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Abstracts and field trip guide

30th Meeting of the Petrology Group of the Mineralogical Society of Poland

„How Can Mineralogical Sciences Support the Mineral Resources Industry?”

16-19 October, 2025,
Lubliniec, Poland

Organised by:
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30th Meeting of the Petrology Group of the Mineralogical Society of Poland

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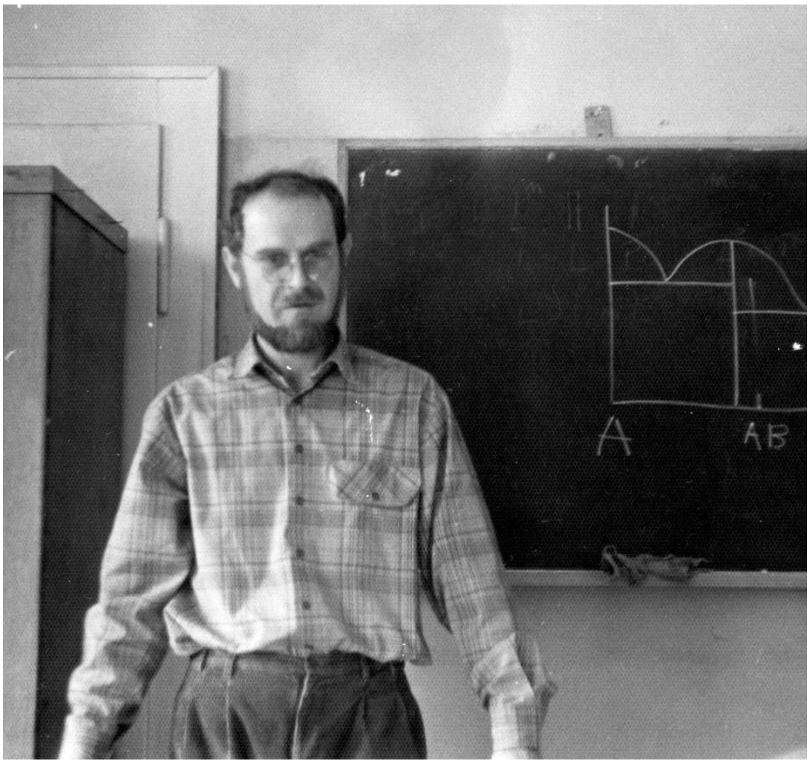
Castle in Lubliniec – the venue of the 30th Meeting of the Petrology Group of the Mineralogical Society of Poland.

Ladies and Gentlemen,

I am writing these words with great pleasure and enthusiasm. I feel truly privileged to be appointed the President of the Mineralogical Society of Poland, when its flagship activity, namely the Meeting of the Petrology Group, celebrates its 30th anniversary. This event has been organized nearly every year since the first one in 1994, when Jacek Puziewicz decided to implement his brilliant idea of creating "Petrology School" workshop for the first time. Originally, the meeting used to gather Polish petrologists only. This has changed with time, and the Meeting of the Petrology Group has become the most attended international conference organized fully by our Society. The conference is a marvelous venue for petrologists investigating crystalline and sedimentary rocks, classical and applied mineralogists, traditional and environmental geochemists, geochronologists, as well as other geologists representing various fields, for example, tectonics, structural geology, and sedimentology. Notwithstanding the latter, the leading topic is always focused on aspects closely related to petrology, as it is this year, when the main emphasis is given to mineral resources, including Critical Raw Materials. This timely topic attracted numerous researchers from Poland and abroad, including widely renowned experts in the fields of economic geology, ore petrology, environmental geochemistry, and carbon dioxide sequestration as the keynote speakers. Based on the above, I am convinced that the 30th Meeting of the Petrology Group of the Mineralogical Society of Poland will be another great scientific and social success. Thus, I wish you all a very successful conference and fruitful discussions, hopefully leading to new, exciting research and scientific collaboration!

Yours truly,
Jarosław Majka
President of the Mineralogical Society of Poland



Dr. Jacek Puziewicz, the first chairmen of the Petrology Group of the Mineralogical Society of Poland (photo taken in 1992).

THE PETROLOGY GROUP OF THE MINERALOGICAL SOCIETY OF POLAND

The Petrology Group of the Mineralogical Society of Poland was established in 1993 thanks to initiative of Professor Alfred Majerowicz from the University of Wrocław, who was supported by Professor Wojciech Narębski from the Polish Academy of Sciences. The first meeting of the Group was organized in Wrocław on October 25th, 1993, and gathered 28 researchers from all academic institutions in Poland in which the petrological research was conducted.

At the beginning of the 90-ties the number of Polish researchers dealing with various aspects of petrology was around 70. Those people did not contact regularly and there was no tradition of systematic meetings. Dr. Jacek Puziewicz, known as "Puzon" ("Trombone"), this time a young scientist, was chosen to be the Chair of the Group. Jacek Puziewicz was of the opinion that the petrological milieu in Poland should organize annual meeting. The idea was to bring the people together and to give those, who are at the beginning of their career, the opportunity to present the results of their work to the audience gathering all Polish petrologists. This was one of many small initiatives which re-shaped Poland after the change of political system in 1990 and related intense reorganization of social life, including also academic science.

The first Session of Petrology Group was organized in October 1994 in Trzebieszowice in the Sudetes. The meeting grouped approximately 40 participants, besides regular presentations Jacek Puziewicz and Stanisław Mazur prepared small workshop on non-coaxially deformed rocks. No abstract book was prepared. The scientific discussions were lively, and the social atmosphere was very good, indicating that the idea of Petrology Group meetings has the chance to work. The second Session of the Petrology Group was organized in October 1995 in Kowary. The number participants was similar (~40), but all the academic centers from Poland in which the petrology was taught were represented. The first conference book was published.

Jacek Puziewicz and his co-workers have organized all meetings in 1994 – 1999, and all of them were hold in Sudetes. This time the external financial support was non existing or minimal, thus the participants had to cover most or all the costs. In consequence, the meetings were organized in rustic hotels, inns or recreation centers which offered low prices. The meetings were always hold outside larger towns with all participants housed in a single hotel, which enabled the intense evening social life (as important during our meetings as the scientific presentations). During the first meetings the number of participants stabilized at the level of 60, which kept for more than 20 years. In recent times it varies between 70 and 90.

The second Session of Petrology Group, hold in Kowary in October 1995, was memorable, because the heating in the hotel got out of order for two days, which *is* a problem in Poland in October. All the participants crowded in small cafeteria in the underground consuming liquid calories which eventually gave the courage to go to cold rooms and sleep some hours.

The important milestone in the history of the Sessions of the Petrology Group was the change of the meeting language from Polish to English, initiated by Jacek Puziewicz in 1999 (one of the thinnest conference books!). After the first “English” meeting in Sobótka-Górka, the psychological barrier was broken (we have been speaking English at the meeting of Polish group hold in Poland…) and the first foreign participants started to come. The first non-Sudetic meeting in 2000 was organized in Osieczany by Professor Marek Michalik (Jagiellonian University, Cracow). Since then the meetings have been organized in various places of Poland, always with some foreign participants attracted by the leading topic or field trip. The first meeting abroad was organized in 2024 by Professor Jarosław Majka (AGH Cracow) in Bobrovec in Slovakian part of Tatra Mts.

During last 30 years, the Sessions of the Petrology Group of the Mineralogical Society of Poland played fundamental role in integrating the Polish researchers focused various aspects of petrology. In Poland, the petrological research is strongly connected with the general geological one, and this tradition continues also in the Petrology Group, albeit topics related to other aspects of mineralogy are also important part of the agenda. Now the Sessions of the Petrology Group are permanent element of organizational framework of Earth Sciences in Poland.

Jacek Puziewicz

MEETINGS OF THE PETROLOGY GROUP OF THE MINERALOGICAL SOCIETY OF POLAND

1994 - 1st Meeting of the Petrology Group of the Mineralogical Society of Poland, 14-16 October 1994, Trzebieszowice, Poland
1995 - 2nd Meeting of the Petrology Group of the Mineralogical Society of Poland, 20-22 October 1995, Kowary, Poland
1996 - 3rd Meeting of the Petrology Group of the Mineralogical Society of Poland, 18-20 October 1996, Lubawka, Poland
1997 - 4th Meeting of the Petrology Group of the Mineralogical Society of Poland, 17-19 October 1997, Pokrzywna, Poland
1998 - 5th Meeting of the Petrology Group of the Mineralogical Society of Poland, 16-18 October 1998, Karpacz, Poland
1999 - 6th Meeting of the Petrology Group of the Mineralogical Society of Poland, 15-17 October 1999, Sobórka Górka, Poland
2000 - 7th Meeting of the Petrology Group of the Mineralogical Society of Poland, 13-15 October 2000, Osieczany, Poland
2001 - 8th Meeting of the Petrology Group of the Mineralogical Society of Poland, 18-21 October 2001, Lądek Zdrój, Poland

2002 - 9th Meeting of the Petrology Group of the Mineralogical Society of Poland, 17-20 October 2002 Szklarska Poręba, Poland
2003 - 10th Meeting of the Petrology Group of the Mineralogical Society of Poland 17-19 October 2003, Głuchołazy, Poland
2004 - 11th Meeting of the Petrology Group of the Mineralogical Society of Poland, 14-17 October 2004, Ustroń, Poland
2005 - 12th Meeting of the Petrology Group of the Mineralogical Society of Poland, 13-16 October 2005, Stary Folwark, Poland
2006 - 13th Meeting of the Petrology Group of the Mineralogical Society of Poland, 19-22 October 2006, Leśna, Poland
2007 - 14th Meeting of the Petrology Group of the Mineralogical Society of Poland, 18-21 October 2007, Bukowina Tatrzańska, Poland
2008 - 15th Meeting of the Petrology Group of the Mineralogical Society of Poland, 9-14 September 2008, Szklarska Poręba, Poland
2009 - 16th Meeting of the Petrology Group of the Mineralogical Society of Poland, 24-27 September 2009, Święty Krzyż, the Holy Cross Mts., Poland
2010 - 17th Meeting of the Petrology Group of the Mineralogical Society of Poland, 14-17 October 2010 Różanka, Sudetes, Poland
2011 - 18th Meeting of the Petrology Group of the Mineralogical Society of Poland, 21-23 October 2011 Bukowina Tatrzańska, Poland
2012 - 19th Meeting of the Petrology Group of the Mineralogical Society of Poland, 19-21 October 2012 Obrzycko, Poland
2013 - 20th Meeting of the Petrology Group of the Mineralogical Society of Poland, 17-20 October 2013, Niemcza, Poland
2014 - 21st Meeting of the Petrology Group of the Mineralogical Society of Poland, 16-19 October 2014, Boguszyn, Poland
2015 - 22nd Meeting of the Petrology Group of the Mineralogical Society of Poland, 8-11 October 2015, Sandomierz, Poland
2016 - 23rd Meeting of the Petrology Group of the Mineralogical Society of Poland, 20-23 October 2016, Stara Morawa, Poland
2017 - 24th Meeting of the Petrology Group of the Mineralogical Society of Poland, 19-22 October 2017, Pawłowice, Poland
2018 - 25th Meeting of the Petrology Group of the Mineralogical Society of Poland, 25-28 October 2018, Brunów, Poland
2019 - 26th Meeting of the Petrology group of the Mineralogical Society of Poland, 24-27 October 2019, Chęciny, Poland
2022 - 27th Meeting of the Petrology Group of the Mineralogical Society of Poland, 20-23 October 2022, Rudy, Poland
2023 - 28th Meeting of the Petrology Group of the Mineralogical Society of Poland, 19-22 October 2023, Bielawa, Poland
2024 - 29th Meeting of the Petrology Group of the Mineralogical Society of Poland, 17-20 October 2024, Bobrovec, Slovakia
2025 - 30th Meeting of the Petrology Group of the Mineralogical Society of Poland, 16-19 October 2025, Lubliniec, Poland

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Carbfix technology – from research project to commercial deployment

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Carbfix technology has been demonstrated as a safe and cost-effective approach to permanently store carbon dioxide (CO_2). This methodology relies on CO_2 solubility and mineral trapping within basaltic formations mimicking the natural process of chemical weathering of silicate minerals. It involves capturing CO_2 from the air or from emission point sources, dissolving it in water and pumping the CO_2-charged water into storage reservoirs at depths greater than 250 m. Once CO_2 is dissolved, it is no longer buoyant and thus will not migrate back to the surface (Sigfusson et al., 2015). The enhanced dissolution of the host rock in the storage reservoir as a result of CO_2-charged water-basalt interaction liberates divalent cations from the host rock which become available for precipitation of carbonate minerals such as calcite, magnesite, and siderite. Through this process, CO_2 is permanently and securely stored.

