included.
- The current geological understanding of CRMs in Switzerland remains limited due to the absence of systematic and coordinated exploration in the past. A structured, stepwise prospection programme would be very helpful to confidently assess the potential for natural CRM resources. This could include the following work steps:
    - Regional-scale geochemical sampling (e.g., stream sediments and soils, see for example the project “Uromine” for the Valais region) could help to identify geochemical anomalies or areas with favourable geological settings.
    - Remote sensing techniques could be applied to refine the mapping of exposed mineralisations, pegmatites or distinct source or host lithologies.
    - Although Switzerland benefits from relatively detailed geological maps, these were not developed with a focus on mineral resources, meaning that potential CRM occurrences may have been overlooked. To address this, exploration efforts could complement existing maps with targeted field investigations including mineralogical studies. Additionally, field mapping in areas where glaciers have recently retreated offers a unique opportunity to examine fresh, previously inaccessible bedrock exposures.
    - The resulting maps, highlighting areas with elevated prospectivity, may help to guide more in-depth exploration including geophysical methods, such as multi-sensing drone systems.
- Extracting lithium from geothermal brines has the advantage of combining energy production with mineral recovery, making the process more sustainable and environmentally friendly than traditional mining. We propose to conduct further academic research on the sources, circulation paths, mineralisation processes and spatial distribution of CRMs (e.g. lithium) in deep geothermal aquifers.
- Future academic research should focus on better understanding the genetic mineral systems of the various types of occurrences known to contain CRMs. According to our results the following areas with favourable geology may represent suitable targets for such investigations:
    - Due to their low Alpine metamorphic overprint, the South Alpine (Ticino) and partly the Austroalpine domains (Graubünden) represent the most promising areas for investigating a variety of CRM-bearing mineral systems (especially copper, manganese, cobalt, graphite), which are apparently associated with Permo-Carboniferous sedimentary and volcanic rocks or the overlying Triassic carbonates and shales.
    - The Upper Penninic (Graubünden and Valais) domain appears most suitable for further investigations on ophiolite-related CRM occurrences including especially copper, manganese, cobalt or nickel.
    - A few REE or lithium-bearing mineralisations or pegmatites are reported in the southernmost Lepontic, the Binntal area (western Lepontic) and in the Aar Massif (Helvetic). Other Late Paleozoic or older potentially REE- or lithium-bearing pegmatites are likely to exist, especially in the external crystalline massifs (Aiguilles Rouges, Mont Blanc and Aar Massifs or the Gotthard nappe) or in the crystalline basement of the Lepontic, Salassic, Middle Penninic, Austroalpine or South Alpine domains. Other Cenozoic potentially REE- or lithium-bearing pegmatites may occur in the Lepontic migmatite belt close to the Periadriatic line or close to the Bergell intrusion in Graubünden.

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