The Carbfix project began in 2006 as a research consortium initiated by former president of Iceland, Ólafur Grímsson. It brought together scientists from the University of Iceland, Columbia University, CNRS in Toulouse along with the Icelandic power companies (Reykjavík Energy, Landsvirkjun Power and HS-Orka) and other local stakeholders. The 2012 pilot study showed that 95 % of the CO_2 that was initially injected mineralized mainly as $CaCO_3$ in the reservoir at 20-50 °C in less than two years (Matter et al., 2016). Followed by its successful outcome, the Carbfix methodology has been the foundation for a number of CO_2 mineralization projects such as Carbfix2, GECO and CO2Seastone. Since 2012, Carbfix has injected over 100,000 tonnes of CO_2 at several sites, including one at the Hellisheiði geothermal power plant and two in collaboration with DAC developer Climeworks. The current focus is on further scaling up the technology and assessing its engineering and geological limits for broader deployment. In addition, challenges related to regulatory frameworks and social acceptance are also addressed as they play crucial role in the successful deployment of large CCS projects.

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Comprehensive resource characterization – key for a sustainable supply of raw materials for Europe

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[2]*Erzlabor Advanced Solutions GmbH, Freiberg, Germany*

Securing a resilient supply of minerals and metals is of fundamental importance for future development. This is particularly relevant to the highly industrialized economies of the European Union as they are currently highly dependent on imports, especially of so-called critical or strategic raw materials (CRMs for short). Since global demand for many CRMs is rising rapidly and there are currently limited opportunities for recycling, the exploitation of geogenic resources will be necessary to meet the demand in the foreseeable future. At the same time, there is a widespread consensus that future exploration, exploitation and beneficiation of geogenic raw materials will have to meet stringent sustainability criteria. They must be economically viable, environmentally benign, and socially acceptable. This mixture of existential challenges creates many exciting research opportunities, especially for (geo-)scientists that readily appreciate the complexity of natural materials. Geoscientists are uniquely positioned to contribute towards the generation of new fundamental knowledge about the origin and nature of ore deposit types, including those particularly enriched in CRMs. Geoscientists are also needed to translate this new knowledge into vectors for exploration of new resources. Finally, comprehensive geoscientific knowledge of nature and composition of orebodies will be necessary to develop so-called geometallurgical models. Such geometallurgical models will inform the environmentally benign, yet comprehensive utilization of ore deposits.

All of the named challenges require, first and foremost, a comprehensive and quantitative knowledge of raw materials properties and compositions across multiple scales. This knowledge includes regional geological and geophysical data at the regional to continental scale. When paired with an understanding of ore-forming processes, this data can be used to construct the mineral systems models needed for efficient exploration and discovery. Additionally, geoscientists have a highly developed understanding of how minor metals are quantitatively incorporated into the crystal structure of common ore-forming minerals at the atomic level. This information is necessary for deportment analyses and to facilitate the efficient metallurgical recovery of by-product CRMs, such as indium, germanium or gallium. This presentation will introduce research currently being conducted in Freiberg to facilitate time- and cost-efficient ore characterization across multiple scales, and the translation of quantitative orebody knowledge into predictive geometallurgical models.

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Mining the Urban Mine: Biohydrometallurgy and E-Waste in the Circular Economy

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The concept of the “urban mine” highlights the vast quantities of valuable metals contained in end-of-life products, particularly electronic waste (e-waste). Harnessing these secondary resources is essential for a circular economy, reducing reliance on primary mining and minimizing environmental impacts. Among the technologies available, biohydrometallurgy — the use of microorganisms to extract and recover metals—offers an environmentally friendly, low-energy, and adaptable pathway for metal recovery from both ores and complex waste streams.

This talk will explore how biohydrometallurgy can be effectively applied to urban mining, with a particular focus on e-waste recycling.

Drawing from recent research and case studies, the presentation will address:

- How mineralogical insights guide biohydrometallurgical treatment of heterogeneous e-waste fractions;
- The role of microorganisms in selectively leaching high-value metals such as copper, gold, and rare earth elements;
- Process integration for closing material loops, from microbial leaching to metal recovery and reintegration into manufacturing cycles.

By bridging mineralogy, microbiology, and process engineering, biohydrometallurgy offers a scalable and sustainable approach to extracting critical metals from the urban mine. This interdisciplinary pathway supports the circular economy by reducing the environmental footprint of metal production, extending resource lifecycles, and transforming waste into a valuable resource base for future technologies.

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Decarbonisation potential of ultramafic rocks – challenges and opportunities

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[2]British Geological Survey, Edinburgh, United Kingdom

Clean energy technologies – from wind turbines and solar panels, to electric vehicles and battery storage – require a wide range of minerals and metals (IEA, 2021). Ultramafic rocks and their alteration products, including fresh and partially serpentinised peridotites, serpentinites and nickel laterites exhibit mineralogical and geochemical properties that are key to these decarbonisation technologies. As the primary source of metals such as nickel (Ni), platinum group elements (PGE), chromium (Cr) or cobalt (Co) globally, these rocks have been mined and processed on a large scale for nearly two centuries now (Mudd, 2010). The metals of interest occur as sulfide and/or oxide assemblages and are typically associated with a range of gangue minerals, including ferromagnesian silicates (olivine, pyroxene) and their alteration products. Depending on the geochemical regime, the alteration can result in the generation of serpentine, talc, chlorite, and smectite minerals as well as a range of oxide/oxyhydroxide phases such as asbolane-lithiophorite and goethite typically found in lateritic settings. A common aspect of the gangue minerals is the relatively high content of divalent cations (Mg^{2+}, Fe^{2+}, Mn^{2+}, Ca^{2+}) that can readily react with CO_2 to form secondary carbonate minerals. Indeed, carbonate alteration of ultramafic rocks is a natural phenomenon and in the last three decades, the learnings from natural analogue studies have been exploited to develop removal technologies for anthropogenically produced CO_2 (mineral carbonation). Today, the CO_2 has been successfully mineralised at laboratory scale and in some instances at pilot, prototype or pre-commercial setups, in either ex-situ scenario utilising ultramafic mine waste rock (the gangue minerals) and tailings or raw quarried materials, etc (e.g., MCi Carbon) or, via the injection of CO_2-bearing fluid at depth into compositionally suitable reservoirs for in-situ reactions (44.01, CarbFix).

In recent years, ultramafic rocks have sparked a new wave of attention from academia, industry and policy makers; owing to their role in the generation of natural hydrogen, a primary low-carbon energy source. Natural hydrogen can be produced by a variety of fluid-rock interaction processes, but serpentinisation of ultramafic rocks, and associated redox reactions between ferrous iron and H_2O, is considered the most prominent. Research and exploration of natural hydrogen is expanding globally, including aspects of the whole value chain from generation to accumulation, extraction, utilisation, environmental impact etc. One, seemingly feasible area of interest is the synergy between the CO_2 mineralisation and simultaneous generation of hydrogen using ultramafic substrate under in-situ or ex-situ conditions (REFS). Although concomitant reactions have been proven in the laboratory scenario, large-scale industrial potential of this proposition is yet to be demonstrated.

Primary mining will remain the main source of minerals and metals for clean energy technologies for some time, as e-waste recycling cannot currently satisfy the rapidly growing demand for relevant materials. Mining offers significant socio-economic benefits, but the extraction and processing of primary ores can also adversely affect the environment, for example through the release of CO_2 and potentially hazardous elements (PHE). In the context of ultramafic systems, additional environmental challenges are related to the presence of carcinogenic pollutants such as hexavalent chromium and asbestiform minerals. The concentration of those, albeit naturally occurring components of the ultramafic systems, can be significantly elevated through mining and ore processing. This can give rise to contamination of air and water in and around mining operations and consequently pose risks to human health.

These negative environmental impacts can be mitigated if the natural resources are well understood and managed, and there is a greater incentive from governing bodies to see beyond the financial benefits of mining globally. To that extent, full system appraisal of all rock components and their potential technological application is key, alongside the development of less-energy intensive and waste producing ore processing, new technologies allowing for reinvention of waste materials and market opportunities for their use. Ultramafic systems can act as an example of sustainable resource management through integrated recovery of Ni, Co, scandium (Sc), Cr or the PGEs; the use of Mg, Fe, Ca for mineral carbonation, and the generation of high purity silica. The toxicity of chrysotile and hexavalent chromium can potentially be managed through the use of mineral carbonation technologies (Lacinska et al., 2016; Lacinska et al., 2024).

Minerals and metals are fundamental to clean energy technologies, which in turn are vital to tackling climate change. The recovery of raw materials must follow strict environmental protocols and be subject to continued technological and sustainability innovation. A full system understanding and utilisation of ultramafic rocks presents an unmissable opportunity for better management of natural resources and more responsible mining operations.

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Can we do it? Thoughts on Europe's future demand for critical mineral raw materials and examples from Austria

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A key objective of the European Critical Raw Materials Act (CRMA) is to reduce the European Union's dependence on third countries for the supply of critical and strategic raw materials. The aim is to cover at least 10 % of the EU's own needs through mining production in EU member states by 2030. Studies by the European Union's Joint Research Centre (Carrara et al., 2023) and published databases such as World Mining Data (Reichl & Schatz, 2025) were used to determine future demand for critical raw materials and the possibility of self-sufficiency. These were used to derive scenarios for the demand for critical raw materials up to 2030. A sharp increase in demand for battery raw materials such as cobalt, lithium, and graphite is expected in strategic sectors and technologies. Based on the Joint Research Centre's data on demand in key technologies for 2030, estimates have been made for the development of total demand for raw materials. Due to the still low share of key technologies compared to conventional demand sectors, total demand for copper and platinum will develop moderately if the share of these technologies does not increase significantly. For the battery raw materials cobalt and lithium, the share is already well over 20 % and will dominate future total demand. Research on active European production sites and projects for cobalt, copper, and lithium provides an estimate of European mining production through 2030. A comparison with published data on European resources and reserves makes it possible to estimate whether the 10 % target set in the Critical Raw Material Act for the materials examined is realistically achievable.

In order to meet the objectives of the Act, EU member states must urgently develop effective strategies to rapidly increase domestic production of mineral raw materials. Although resources are available for many critical and strategic raw materials, the economically recoverable reserves are often unknown and there is little social acceptance and political support for domestic mining projects. Covering 10 % of domestic demand with production from EU member states in 2030 therefore does not appear realistic for many critical raw materials at present.

Austria serves as an example of critical raw material deposits in Europe. It is home to very significant magnesite and graphite deposits and is Europe's largest producer of tungsten from the Felbertal scheelite deposit. In addition, carbonate-hosted Alpine-type Pb-Zn deposits have potential for extraction of valuable trace metals from sphalerite. The world-class Bleiberg mine, which closed in 1993, was a significant producer of germanium and cadmium in the 1980s. Recent studies have revealed further potential for critical metals in the Eastern and Southern Alps (Melcher et al., 2023). Active exploration in Austria focusses on lithium in pegmatites of Permian age in the high-pressure Koralpe-Wölz nappe system in central and southern Austria. If some of the projects were to enter production in the foreseeable future, this could make a decisive contribution to achieving the CRMA targets.

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Unrevealing the potential of nature - bio-based technologies for metal recovery from primary and secondary resources

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The development of new technologies has led to an increase in the demand for essential metals in recent years. At the same time, the extraction of these metals is not always environmentally friendly. Toxic metals can pollute waters and enter the environment both during extraction and processing or through disposal. In addition, recycling rates are still low and economic recycling technologies are still not existing. Therefore, new environmentally friendly technologies are needed that prevent their entry into the environment or efficiently contribute to the recovery and recycling of the elements. Biotechnology can contribute to this.

Such technologies exploit the natural ability of organisms, biocomponents and biomolecules to interact with metals. In addition, modern methods of molecular biology and synthetic biology enable the development of tailor-made biomolecules that interact with metal ions or surfaces. Metabolic pathways can be designed to enable cost-effective production of bioreagents, and organic waste can be used as substrates to create additional added value. The biomolecules can be integrated into metal recovery technologies, e.g., as extraction agents, metal filters or reagents in flotation processes. This presentation will introduce some of these technologies and their potential for environmentally friendly recovery of metals from various resources and for the treatment of metal-containing wastewater.

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Current state of research on the mineralogy of Baltic nodules

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In recent years, substantial progress has been made in understanding the nature of ferromanganese (Fe–Mn) nodules occurring on the seafloor of the southern Baltic Sea (Szamałek et al., 2018; Zglinicki et al., *in press*). Since 2018, intensive research has been conducted within the Polish Exclusive Economic Zone (Polish EEZ). Samples collected at the junction of the Slupsk Furrow and the Gdansk Basin, as well as on the sill between the Slupsk Furrow and the Bornholm Basin (locations P1 and P2, respectively), revealed that the nodules are composed primarily of authigenic, XRD-amorphous iron and manganese phases, as well as detrital minerals such as quartz, feldspars, Fe-chlorite, illite, and kaolinite. The dominant Fe–Mn phases identified include goethite, birnessite, and vernadite (7Å and 10Å varieties), confirmed by XRD, SEM-EDS, and EPMA analyses. The nanocrystalline nature of these phases (3-50 nm) supports their authigenic origin in a dynamic, shallow-marine environment.

Nodules from site P2 are richer in manganese, with Mn/Fe ratios ranging from 0.50 to 1.25, while samples from site P1 show higher iron content and lower Mn/Fe ratios (0.12 - 0.43). These differences reflect variations in redox conditions and the alternating influence of diagenetic and hydrogenetic processes during nodule growth. A significant finding is the pronounced lithium enrichment in nodules from site P1 (up to 444 ppm), potentially resulting from the migration of deep, low-temperature hydrothermal fluids or formation waters from hydrocarbon reservoirs along fault zones. Lithium is primarily associated with manganese phases, consistent with both our observations and published data (Jiang et al., 2007; Hein & Koschinsky, 2014).

New data obtained through Mössbauer spectroscopy (^{57}Fe) enabled a detailed assessment of iron speciation in the nodules (Fig. 1). The spectra indicate that Fe^{3+} is the dominant component (81-94 %), mainly occurring in ultra-fine nano-phases (possibly ferrihydrite) with superparamagnetic behavior. Two Fe^{3+} components were distinguished: (a) in silicate structures (e.g., illite, chlorite) and minor oxides, and (b) superparamagnetic nano-(oxides/hydroxides) of Fe^{3+} (<10 nm). Fe^{2+} (6-20 %) was attributed to clay minerals. In only one sample (P2-05), larger hematite crystals (Fe_2O_3, 22 %) were identified, suggesting local conditions favoring crystallization and oxidation. Mössbauer parameters (IS ~0.35 mm/s; QS ~0.5–0.9 mm/s) are characteristic of ferrihydrite, confirming its dominant role in the southern Baltic nodules. The internal structure of the nodules exhibits well-defined lamination with alternating Fe- and Mn-rich zones, reflecting the alternating nature of diagenetic and hydrogenetic processes. The presence of phosphorus in outer layers, particularly at site P1, suggests the influence of anthropogenic pollution (Glasby et al., 1996).

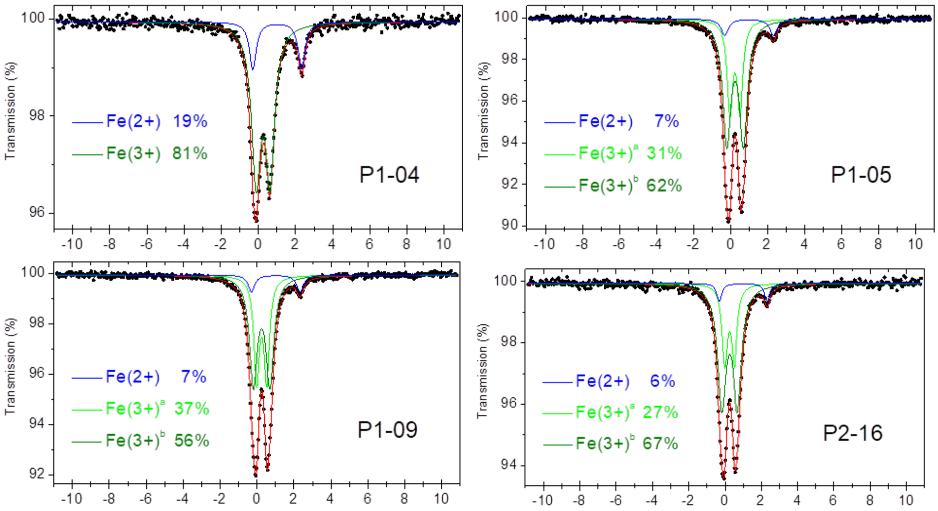

Figure 1. Mössbauer spectra of samples P1-04, P1-05, P1-09, and P2-16 reveal dominant Fe^{3+} components (58–81 %) associated with silicates and ultra-small iron oxide nanocrystals, alongside minor Fe^{2+} signals (6–19 %) in illite/chlorite. The data indicate progressive oxidation and superparamagnetic behavior of Fe-bearing phases.

Although Baltic nodules show relatively low concentrations of critical metals (Ni+Co+Cu; average for P1: 173.5 ppm; P2: 351.2 ppm), they may hold economic potential due to their lithium content. Given the growing demand for lithium in the context of energy transition and electromobility, further studies on the genesis and exploitation potential of such deposits in the Baltic region are fully justified.

Acknowledgements: The authors would like to express their sincere gratitude to Mr. Artur Błahowski from the AGH University of Science and Technology for conducting the Mössbauer spectroscopy analyses of iron presented in this study. This abstract serves as a prelude to a forthcoming joint publication on iron nodules.

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30th Meeting of the Petrology Group of the Mineralogical Society of Poland

Abstracts

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The ASTRA beamline at the SOLARIS Synchrotron: Advanced X-ray Absorption Spectroscopy in Environmental Science and Mineralogy

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The presentation will provide an overview of the ASTRA beamline at the SOLARIS synchrotron (Krakow, Poland) and demonstrate its diverse research applications through selected experimental results. ASTRA (**A**bsorption **S**pectroscopy beamline for **T**ender energy **R**ange and **A**bove) is a bending magnet beamline for X-ray Absorption Spectroscopy (XAS). It operates within a photon energy range between 1 and 15 keV with particular optimization for the 1.8 - 12 keV range, encompassing tender and hard X-ray energies, as an ideal tool for studying light elements and their chemical environments.

The beamline features several advanced capabilities. An integrated X-ray camera ensures accurate sample positioning, improving data quality and reproducibility. Specially designed sample cells allow liquid-phase measurements or experiments under dynamic conditions in the tender energy range. Additionally, a Raman microscope with dual laser sources (532 nm and 782 nm) enables combined XAS-Raman measurements. This integrated approach creates an attractive platform for comprehensive materials characterization.

The versatility of ASTRA is demonstrated through diverse research applications across multiple scientific disciplines. Examples from the field of earth sciences and mineralogy focus on speciation of metallic elements during mineral carbonation of ultramafic rocks and characterization of metallurgical slags. Environmental science applications include analysis of urban air pollution and investigation of uranium and thorium adsorption mechanisms on porous sorbents in aqueous solutions. Archaeological applications demonstrate provenance determination of ceramics from the Museum of the Royal Wawel Castle using combined tender and hard XAS.

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The kinetics of organic maturation in the Torres del Paine contact aureole and lessons for RSCM thermometry

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Raman Spectroscopy of Carbonaceous Matter (RSCM) thermometry is a widely utilized method for estimating peak metamorphic temperatures based on the crystallinity and composition of carbonaceous matter (CM). However, a review of studies applying RSCM thermometry to contact metamorphic aureoles around different sizes of intrusions show that in this setting maximum temperatures are often underestimated and underscores the critical role of the heating pulse duration. Hence, RSCM thermometry needs to take into account the thermal history, as was similarly shown for sedimentary basins and Anchizonal metamorphism (Sweeney & Burnham, 1990).

In this study, we apply RSCM thermometry to samples from the contact aureole of the Torres del Paine Intrusive Complex (TPIC) and compare these temperature estimates with constraints from phase petrology and thermal modeling. While Raman spectra reveal a systematic increase in CM crystallinity toward the intrusion, peak temperatures estimated with RSCM are consistently lower than the modeled temperatures in the outer and middle part of the aureole. By contrast, both approaches give consistent temperatures close to the contact. Our 2-D thermal models suggest that the heating of the TPIC contact aureole occurred over 2,000–10,000 years, while cooling occurred over some tens of thousands of years, depending on proximity to the intrusion, as well as the relative position of the sample with respect to the intrusion (roof, side, or below).

To address this discrepancy, we extend a first-order kinetic model originally developed for vitrinite reflectance by Sweeney & Burnham (1990) to describe CM crystallinity evolution. The original model includes 20 parallel reactions but does not account for the higher activation energy reactions that dominate maturation at higher temperatures, responsible for transforming amorphous CM into graphite. We extended this model to include 14 new reactions with higher activation energies to account for these higher temperature reactions. Using this approach, we find a better agreement between RSCM thermometry and maximum temperatures obtained in the Torres del Paine contact aureole. Our results highlight the importance of kinetic effects for RSCM thermometry. This model expands the potential for application of RSCM thermometry to systems that experienced short-lived thermal pulses when approximate constraints on the temperature-time history are known.

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Exsolution records Ultra-High Temperature (UHT) metamorphism in the Bunger Hills, East Antarctica

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Extreme Ultra-High Temperature (UHT) metamorphism (>900 °C) provides clue to the thermal tolerance during intense heating of the Earth's crust. Minerals in high to UHT-grade metamorphic rocks reveal thermal regimes and tectonic settings, enhancing our understanding of the subsurface crustal processes, orogenesis, crustal reworking, lithospheric evolution and continental correlation. Within optimal bulk compositions, UHT conditions also stabilize rare high-temperature aluminous phases of economic importance like corundum (ruby) and spinel. This study investigates the mineral evolution and metamorphism of the Bunger Hills (BH) in East Antarctica using petrography, mineral chemistry, geothermobarometry, and geochronology. Four samples were analyzed: two diorites from southern region of BH (Algae Lake and Polanski Lake) and two charnockitic biotite gneisses from Polanski Lake and Garnet Hill located in the south-central part of BH.

Zircon U-Pb dating of the gneisses shows age range between ~1.7-1.5 Ga (cores) and ~1.3-1.1 Ga (rims). Their reconstructed (Raase, 1998) exsolved feldspars (Fuhrman and Lindsley, 1988), i.e., '*Parent Feldspar* (*PF*)', '*Parent Antiperthite'* (*PA*; 95 % abundance), '*Parent Perthite'* (*PP*; 5 % abundance) records temperatures exceeding 1000 °C, ~980 °C, and ~800 °C, respectively. The ilmenite-magnetite pair in these gneisses stabilized between ~600-500 °C. In diorites, the two-pyroxene thermometry also reflects temperatures exceeding 1000 °C.

The analysed samples from the BH regions have undergone a UHT metamorphism, recorded in the pyroxenes of the diorites and in the reconstructed immiscible parent feldspars *(PF* and *PA)* of the gneisses. The *PF* unmixes into *PA* and *PP*. Nevertheless, the majority of the antiperthite and perthite in these gneisses equilibrated between ~980-500 °C and ~800-500 °C, respectively. The ~1.3-1.1 Ga age of these gneisses possibly represents the age of UHT metamorphism during Rodinia assembly (Liu et al., 2017; Tucker et al., 2017), while the ~1.7-1.5 Ga age is likely related to a Paleo-Mesoproterozoic tectonothermal event.

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Prehistoric Ceramic Production in Tsakhiurtyn Hundi, Mongolia: Evidence from Petrographic Analysis

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On the edge of the Gobi Altai in Mongolia, in the Arts Bogdyn Nuruu region, lies the vast prehistoric site of Tsakhiurtyn Hundi, which contains the remains of settlements belonging to both Pleistocene hunter-gatherers and early Holocene communities. Thin-walled (5–8 mm) pottery made using coils or a mixed technique i.e. coils and slabs, with impressed ornamentation was found at this site. Radiocarbon analysis indicates that it is the oldest pottery discovered in Mongolia to date, with a chronological age of 11,250–10,500 years BP.

Complementary analytical techniques, including polarising microscopy, scanning electron microscopy (SEM), thermal analysis (DSC-TG) and powder X-ray diffraction (PXRD) were applied to ceramic sherds from two vessels (three samples from vessel FV139B and three from vessel 139C, taken from the neck as well as the middle and lower parts of the belly). The ceramics display a range of colours from light grey or beige to reddish and dark grey, occurring on the same vessel. In contrast, the fracture surfaces consistently reveal a uniform dark grey colour. Petrographic analysis shows that all samples share a similar composition of non-plastic inclusions, dominated by feldspar and quartz, with lithoclasts (granitoids and possibly quartzite) also present. Accessory components include ilmenite and mica.

Instrumental analyses of the clay matrix revealed no differences between the various parts of the vessel. The matrix consists of a Si-Al-rich mass containing occasional relics of book-like structures (kaolinite or other kaolin-group minerals) and accessory muscovite flakes. No evidence of vitrification was observed. This indicates the of low-iron, non-calcareous clay ($CaO < 6$ %) rich in kaolinite for ceramic production. The mineral assemblage—comprising quartz, feldspar, and muscovite, with sparse kaolinite, identified by PXRD and confirmed by SEM observations, suggests firing temperatures of 550–650 °C. This range corresponds to the advanced breakdown of the kaolinite crystalline structure and the formation of metakaolinite, but remains below 750 °C, the threshold for vitrification. The presence of calcite and gypsum is interpreted as a result of post-burial alteration.

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New data on the isotope composition of Neogene andesites from the Pieniny Klippen Belt, Western Carpathians

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Neogene andesitic rocks in the Pieniny area form small-volume volcanic bodies that include hypabyssal dykes and sills. They occur along the contact of the Pieniny Klippen Belt and the Magura unit of Outer Carpathians (Birkenmajer, 2003). The Pieniny Klippen Belt is a narrow, tectonically deformed sedimentary sequence that separates the Outer and Inner Carpathians and comprises mainly limestones and marls (Middle Jurassic to Miocene). The Magura unit (Outer Carpathians) mainly consists of Lower Createaceous to Oligocene flysch sediments. The age of magmatism in the area ranges from ca. 12.8 to 10.8 Ma (e.g., Anczkiewicz & Anczkiewicz, 2016). To better understand the formation and origin of the Pieniny andesites, whole rock major and trace elements, as well as Sr, Nd, and Pb isotope compositions were obtained.

The $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotope compositions range from ~0.5120 to 0.5124 and from ~0.7052 to 0.7064, respectively (Fig. 1). The Pb-isotope compositions range from ~18.56 to 18.84 for $^{206}Pb/^{204}Pb$, from ~15.61 to 15.70 for $^{207}Pb/^{204}Pb$, and from 38.65 to ~39.15 for $^{208}Pb/^{204}Pb$.

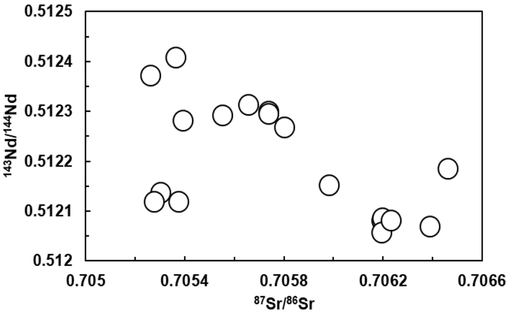

Figure 1. The $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ isotope compositions of the investigated rocks.

The combined Sr-Nd-Pb isotope compositions of the investigated rocks are showing slight enrichment indicating the influence of continental crust. The Pieniny andesites likely represent mantle-derived magmas that were variably contaminated by continental material during their ascent and emplacement in the upper crust.

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The increased value of vanadium on the Permian-Triassic boundary in the Holy Cross Mountains - truth or myth?

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Increased vanadium contents (up to 9000 ppm) in sediments from the Permian-Triassic boundary were found during copper ore exploration works carried out in the 1970s and 1980s in the Permian-Mesozoic margin of the Holy Cross Mountains (Kowalczewski et al., 1974; Kowalczewski et al., 1983; Lenartowicz 1980). The main goal of our research was to verify the presence and provide preliminary identification of zones enriched in this element. We also planned to identify the nature of vanadium mineralization and provide a detailed mineralogical and petrographic characterization of the host rocks. For this purpose, we first conducted the analyses with the use of Olympus Delta p-XRF spectrometer, then we selected samples for analysis, and performed detailed SEM studies as well as chemical composition of the whole rocks.

The results of p-XRF analyses of vanadium content in rocks from the Siodła IG-1 and Jaworze IG-1 boreholes were mostly below 100 ppm. Only a few analyses showed vanadium contents above 100 ppm. The average vanadium content in these drill cores is only about 41 ppm and 34 ppm, respectively. SEM and chemical analysis results also did not indicate any elevated vanadium contents.

Despite the use of various research methods, no elevated vanadium content was detected in the analyzed drill core intervals. The lack of confirmation of the previously described elevated vanadium content in the rocks of the Holy Cross Mountains margin is crucial information for the ore deposit identification of various orogens in Poland. We are unable to reconstruct the research process conducted last century and therefore cannot determine the source of the elevated results. However, this information is very valuable and sheds new light on previous research – a new look at the archival results is necessary.

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The geochemical survey of the King George Island volcanic sequence, South Shetland Islands, Antarctica

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King George Island is located in the South Shetland Archipelago, northwest of the Antarctic Peninsula. It is built mainly of basaltic and andesitic rocks with minor dykes and volcanic plugs (Birkenmajer, 2003). Occasionally some sedimentary intercalations as well as glacial and interglacial sediments occur (Birkenmajer, 2001; Troedson & Smellie, 2002).

The large set of samples were investigated and analyzed with use of Olympus Delta Premium portable XRF in the vicinity of the Western Shore of Admiralty Bay, Potter Peninsula and Barton Peninsula (King George Island) in cooperation with Argentinian Geological and Mining Survey (SEGEMAR). Preliminary results show that the contents of the analyzed elements well correspond to the typical levels of such elements for extrusive rocks such as basalts and andesites. Only a few analyses revealed concentrations of the elements that are significantly deviated from the average values. For example, Cu contents vary from 9 to 2754 ppm with an average content ca. 127 ppm, with only one data point exceeding 500 ppm. The Pb and Zn contents vary from 2.6 to 82 ppm (average ca. 11 ppm) and from 12.2 to 622 ppm (average ca. 55 ppm), respectively.

The obtained chemical data will be part of a larger project involving geological mapping of rock formations beneath the ice using magnetometric surveys with a flying drone. The combination of geophysical data, isotope dating, and geochemistry will allow for the development of preliminary geological maps of inaccessible areas.

Acknowledgements: The study was supported by the grant of the National Fund for Environmental Protection and Water Management (project no 22.9901.2501.00.1). The fieldwork was carried out during the 49th Polish Antarctic Expedition to the Arctowski Station.

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Fluid inclusions in garnets and clinopyroxenes of Bystrzyca Górna garnet clinopyroxenite (Góry Sowie, Poland)

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Subduction is the process that makes crust-mantle interaction and elements transfer to the mantle possible. During subduction, volatiles (e.g., H_2O, CO_2, Cl, F, S and N_2) and other incompatible elements concentrated in the crust are released in melts and fluids that then interact with the overlying mantle. Targeting melts and fluids responsible for the elements transfer is a direct way to investigate the interaction between the crust and the mantle. Here, we report the occurrence of volatiles-bearing fluid inclusions in clinopyroxene and garnet of a garnet clinopyroxenite lens in a mantle body in Bystrzyca Górna (Góry Sowie, SW Poland).

In this area, migmatitic gneisses contain subordinate granulites and bodies of garnet peridotites and metabasites (Kryza & Pin, 2002). The garnet clinopyroxenite lens contains garnet and clinopyroxene with minor amphibole, and locally orthopyroxene porphyroblasts in a fine-grained matrix. Clinopyroxenes and garnets contain micrometric fluid inclusions.

Inclusions in clinopyroxene are primary – isolated or in small clusters – and thus trapped while the host was growing in the presence of a fluid phase. Their main phase assemblage, determined by micro-Raman spectroscopy, comprises dolomite, calcite, cristobalite, N_2, CH_4, and kokchetavite. Garnets contain primary and pseudosecondary (i.e., distributed along fractures occurring during garnet growth) fluid inclusions. The assemblage is constant in all inclusions and consists of CO_2, dolomite, pyrophyllite, N_2, CH_4, and rare graphite. The residual fluid is CO_2-rich (~88 mol %) with minor N_2 (~9 mol %) and CH_4 (~3 mol %).

The assemblage in the inclusions trapped in clinopyroxene is dominated by anhydrous phases rich in carbon and silica with a minor concentration of gaseous species. In contrast, the presence of carbonates, OH-bearing phases, and N_2 in the assemblage of the inclusions in garnets suggests the entrapment of a COHN fluid.

Further studies will better constrain the fluids' nature and quantify the budget of carbon in the different C-bearing phases (solid and gaseous) and N_2. Fluids in subduction zones can interact with the mantle, metasomatizing it, and our data will help to better constrain their importance for volatiles mobilization and transfer to the mantle.

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The recent data on the Bibiela PIG-1 borehole as well as seismic 2D profile Sosnowiec-Starcza: new evidences on the tectonic evolution of the Kraków-Lubliniec Fault Zone and its metallogenic potential

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Systematic geological investigations carried out over the past three decades in Upper Silesia and western Lesser Poland have refined structural models of this region, confirming the existence of two major tectonic units: the Upper Silesian Block and the Małopolska Block, separated by the Kraków–Lubliniec fault zone. Both of these blocks differ in the architecture of their Precambrian basement as well as in the palaeogeographic and palaeotectonic evolution of their Paleozoic sedimentary successions (e.g., Buła et al., 2015). New insights were provided by the Bibiela PIG-1 (2017) borehole (Habryn et al., (eds.) 2023), which intersected Ordovican rocks, drilled through Ediacaran sediments and revealed evidence of weak hydrothermal alterations associated with Variscan magmatism, as well as poor polymetallic mineralization.

Between 2019 and 2023, reinterpretation of the deep geological structure of the northern part of the Upper Silesian Block was undertaken using data from the new 2D seismic profile (Sosnowiec–Starcza), together with new gravimetric, magnetic and magnetotelluric measurements. These results have shown that a structural model of the area is more complex than previously assumed. Magnetotelluric investigations revealed two zones of particular interest from the perspective of ore deposit geology. Moreover, regions of potential economic significance were identified.

These findings underscore the necessity of developing a revised structural model for the eastern margin of the Upper Silesian Block and open new perspectives for mineral exploration strategies.

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MINERALOGICAL SOCIETY OF POLAND

Remnants of HP-LT metamorphism found in mica schists of the Orlica Śnieżnik-Dome (NE Bohemian Massif, SW Poland)

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The Orlica Śnieżnik-Dome (OSD), located at the NE margin of the Bohemian Massif (Sudetes), is a mantled gneiss dome composed of orthogneisses with UHP-HT eclogites and granulites lenses, surrounded by amphibolite-facies metasedimentary rocks (e.g., Chopin et al., 2012b; Jastrzębski 2009). Previous studies have suggested a HP-LT metamorphic event (20-21 kbar, 550 °C) predating medium-pressure metamorphism, motivating our investigation of its extent and record in the OSD metapelites (Faryad & Kachlik, 2013).

We studied four mica schist samples from the Stronie Formation: KV2A and PG2 from the western OSD, and KB1 and NW1 from the eastern OSD.

Investigated mica schists are characterized by a poorly preserved mineral assemblage typical for HP metamorphism: Grt + Phg + Chl + Qz + Rt ± Prg ± Cld ± [Jd, preserved as pseudomorphs of Ab + Qz]. The Phengite in all samples contains 3.34–3.38 Si apfu, corresponding to pressures of 22.5–23.8 kbar at ~550 °C according to Si-in-phengite barometry. Quartz-in-garnet elastobarometry indicates that pressures likely exceeded 10 kbar during garnet growth. This HP-LT mineral assemblage is commonly replaced by amphibolite facies mineral assemblage comprising Ms + Bt + Kfs + Pl ± St+ Qz + Ilm.

Results suggest that the Stronie Formation recorded a HP–LT metamorphic episode predating the amphibolite-facies overprint, and that this stage can be identified throughout the OSD, though its mineral record varies by locality.

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Syn- and anti-taxial quartz veins

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Introduction

Mafic dykes are widespread in ancient crustal domains, especially from the Precambrian, where dyke swarms are common, such as in southern Africa (de Kock et al., 2019). However, very little is understood about the mechanisms that form them, and the subsequent features that develop within them.

Veins

In this study, we present a feature observed in a mafic dyke from the south-easternmost margin of the Archean Kaapvaal Craton in southern Africa. This feature is most likely a vein, and is aligned perpendicular to the mafic dyke it has formed in. The host mafic dyke contains a mineral assemblage typical of such rocks, being composed mostly of plagioclase feldspar and pyroxene, which has been slightly partially altered at greenschist facies into patches of sericite, amphibole, chlorite, quartz and epidote. Whereas the vein shows a sharp contact with the mafic dyke, its centre contains coarse-grained quartz and feldspar, and has a sharp contact with a halo of fine-grained minerals, including chlorite, amphibole, and epidote.

Petrogenesis

This observed feature is similar to such features seen in syn- and anti-taxial quartz veins, with the presence of a fine-grained mafic halo around a coarse-grained felsic core. It would appear to indicate the presence of anti-taxial quartz vein, with inward crystal growth. However, it remains to be determined whether this feature is related to emplacement of the mafic dyke, where quick cooling can create brittle cracks into which interstitial fluid can flow, or whether later extension in the geological record and associated fluid flow lead to the genesis of these type of veins.

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Investigation of the Coesite-Quartz phase boundary at LT-HP conditions: preliminary results from an experimental approach

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Coesite was first synthetized in the early 1950s (Coes, 1953), then discovered in nature in 1960 (Chao et al., 1960), and its first application as mineral index for pressure-temperature (P-T) metamorphic condition and tectonic setting occurred in 1984 (e.g., Chopin, 1984). Over the following decades several studies investigated the P-T position of the coesite-quartz phase boundary, focusing mostly at high-temperature and high-pressure (HP) conditions. There is general agreement amongst various studies, but differences in the high-temperature results are amplified in extrapolations to lower temperatures that are relevant to several natural coesite occurrences. For example, at 550 °C the coesite-quartz phase boundary ranges between 28 to 23 kbar. The increase in discoveries of coesite inclusions in host minerals from different terranes highlights the importance of precisely locating this phase boundary for applications to relatively low-temperature (LT) rocks. This study aims to precisely locate the coesite-quartz phase boundary at LT (550-650 °C) and HP (28-30 kbar) conditions applicable to several natural coesite occurrences crystallized in subduction zone settings. Our experiments were conducted in end-loaded piston-cylinder apparatuses using 12.7-mm diameter experimental assemblies composed of MgO filler pieces, graphite heater tubes, borosilicate glass insulators, and NaCl. Silver capsules, with volume varying from 20 to 15 mm^3, were filled with amorphous SiO_2 powder and deionized H_2O (≈2:1 ratio). The experiments presented here were run along the 550 °C and 650 °C isotherms at 28, 29, and 30 kbar for 48-72 hours. In summary, at 650 °C we obtained 100 % coesite at 30 kbar, 100 % quartz at 28 kbar and both large crystals of coesite (>200 μm) and small crystals of quartz (<100 μm) at 29 kbar. At 550 °C we obtained 100 % of small coesite crystals (<70 μm) at 30 kbar, 100 % quartz crystals at 28 kbar, and both coesite and quartz at 29 kbar. These preliminary results suggest that the coesite-quartz phase boundary at relative low temperature maybe at higher pressure that what previously determined. Ongoing experiments including reaction reversals will precisely locate the coesite-quartz phase boundary at LT-HP conditions relatable to subduction zone settings where coesite likely crystallized in natural rocks.

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MINERALOGICAL SOCIETY OF POLAND

Cadmium occurrence and distribution within sulfide minerals of the Kupferschiefer-series in SW Poland

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The Kupferschiefer polymetallic mineralization exhibits both vertical and horizontal metal zonation. Laterally, mineral zoning progresses outward from oxidized (*Rote Fäule*) rocks in the following sequence: hematite - chalcocite - bornite - chalcopyrite - galena - sphalerite. This study aims to investigate the distribution, mineralogical hosts, and geochemical behavior of Cd within the Kupferschiefer-series focusing especially on its occurrence in sphalerite. A representative suite of samples derived from archival boreholes in sphalerite-rich zones of the Kupferschiefer-series in the Fore-Sudetic Monocline constitutes the basis of the examination. The analysis combined reflected light microscopy with SEM and EPMA enabling qualitative and quantitative assessment of Cd.

Cadmium is mainly present as a trace element in sulfides, particularly in Cd-bearing sphalerite, the primary Cd carrier in the Kupferschiefer-series. Its content in sphalerite is highly variable ranging from a few tens of ppm to 9.1 wt. % and averaging ~ 0.5 wt. %. EPMA studies revealed submicron- to micron-sized greenockite blebs and surface forms over sphalerite, occasionally reaching 200 μm in size. The highest Cd concentrations appear in sphalerite with greenockite ingrowths, though greenockite itself is relatively rare. Additionally, smaller quantities of Cd are found in several minerals associated with sphalerite, including chalcopyrite (0.34 wt. %), bornite (0.33 wt. %), pyrite (0.33 wt. %), and galena (0.17 wt. %). It is also present in Ag-bearing minerals such as argentite, luanheite, eugenite, mckinstrite, stromeyerite, and balkanite. Additionally, Se occurs in Mn-bearing minerals like hauerite and alabandite, as well as in sulphosalts including tennantite and tetrahedrite. Se is further found in accessory minerals such as skutterudite and nowackiite.

High Cd concentrations in the Kupferschiefer-series are mainly controlled by the location of sphalerite-rich zones rather than by lithology, occurring above Cu–Ag ore bodies where Cu–Fe–S sulfides coexist with sphalerite and galena, forming Pb–Zn intervals. This implies that Cd accumulated primarily in the distal parts of the Kupferschiefer-series relative to the redox front, where reduced conditions enhanced its mobilization and distribution into specific mineral assemblages. The distribution of Cd in the Kupferschiefer-series follows a zonal pattern, with concentrations increasing from chalcopyrite-to-galena-rich zones and attaining highest values in sphalerite-rich areas. This zonation reflects the control exerted by the large-scale Cu–Ag Kupferschifer system. Recent studies on Cd geochemistry in sedimentary ore deposits, including the Kupferschiefer-series, confirm its typical association with sphalerite precipitated under reduced conditions. Understanding the spatial distribution of Cd is essential for exploration targeting since Cd anomalies may act as additional geochemical vectors, especially where conventional pathfinders are indecisive.

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Legacy of iron ore mining: Assessing waste heaps in the post-industrial landscape of the Częstochowa region

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The landscape of the Częstochowa region in southern Poland has been strongly shaped by historical iron ore mining, which left behind numerous heaps and altered landforms. The region has been a site of iron ore mining since the 14th century. According to estimates, the waste heaps created during different mining phases across the region contain nearly 5.8 million tonnes of residual siderite ore. Previously seen as industrial waste, these anthropogenic structures are now recognized as key components of the post-industrial environment and call for economic reassessment.

The project *"Evaluation of critical metals content in spherosiderites of selected regions in Poland"* was carried out by PGI-NRI during 2022–2023. The examination sought to identify and quantify CRMs in the iron-mining waste heaps of Częstochowa area. Research involved collecting representative samples from 72 heaps in the Częstochowa iron ore district with locations determined using the *HAŁDY (heaps) geodatabase* and field reconnaissance. Mineralogical and petrographical analyses provided crucial information on the composition of the studied rocks, which were classified into four main types: siderite nodules, phosphate-calcareous nodules, calcareous (calcite) nodules, and sideritic sandstones. The results reveal significant variations in the content of CRMs among the studied rock types. Siderite nodules, calcareous (calcite) nodules, and sideritic sandstones show low levels of REE+Y as well as other CRMs, such as Cu, Ni, Co, V, Bi, As, Sb, W, Sc, Be, Sr, Ta, Ga, Hf, and Nb. In contrast, phosphate-calcareous nodules are strongly enriched in REE+Y, with concentrations ranging from 1120 to 5272 ppm and an average value of approximately 3876 ppm. Ultimately, the Częstochowa mining waste heaps may serve as more than historical relics. They are complex markers of past geological and metallurgical activity and potential sources of CRMs. This case shows how post-mining sites can be turned into valuable resources through sustainable practices, supporting recycling, reuse, and innovative material management solutions.

Further examination of iron ore heaps from the Częstochowa region will be undertaken within the ongoing project "*Estimation of the potential for recovering critical raw materials from mining waste*", which has been conducted by PGI-NRI since 2025. The project's main objective is to identify the occurrence of CRMs within waste heaps and to evaluate their potential for recovery. Mining heaps and similar structures represent an increasingly important resource base for sustainable development and the European Union's resource strategy. Unlocking this potential requires strong interdisciplinary collaboration among geoscientists, planners, professional ecologists, mineral engineers, and policy makers, ensuring that both environmental risks and economic opportunities are assessed within a coherent and integrated framework.

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Petrographic evidence of covellinization processes of copper sulfides: Case study from the Kupferschiefer-series, SW Poland

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This research examines the geochemical and petrographic aspects of covellinization processes in the Kupferschiefer-series of SW Poland. Samples were taken from selected archival boreholes across the Fore-Sudetic Monocline to capture aspects of covellite formation and were used for detailed microscopic studies in reflected light as well as SEM and EPMA analyses.

The covellinization process begins with the chemical destabilization of primary Cu-S sulfides, such as chalcocite, digenite, anilite, geerite, spionkopite, and Cu-Fe-S sulfides like bornite and chalcopyrite, triggered by changing geochemical conditions, and culminates in the formation of covellite as a secondary mineral. The outcome of these transformations depends on the initial geochemical composition of the sulphides undergoing alteration. This process typically follows two distinct transformation pathways reflecting different conditions influencing the alteration of primary Cu-sulphides. The first pathway is linked to the oxidative front (*Rote Fäule*), where Cu-poor sulphides such as yarrowite and spionkopite - particularly prone to oxidation - transformed into covellite, followed by alteration of Cu-rich sulfides including chalcocite, digenite and bornite. This partial replacement often preserves the original crystal habit and forms covellite along rims, fractures, and veinlets, ultimately leading to the complete replacement of the primary copper sulfides. Furthermore, covellite frequently incorporates trace elements including Au, Ag, Hg, and Se, sometimes as fine inclusions of native metals or selenides. The second mechanism, occurring under reducing conditions, influences Cu-sulfides in the upper parts of Kupferschiefer-series and is unaffected by oxidation. It involves gradual dissolution-reprecipitation, producing porous textures and incorporating trace elements like Ag, Hg, and Fe. While it can lead to the total replacement of primary sulfides, partial replacement of Cu-sulfide is more common. Unlike the well-defined rims and fracture fills in oxidized zone, covellite in reduced rocks appears in a more irregular and dispersed manner.

Both mechanisms significantly control the Kupferschiefer mineralization, shaping zonation patterns. The extent and nature of alteration is sensitive relative to the redox front under specific conditions essential for covellinization. These observations provide insights into the dynamic evolution of the ore-forming system. The alteration of primary Cu-sulfides reflects a complex interplay of redox conditions and fluid flow, influencing Cu mobility and secondary enrichment. This process further highlights fluid pathways and the redistribution of elements that controlled the development of the Kupferschiefer mineralization.

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Selenium distribution in sulfide assemblages of Kupferschiefer-series in SW Poland

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The presented outcomes were obtained through several research projects conducted at PGI-NRI as complementary studies focusing on Cu-Ag mineralization in the Fore-Sudetic Monocline and characterizing selenium distribution in sulphides of the Kupferschiefer-series. Mineralogical observations and microprobe analyses were conducted on sulfides across the oxidation front in various lithologies of the Kupferschiefer-series, including Weissliegend sandstone (Ws), Kupferschiefer shale (T1), and Zechstein Limestone (Ca1).

The investigated Kupferschiefer-series profiles, originating from both active mine galleries and archival boreholes of the Lubin-Sieroszowice Copper District, reveal three geochemical zones: (1) an oxidized zone (*Rote Fäule*) depleted in ore minerals but enriched in iron oxides/hydroxides; (2) a reduced zone enriched in ore minerals but lacking iron oxides/hydroxides; and (3) a transition zone with intermediate features, including relict sulfides and iron oxides/hydroxides. These zones intersect lithological boundaries, reflecting the transgressive nature of mineralization. High Se concentrations in sulfides occur mainly in the transition zone, with some anomalies in the upper oxidized zone. In contrast, the reduced zone shows a marked decrease in Se-bearing phases and Se substitutions in ore minerals. The main Se minerals in the Kupferschiefer-series include: native selenium, tiemannite, clausthalite, athabascaite, and cotunnite. Cu-poor sulfides such as covellite, yarrowite, and spionkopite contain the highest amounts of Se, typically up to 1.9 %, and occasionally as much as 12.61 %. Notable contents of Se were also detected in chalcopyrite, bornite, tennantite, tetrahedrite, and cobaltite, with minor quantity in galena, pyrite, chalcocite, digenite, anilite and roxbyite. Selenium is mainly associated with relict sulfides as isomorphic substitutions ("*invisible Se*"), while Se-bearing minerals are secondary. Hematite and goethite are low in Se. Highest Se occur in Kupferschiefer shale with a well-developed transition zone. Se decreases with distance from the oxidized zone, occurring mainly as accessory minerals under oxidative conditions, which reflects its mobility. It is also present as traces in ore minerals and becomes concentrated during advanced oxidation near redox front. This pattern of Se distribution is linked to the stabilization of the redox front and distance from the transition zone, showing that reduced conditions limit Se incorporation into ore minerals.

Recent studies show that Se is linked to oxidation-related processes in sulfides. The evolution of the mineralization system and the variable position of the oxidation front in the Kupferschiefer-series caused progressive changes in mineralogical composition near the redox interface, leading to metal redistribution and Se precipitation mainly in the oxidized rocks.

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Ex situ mineral carbonation of ultramafic rocks from SW Poland: Potential, advantages, and limitations for CO_2 sequestration

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Numerous studies have shown that peridotites and serpentinites can rapidly sequester CO_2 through reaction with silicate minerals rich in Mg^{2+} and Ca^{2+}. The carbonation process yields stable carbonates, facilitating secure and long-term CO_2 storage. In southwest Poland, ultramafic rocks occur as an exhumed mantle part of the Central-Sudetic Ophiolite (CSO).

The theoretical maximum CO_2 sequestration capacity (C_{pot}) was estimated using the stoichiometric method of Renforth (2019) applied to whole-rock oxide data for three ultramafic lithologies from the CSO of varied mineral composition, assuming complete conversion of CaO and MgO to carbonates. Validation was performed using single-stage ex situ carbonation experiments, where the CO_2 mass in the reacted samples was derived from their measured total carbon content, assuming all carbon occurs as magnesite (Table 1).

Table 1. Maximum CO_2 capacity estimated using the equation of Renforth (2019) and results from ex situ mineral carbonation experiments lasting 4, 17, and 48 hours at 185 °C and PCO_2 of 150 bar. Values are reported as kilograms of CO_2 per tonne of rock. Experiments were conducted on powdered samples.

Locality	Type of rock	C_{pot}	C_{exp4h}	C_{exp17h}	C_{exp48h}
Przemiłów	Serpentinite	396.7	36.7	71.5	74.1
Szklary	Serpentinized peridotite	424.4	28.6	69.7	65.6
Grochowa	Serpentinized peridotite	423.1	39.2	187.4	194.3

The results indicate substantial carbonation and CO_2 storage potential across CSO lithologies. The Grochowa serpentinized peridotite achieved 45 % of theoretical C_{pot} within 48 h of *ex situ* carbonation. Despite similar theoretical C_{pot}, the samples show different carbonation rates, governed by contrasts in mineral dissolution kinetics (?) or by carbonate microcrystallites in Grochowa that likely enhanced nucleation (?). The efficiency of *ex situ* carbonation also depends on chemical and mechanical pretreatment, with thermal activation beneficial for serpentine-rich rocks. Future studies should establish an efficient carbonation procedure to maximize CO_2 uptake, particularly for rocks from Przemiłów and Szklary.

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Mineralogy and geochemistry of monzogabbro from Punta de los Órganos, Anaga Massif, NE Tenerife: Preliminary results and ideas

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The Anaga Massif (NE Tenerife, Canary Islands) is a Pliocene-aged, deeply eroded shield volcano. Extensive exposure of its subvolcanic “Old Basaltic Series” provides direct access to rocks that document in situ crystallization and intravolcanic magmatic processes (Ancochea et al., 1990). During the 2021 field campaign, samples of leucocratic rocks were collected at Punta de los Órganos, on the south coast of the Anaga Massif.

The rock is medium-grained, mostly equigranular, and phaneritic, with a random texture, indicating a plutonic origin. Whole-rock chemistry reveals SiO_2 concentrations ranging from 43.9 to 45.0 wt. % and total alkali ($Na_2O + K_2O$) concentrations from 5.3 to 5.5 wt. %. The remaining major oxides are: Al_2O_3 17.9 to 18.1 wt. %, TiO_2 2.7 to 2.9 wt. %, P_2O_5 1.1 to 1.3 wt. %, Fe_2O_3 10.5 to 11.3 wt. %, MgO 2.7 to 3.0 wt. %, CaO 7.4 to 8.0 wt. %. Rock exhibits strong enrichment in LREE ($\Sigma LREE/\Sigma HREE=12.4$). The accessory assemblage includes abundant ilmenite and lesser amounts of magnetite, fayalite, fluorophlogopite, and fluorapatite. A rare Nb-enriched zirconolite has been identified exclusively as inclusions within ilmenite crystals. The presence of nepheline is also plausible, but it remains unconfirmed by single-spot chemical analyses.

The whole-rock chemistry indicates an alkaline affinity, and the phase assemblage supports classification as monzogabbro. At this early stage of the research, we hypothesize that the monzogabbro from Punta de los Órganos may represent differentiated magma that crystallized in deep parts of the Anaga shield volcano plumbing system. This interpretation appears to be consistent with whole-rock LREE and HFSE enrichment (e.g., elevated TiO_2 and P_2O_5 content) and the presence of F-bearing phases alongside Fe-Ti oxides, all of which indicate crystallization from an evolved, Fe-Ti-P-enriched residual silicate melt (Lindsley & Epler, 2017).

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Lower Palaeozoic protolith ages for eclogites in the Norwegian Caledonides: Iapetus Ocean terranes within a giant subducted continental crust complex?

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In the Western Gneiss Region (WGR) of the Scandinavian Caledonides, eclogite generated during the Scandian collisional orogeny is usually hosted within granitoid orthogneisses that are reworked elements of the Fennoscandian shield. They are conventionally thought to have had protoliths in Meso- to Neoproterozoic intrusions. However, an eclogite in the northern WGR (Roan) is now known to have had a late Cambrian to early Ordovician protolith with MORB geochemistry (Möller et al., 2024). This has motivated a re-evaluation of eclogites in the main outcrop of the WGR, particularly some large massifs found in an enigmatic supracrustal assemblage, the “Blåhø Nappe”. Of these, the large Tverrfjella-Talstadhesten massif near Molde has circumstantial indications of an oceanic precursor such as MORB to island-arc basalt composition, association with marble, quartzite, Cu ores, ultramafic bodies, metapelites and acid metavolcanites (Harvey, 1983). This assemblage is consistent with an ophiolitic precursor. O, C and Sr isotopes of associated marbles have Palaeozoic carbonate signatures (Tronnes & Sundvoll, 1995). Previous work on the Ulsteinvik and Lesjåskog eclogites revealed a few zircons with Ordovician magmatic cores (Walsh et al., 2007; DesOrmeau et al., 2015). New investigations of Blåhø Nappe eclogites at Lesjåskog, Ulsteinvik and Gossa (Nordøyane) have revealed probable magmatically-cognate leucotonalite horizons yielding zircon with typical magmatic cores, which gave magmatic protolith SIMS U-Pb zircon ages ranging from early Ordovician to early Silurian. No leucotonalites have yet been found in the Visnes-Averøya and Tverrfjella massifs, hence these important bodies require further work. The new ages reinforce the proposal, based on the Roan eclogite, that the products of Lower Palaeozoic magmatism within the Iapetus Ocean, or perhaps small ocean basins between continental ribbons rifted from Baltica, have been tectonically incorporated into the mainly continental crust that dominates the WGR.

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Fingerprinting hydrothermal events in the Karkonosze–Izera Massif with Fe–S isotopes and trace elements

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The Rudawy Janowickie Mountains (SW Poland) form part of the Karkonosze–Izera Massif, long known for polymetallic mineralization linked to the granite contact zone and Variscan tectonothermal evolution. The area offers a natural laboratory to explore isotope–element systematics in hydrothermal sulfides. Previous studies described paragenetic successions and limited sulfur isotope data, typically showing narrow ranges ($\delta^{34}S \approx 1$–3‰) consistent with hydrothermal sulfur sources. Our observations significantly extend $\delta^{34}S$ results and combine it with in-situ iron isotope data from pyrite and chalcopyrite, together with LA-ICP-MS trace element analyses and petrographic observations.

Pyrite $\delta^{34}S$ values extend from –5.5 to +17.6 ‰ (VCDT), while chalcopyrite ranges from –2.3 to +17.6 ‰. Most samples cluster between 0 and +5 ‰, consistent with magmatic–hydrothermal sulfur. However, one locality yields consistently heavy $\delta^{34}S$ in both pyrite and chalcopyrite (+15.9 to +17.6 ‰), suggesting the involvement of a ^{34}S-enriched source, probably a sulfate-derived component, and marking this sample as a distinct subpopulation. Iron isotopes also vary widely: pyrite $\delta^{56}Fe$ spans –0.68 to +1.78 ‰, chalcopyrite –0.94 to +0.93 ‰, with indications of both kinetic growth effects and later re-equilibration.

Trace element analyses complement the isotope data. Pyrite shows large spreads in Co (<1–997 µg/g), Ni (<5–2800 µg/g), As (to ~6000 µg/g), and Se (to ~380 µg/g), with Te mostly near detection. Chalcopyrite is As-poor but Se-rich (>300 µg/g in places). Multivariate statistics separate Co–Ni–Se-rich versus As-rich pyrite, and Se-dominant versus Te/As-bearing chalcopyrite, implying variable fluid compositions. Notably, the heavy-sulfur sample combines high As with elevated Co–Ni–Se, supporting the interpretation of a separate fluid event.

The integration of isotopic and trace-element data highlights the role of redox-driven fractionation and subsequent recrystallization in generating isotopic heterogeneity in sulfides. These results not only reconstruct the hydrothermal history of the Rudawy Janowickie system but also contribute to a broader understanding of Fe–S isotope behavior and trace element partitioning in ore-forming environments. We further suggest that the Rudawy Janowickie sulfides preserve superimposed pulses of mineralizing fluids with contrasting sulfur sources and redox states, underlining the potential of integrated isotope–element approaches to refine genetic models of Sudetic ore systems.

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Primary results on bulk Cu–Fe isotopes in Kupferschiefer-type copper deposits: tracing redox evolution

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Understanding how redox conditions evolve during the formation of stratiform copper deposits remains a central challenge in ore geology. The Kupferschiefer system in Central Europe, extending from southwestern Poland to central Germany, is one of the largest sediment-hosted Cu provinces worldwide and an exceptional natural laboratory for such studies. Mineralization typically occurs as disseminations within sandstone, shale and dolomite, while massive sulfide accumulations are rare and have only locally been described (Król & Sawłowicz, 2017; Foltyn et al., 2025). The coexistence of these contrasting mineralization styles offers a unique window into the processes of host-rock buffering, hydrothermal fluid influx and late-stage oxidation.

To capture these transitions, we analyzed bulk Cu and Fe isotopes (δ^{65}Cu, δ^{56}Fe) from host lithologies, dispersed ores, and massive sulfide veins in the Fore-Sudetic Monocline and North-Sudetic Basin (Poland). Dolomite and sandstone show near-zero δ^{56}Fe (~0 ‰) with δ^{65}Cu also close to 0 ‰, reflecting depositional background conditions. Shale- and limestone-hosted ores yield intermediate compositions (δ^{56}Fe up to +0.19 ‰, δ^{65}Cu between –0.5 and +0.3 ‰), pointing to early reductant-rich traps that captured metals under mixed fluid–rock conditions. Massive sulfides dominated by chalcopyrite, bornite and chalcocite are characterized by consistently negative δ^{56}Fe (–0.6 to –0.9 ‰) and δ^{65}Cu (–0.2 to –0.6 ‰), consistent with precipitation from reduced, sulfur-rich hydrothermal fluids. Secondary malachite assemblages preserve negative δ^{65}Cu but show positive δ^{56}Fe (up to +0.3 ‰), indicating oxidative overprint.

These findings provide the first bulk Fe isotope dataset from Kupferschiefer-type Cu deposits and demonstrate a systematic isotopic progression from host-buffered to sulfide-dominated conditions. The combined Cu–Fe isotope record offers new constraints on redox pathways and fluid evolution in one of the world's most important stratiform copper systems.

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Polish Strategic Clay Raw Material Reserves for Nuclear Waste Repository Buffers

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The recently launched Polish nuclear energy program is a key element of Poland's energy independence and an important contribution to reducing emissions that drive climate change. One of the few negative aspects of nuclear power is the generation of radioactive waste in the form of spent nuclear fuel. Such waste must be placed in an underground repository that ensures its isolation from the biosphere for the thousands of years required for the activity of long-lived isotopes to diminish. The geological and geotechnical conditions of deep geological rad-waste repositories (DGR) must allow for the prediction of complete waste isolation for a period of no less than 10,000 years.

Bentonites and other smectite-rich clay materials are planned for use as buffer materials in various DGR designs. In such environments, these materials are intended both to block incoming water migration and to retain radioactive elements released from damaged canisters. The buffer will be exposed to elevated temperatures due to the decay of radioactive waste over extended periods, and its hydration state is expected to change over time.

Global research on buffer materials for nuclear waste is being conducted jointly by several dozen countries. As part of Poland's strategic security, barrier materials for a DGR should be obtainable from within Polish territory. The aim of this project is to study the deposits of such materials in Poland and to determine their material properties according to internationally accepted DGR criteria.

Here, we present the results of surveys of nine major clay material deposits in Poland, assessing material quality and deposit heterogeneity in terms of mineral composition, cation exchange capacity, and smectite layer charge. We also report data on what is likely the purest bentonite in the world, found in Poland's Kielce region.

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Does detrital rutile in the Magura Nappe of the Western Carpathians record subduction of Alpine Tethys?

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Detrital rutile geochronology combined with trace-element analysis provides powerful constraints on the temporal and tectonothermal evolution of orogens. This approach allows: (i) estimation of metamorphic temperatures from Zr concentrations (under comparable pressure conditions), (ii) discrimination of source lithologies (metamafic, metapelitic, or hydrothermal) using diagnostic elements such as W, Zr, V, Cr, Nb, and Fe, and (iii) identification of specific rock types, including mafic low-temperature/high-pressure assemblages, by integrating H_2O contents with Zr, Nb, W, and Sn signatures. We applied U–Pb dating and trace-element analysis to detrital rutile from medium-grained sandstones of the Magura and Silesian nappes in the Western Carpathians. Twelve sandstone samples were collected along a profile in the Magura Nappe, supplemented by three from the Silesian Nappe and three from the Altengbach Formation of the Rhenodanubian Flysch (Greifensteiner Decke). From each sandstone, ~200 rutile grains were separated, with about half investigated in detail. U–Pb results reveal a broad range of rutile ages, with prominent clusters corresponding to Variscan (ca. 400–280 Ma) and Alpine (ca. 160–90 Ma) tectonothermal events. We present a compiled dataset of trace-element analyses from ~350 Alpine-age rutiles, complemented by exploratory H_2O measurements in one sample. Zirconium-in-rutile thermometry indicates that much of the Alpine rutile formed along a steep geothermal gradient, while elevated H_2O contents point to crystallization within a subduction channel. Collectively, the data demonstrate unequivocal blueschist- to eclogite-facies sources for detrital rutile in the Magura Nappe. The provenance of Alpine rutiles reflects distinct source regions: older grains (ca. 160–150 Ma) are linked to Meliata/Vardar-related complexes, whereas younger ones (ca. 100–90 Ma) derive from the Veporic Superunit of the Western Carpathians and their Austroalpine equivalents (notably the Koralpe, Saualpe, and Pohorje units). None of the observed sources can be directly related to the closure of the Alpine Tethys.

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Structural and chemical characterization of Tl-bearing sulphates in the Tl–Fe–S–H_2O system: insights into dorallcharite formation and thallium retention

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Minerals of the jarosite-group significantly influence the mobility and fate of trace elements in acidic, sulphate-rich environments, such as those impacted by mining. However, the interactions between these minerals and the highly toxic element thallium are not well understood. In the natural Tl(I)–Fe(III)–S(VI)–H_2O system, the formation of small (up to 10 μm) rhombohedral crystals of dorallcharite, a Tl-dominant member of the jarosite group, has been observed. Dorallcharite, nominally $TlFe^{3+}_3(SO_4)_2(OH)_6$, is the main Tl sink in the Tl and sulphate-rich, acidic environments affected by mining, as well as in associated soils and sediments. Due to its poor crystallinity, its structural and compositional characteristics have remained only partially understood. To address this, we synthesized high-quality single crystals of $[Tl_{0.94}(H_3O)_{0.06})]^+Fe^{3+}_3(SO_4)_2(OH)_6$ (**I**) and $Tl^+Fe^{3+}(SO_4)_2$ (**II**) using hydrothermal methods. These crystals were thoroughly characterized through single-crystal X-ray diffraction (SC-XRD), Raman spectroscopy, scanning electron microscopy (SEM) with energy dispersive spectroscopy (EDS), and transmission electron microscopy (TEM). Both sulphates crystallize in trigonal centrosymmetric space groups: **I** in $R\bar{3}m$ (No. 166) with a = 7.3330(4), c = 17.7118(6) Å, V = 824.81(9) Å^3, Z = 3 and **II** in $R\bar{3}$ (No. 148) with a = 4.8375(2), c = 24.7905(9) Å, V = 502.41(5) Å^3 and Z = 3. SEM-EDS and TEM-EDS investigations have been shown that K^+ substitute Tl^+ and Al^{3+} substitute Fe^{3+} in very small amounts at mixed atom sites. The chemical composition of **II** corresponds to the formula $Tl^+(Fe_{0.8}Al_{0.2})^{3+}(SO_4)_2$ based on 2S atoms p.f.u., which agrees with the chemical compositions obtained from crystal-structure refinements. These comprehensive chemical and structural analyses provide new insights into dorallcharite's chemical composition and crystal structure, advancing our understanding of how it forms in nature. Additionally, **II** is a compound that may also be present in natural environments. These findings offer valuable insights into the role of sulphates in the environmental cycling of Tl, contributing to a deeper understanding of this complex system.

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From metal retention to metal release in ferronickel slags

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Building on our previous study of both historical and fresh ferronickel slags produced from the smelting of lateritic Ni ores (Đorđević et al., 2024), we further investigated the retention and mobility of metals in electric furnace slags (EFS) using scanning and transmission electron microscopy (SEM and TEM), as well as Raman spectroscopy. Our analyses revealed the presence of crystalline Fe-rich forsterite, ortho- and clinopyroxenes (e.g., enstatite, pigeonite, augite), spinel-group phases (e.g., magnesiochromite, trevorite), an amorphous slag matrix as well as regions enriched in intermetallic Fe_xNi_y particles and Ni- and Fe-sulfides. On the microscale, Fe_xNi_y particles and sulfides are commonly intergrown. Additionally, Fe_xNi_y nanoparticles (<10 nm) were observed embedded in the glass matrix. Due to their high surface area, these nanoparticles may significantly influence slag reactivity, both in terms of potential applications and environmental metal release.

To assess long-term metal mobility, we conducted an 18-month leaching experiment under quiescent-flow conditions using solutions adjusted to pH values of 2.9 and 4.8. Notably, older slags released up to 90 wt. % of their Ni content, primarily due to the dissolution of Fe-Ni-sulfides and fine-grained ferronickel alloys. Cobalt exhibited a similar trend. Magnesium mobilization (up to 2.1 wt. %) was associated with the breakdown of forsterite, while chromium release from magnesiochromite-bearing slags ranged from 0.3 wt. % to 0.6 wt. %.

Leaching intensity was strongly pH-dependent: at pH 2.9, Ni concentrations in the leachate were up to 135 times higher than at pH 4.8 in some samples. Other potentially toxic elements (PTEs) showed similar behavior, with release rates 4 to 76 times greater under more acidic conditions (pH 2.9). Over time, concentrations of some metals in solution declined, suggesting the progressive formation of secondary phases capable of re-adsorbing or immobilizing dissolved metals, particularly under stagnant conditions.

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Sediments from copper ore processing as a potential source of critical metals

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Introduction

The deposits of the Legnica-Głogów Copper District are stratified hosted deposits in sedimentary formations that constitute some of the most important sources of copper and silver in the world. Copper ores consist of sulphides and oxysulphides which forms the ores of copper, silver, zinc and lead (Kucha & Mayer, 2008). The deposits contain chalcocite, digenite and covellite, chalcopyrite and bornite. Rare and precious metals, e.g., silver, gold, nickel, molybdenum occur both in the form of their own sulphide minerals as well as in the form of isomorphic substitutions in the major ore minerals of copper and gangue minerals. These work indicate the distribution of these metals.

Results and discussion

The concentration of selected critical metals and their variability in tailing storage facilities of the old and new copper district, were determined using ICP – MS. Grain size analysis, optical microscopy and scanning electron microscopy (SEM-EDS), and microprobe studies were performed according to methodology in Duczmal – Czernikiewicz (2013). Mainly copper with addition of silver, lead, zinc, nickel, and molybdenum have been found in sediments. Other metals were found in trace amounts. These metals was related with inclusions in sulphide mineralization in carbonate and shale ore fragments. The amount of copper ranges from 58 mg/kg to 1482 mg/kg in the new copper district and from 31 mg/kg to 2856 mg/kg in the old copper district. Silver and molybdenum content varies from 4 to 10 mg/kg , and cobalt from 10 to 15 mg/kg. The content of critical metals correlates with copper diversity in of carbonates and shale ore fragments.

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Conditions of host rock formation in the karst Rovte region, Slovenia

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To better understand the speleogenetic processes, the conditions under which the host rock formed in the karst Rovte region of central Slovenia were examined. The relationship between a redox environment on the susceptibility of the rock to karstification remains poorly understood. For this purpose, samples of dark gray Triassic limestones and dolostones were collected. Volatile content (VOC) was determined to assess organic matter maturity and the content of total (TC) and organic (TOC) carbon and sulphur (TS) to find depositional conditions. These data were supported by the occurrence of biomarkers.

Total carbon contents varied from 1.73 to 13.08 wt. % (avg. 7.79), TS values were 0.55 wt. %, and TOC 0.43 wt. % on average. The extract yields were extremely low, 0.005 wt. %, on average. The predominant compounds were *n*-alkanes, which comprised 90 % of the extracts in most samples. Their distribution was of the Gaussian type, with the concentration maximum ca n-C_{26} - n-C_{27} and CPI values ~1.0. Most of the extracts lacked common biomarkers such as hopanes and steranes, or biomarkers were present as traces. Pristane (Pr) and phytane (Ph) were found in three samples of the 13 sample set. Pr/Ph values were in the range of 0.35-0.75, whereas Pr/n-C_{17} and Ph/n-C_{18} in the range of 0.68-0.83 and 0.72-1.05, respectively. A complete hopane distribution found in one sample comprised compounds from Ts to C_{35} hopane, with values of Ts/(Ts+Tm) being 0.73, C_{31}S/(S+R) 0.61, and C_{29}Ts/(C_{29}+C_{29}Ts) 0.20. All extracts were rich in elemental sulphur (S_8). VOCs contents were in the range of a few percent, pointing to high maturity of kerogen, which is also confirmed by the absence of most biomarkers.

TOC versus TS and Pr/Ph values indicate the anoxic sedimentary environment. Other features suggest OM-poor rocks with kerogen of high maturity, possibly additionally changed by secondary processes within a deposit.

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Pfaffenbergite & bonaccorsiite, new minerals crystallizing in nanorocks

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The study of nanorocks (crystallized inclusions of anatectic melts) via micro-Raman Spectroscopy (MRS) has revealed that the mineral phases crystallizing from these aliquots of melt are distinctive, for example, feldspar polymorphs (kokchetavite, kumdykolite, svyatoslavite and dmisteinbergite) and the SiO_2 polymorphs cristobalite and tridymite (Wannhoff et al., 2022). In addition, nanorocks from numerous localities worldwide contain two novel crystalline phases. The first is pfaffenbergite (Ferrero et al., 2024), $KNa_3(Al_4Si_{12})O_{32}$, which has the composition of an unmixed binary K-Na feldspar, hence it can be regarded as a feldspar polymorph. Its micro-Raman spectrum is characterized by a very strong vibrational mode at 412 cm^{-1}, two secondary peaks at 105 cm^{-1} and 832 cm^{-1} and two weaker peaks at 130 cm^{-1} and 470 cm^{-1}. Three-dimensional electron diffraction (3DED) data collected with a Transmission Electron Microscope revealed that pfaffenbergite is a hexagonal mineral, crystallizing in space group $P6/mcc$. This mineral can be classified as a sheet silicate and it is isostructural with kokchetavite ($KAlSi_3O_8$) and wodegongjieite ($KCa_3(Al_7Si_9)O_{32}$). The latter is a mineral recently found as crystallization product of melt inclusions found in corundum from the Luobusa ophiolite (Tibet, China; Mugnaioli et al., 2022), and subsequently with pfaffenbergite in garnet from the Saxony Granulite Complex. The second novel mineral is bonaccorsiite (IMA No. 2025-028). Its micro-Raman spectrum displays a main peak at 430 cm^{-1}, three secondary peaks at 186 cm^{-1}, 264 cm^{-1} and 292 cm^{-1}, along with two weaker peaks at 485 cm^{-1} and 823 cm^{-1}. Our results show that this phase has the ideal formula $KK_2Na_3(Al_6Si_{36})O_{84}$ and crystallizes in the $P6/mcc$ space group. The arrangement of its tetrahedral sites (Si,Al) resembles that of frameworks in feldspathoids, but with a topology not yet reported as far as we know. We interpret pfaffenbergite, wodegongjieite and bonaccorsiite as metastable phases crystallizing rapidly in a silicate melt enclosed in a small pore under non-equilibrium conditions. The increasing number of recent findings of metastable phases suggests that these minerals are more common than expected.

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Chemistry of apatite from AMCG-related ilmenite-apatite deposits of the Ukrainian Shield: petrogenetic indicators and economic potential

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The assimilation of continental crust exerts significant control over the compositional variations of massif-type anorthosites and the economic potential of the associated Fe-Ti-V±P deposits depends both on the starting magma composition and subsequent magmatic processes. Kieffer et al. (2024) demonstrated that the chemical composition of apatite can effectively record petrogenetic processes in mafic layered intrusions and presented a set of proxies for crustal contamination, corroborated by isotopic signatures. The purpose of this study is to utilize this approach to study ilmenite-apatite ores hosted by gabbroid intrusions within the Paleoproterozoic Korosten and Korsun-Novomyrhorod anorthosite-mangerite-charnockite-granite (AMCG) complexes in the Ukrainian Shield.

The ore-bearing rocks of the Fedorivka and Stremyhorod intrusions contain accumulations of ilmenite, apatite, and minor titanomagnetite, while the Nosachiv intrusion is devoid of magnetite and comprises two distinct ore types, each resulting from separate intrusive phases. The first one (I) formed olivine-bearing, apatite-rich lithologies, while the second phase (II) is characterized by abundant ilmenite, much lower apatite content, and an almost total absence of olivine.

Apatite from Fedorivka exhibits a mostly uncontaminated character, comparable to Sept Iles MCU II samples, while those from Stremyhorod suggest crustal contamination. Apatite from the two intrusive stages in Nosachiv plots in separate fields. The olivine-bearing Nosachiv (I), plots near the Fedorivka samples but simultaneously shows an increase in Th relative to the HREE. Nosachiv (II) exhibits distinctively higher $(La/Nd)_N$ ratios, which might indicate contamination by more differentiated rocks (e.g., syenite). Apatite from Nosachiv (II) (∑ REE 3327-8663 ppm) and Stremyhorod (∑ REE 3700-6411 ppm) are significantly richer in REE than those from Fedorivka (∑ REE 1058-2008 ppm) and Nosachiv (I) (∑ REE 1753-2928 ppm). The Eu anomaly and Sr/Y ratio serve as indicators of fractional crystallization, with a decrease in Eu/Eu* from Fedorivka (0.47-0.53), Stremyhorod (0.24-0.27), Nosachiv (I) (0.13-0.15) to Nosachiv (II) (0.09-0.11).

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Ultra-high Pressure meta-ophiolites recorded diachronous peak ages: new constraints for subduction and exhumation of the Western Alps

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Ultra-high pressure (UHP) units represent the deepest portion of a subduction zone that returned to the surface, escaping their fate of disappearing into the mantle. Tracing their distribution and timing provides crucial constraints on the dynamics of subduction and exhumation across the entire mountain belts. The occurrence of UHP index minerals, e.g., coesite, in orogenic belts is fundamental because they are often the sole remnants of UHP paragenesis in largely re-equilibrated rocks. Such minerals are generally found as inclusions within garnets acting as strongboxes. UHP tectono-metamorphic units in subducted oceanic lithosphere are of particular interest because they are natural laboratories to study fluid-rock interaction and deep processes occurring at depths > 80 km. In this context, the meta-ophiolites of the Western Alps are the perfect case study, as they offer a continuous outcrop along the entire belt. Here, we focus on the UHP meta-ophiolites of the Internal Piedmont Zone (IPZ), where coesite inclusions in garnet have recently been found in three different localities: i) Lago Superiore Unit, Monviso Massif (Ghignone et al., 2023), ii) Susa Valley (Ghignone et al., 2024), and iii) Ala Valley (Maffeis et al., 2025). They lay in the same structural position of the Lago di Cignana Unit, where coesite was discovered in the early 90's (Reinecke, 1991). In addition, these UHP localities share similar metamorphic peak PT conditions, being on the same metamorphic gradient (~6 °C/Km). In all these different UHP localities and in newly collected samples, the presence of coesite is limited to a specific garnet domain (e.g., core, mantle), pinpointing the stage of garnet growth at UHP conditions. Other garnet domains instead contain quartz, and they are devoid of evidence of growth at UHP conditions. Here we present the preliminary results of the U-Pb dating on coesite-bearing garnets, carried out on five coesite-bearing localities of the Internal Piedmont Zone (IPZ). The results reveal two clusters of UHP metamorphic ages (40–45 Ma and 50–55 Ma) identified in different areas, suggesting a diachronous attainment of peak at UHP conditions across the IPZ. Our data provide new opportunities to advance our understanding of deep processes taking place along subduction zones.

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REE-enriched calcite veins in Permo-Carboniferous volcanics of the Intra-Sudetic Basin (the Central Sudetes, SW Poland)

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A still increasing demand for the Rare Earth Elements (REE) drives studies on their mobility and accumulation into non-traditional geological environments. Due to an ongoing prospecting within the European Union, and crucial economic and geochemical differences among the REEs, their subdivision into light (LREE: La–Nd and Sm) and heavy (HREE: Eu–Lu and Y) as defined by the European Commission, Study on the Critical Raw Materials for the EU 2023 – Final Report (Grohol et al., 2023), was utilized. Elevated total REE contents (ΣREE ≤431 ppm) of Permo-Carboniferous trachyandesites and basaltic trachyandesites of the Intra-Sudetic Basin (the Central Sudetes, SW Poland) have already been documented (Powolny et al., 2018, 2019), although a relatively low HREE content (≤93 ppm; Powolny et al., 2018, 2019) jointly with a majority of REE hosting in silicate and phosphate minerals, makes this content uneconomic. However, our preliminary examination of up to ca. 5 cm thick calcite veins, cutting trachyandesites exposed in the operating quarry at Grzędy, revealed even higher enrichment in ΣREE (≤517 ppm), with a notable enrichment in HREE (≤168 ppm) of some veins. Calcite $\delta^{13}C_{PDB}$ value = -4.8 ‰ suggests a mantle source for carbon in mineralising fluids, albeit does not exclude the influence of fluids derived from sedimentary strata of the Intra-Sudetic Basin. In contrast, calcite $\delta^{18}O_{SMOW}$ value = +18.3 ‰ is highly elevated relative to the upper mantle and mantle-derived carbonates, and suggests a significant sedimentary influence. The high REE content, along with a majority of REE hosting in non-silicate phases and high contribution of HREE, justify further studies on the REE potential of the Permo-Carboniferous intermediate–mafic volcanics and possible further prospecting in the Intra-Sudetic Basin.

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Examining “The Room Problem” through geochronology and geochemistry analysis of zircon and titanite from the Western Idaho Shear Zone, USA

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The “Room Problem” refers to the mechanism by which magma intrudes into the crust in a contractional tectonic setting. This mechanism can be analyzed by studying the geochemistry and geochronology of titanite and zircon, two minerals that preserve records of geologic processes. Titanite records metamorphic events, while zircon records igneous crystallization temperature. The Western Idaho Shear Zone (WISZ) experienced multiple episodes of magmatism and metamorphism due to the collision of oceanic-arc rocks with the existing continental crust. This study focuses on the emplacement and deformation of the Hazard Creek Complex (HCC), a group of plutons that intruded accreted oceanic-arc rocks in the western WISZ. Our data suggest that episodes of magmatism in the HCC occurred 160 and 115 million years ago, and that high temperature deformation was ongoing throughout this entire time. These findings suggest that deformation can facilitate magmatism, and reveal the timescales involved in large-scale crustal accretion events.

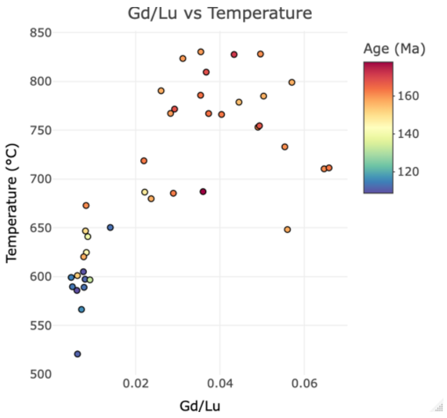

Figure 1. Two age populations of Zircon in HCC Sample 15A.

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Deciphering gases generated from self-heating coal waste dump in northern France based on geochemical and isotopic data

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Spontaneous ignition of organic material within coal waste deposits can initiate self-heating processes, leading to the release of various hazardous gases into the atmosphere. This study examines greenhouse gases (GHGs) and trace compounds from a self-heating coal waste dump located in Hénin-Beaumont in Northern France, during a field campaign conducted in September 2024. Thermal and gas emission mapping of the dump surface revealed distinct spatial patterns in temperature and gas concentrations. Subsurface temperature measurements, taken from boreholes up to 0.6 meters deep on the top surface and slopes of the dump, ranged from +51.0 to +83.1 °C. The temperature variations result from heterogeneities in the composition of coal and carbonaceous rock materials, differences in air permeability and oxygen availability across the site. The chemical composition and origin of gases released during self-heating are closely linked to the waste material's thermal state. Emission patterns correspond to specific thermal processes, mainly low-temperature oxidation and pyrolysis. In well-ventilated, oxygen-rich areas at the top of the dump, with temperatures below +68 °C, emissions are dominated by CO_2, reaching 12.8 vol. %. Conversely, on oxygen-limited slopes of the dump with higher thermal activity (temperatures near +80 °C), a shift toward pyrolysis is evident. Here, CO_2 levels peak at 18.3 vol. %, and oxygen drops to 1.48 vol. %. These areas also show significantly higher concentrations of other gases, including: CH_4 averaging 4260 ppmv, CO reaching 54 ppmv, H_2 levels above background, C_2H_6 up to 327 ppmv, C_3H_8 up to 69 ppmv, and higher hydrocarbons (C4–C6).

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Hydrometallurgical and Nanofiltration Approaches for Sustainable Recycling of Photovoltaic Waste

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The transition to a net zero economy will require the substantial expansion of renewable energy technologies, driving unprecedented demand for mineral raw materials. Photovoltaics (PVs) have experienced almost exponential growth in global installed capacity in recent years (International Energy Agency, 2024). Beyond conventional Si based modules, thin film technologies, particularly perovskite solar cells (PSCs), are expected to gain momentum due to their potential for higher power conversion efficiencies. Consequently, end-of-life PV modules are projected to become one of the fastest growing waste streams worldwide, while at the same time representing a considerable secondary source of critical raw materials (CRMs) such as metallic silicon, silver and indium (International Energy Agency, 2022).

Here we outline hydrometallurgical processes combined with membrane filtration as an effective pathway for CRM recovery from a variety of PV technologies. Silver has been recovered from organic photovoltaics (Søndergaard et al., 2016), copper indium gallium selenide (CIGS) cells(Zimmermann et al., 2014) and PSCs (Amrein et al., 2025), while indium has been recovered from both CIGS and PSCs. Nanofiltration (NF) has been repeatedly applied as a central step in these processes, enabling the virtually chemical free separation of Ag^+ from In^{3+}. For PSCs, crystalline PbI_2 of high purity was obtained through hot water extraction (Schmidt et al., 2023), a process independently shown to reduce global warming potential compared with alternative approaches. From the remaining glass culets, indium and silver were leached with nitric acid and subsequently separated using tailor made NF membranes, which outperformed commercial alternatives in terms of efficiency and energy demand (Amrein et al., 2025).

These results highlight environmentally benign strategies to access valuable CRMs from end-of-life solar cells. They demonstrate how next generation recycling approaches can be developed to address future resource challenges as today's PV modules reach the end of their service life.

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Geochemical insights into the origin of eclogites in the Kamieniec Metamorphic Belt (Fore-Sudetic Block, SW Poland)

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The Kamieniec Metamorphic Belt (KMB) is a supracrustal succession (mica schists, small bodies of paragneisses, quartz-graphite schists, calc-silicate rocks, amphibolites and eclogites) exposed at the NE part of the Bohemian Massif. Provenance studies of KMB metasediments (maximum depositional age: 529 Ma) suggest that their protolith was derived from the Cadomian orogen and deposited in basins located on the Gondwana margin (Szczepański et al., 2023). The objective of this study was to provide tentative geochemical constraints on the origin of the protolith of the KMB eclogites, which, in conjunction with metasediments, were subjected to HP-LT Variscan metamorphism.

The chemical composition of the studied KMB eclogites corresponds to that of basalts (SiO_2 45.7–50.3 wt. %) with moderate to high contents of TiO_2 (1.7–3.2 wt. %), Al_2O_3 (14.7–17.9 wt. %). The MgO content is moderately low (4.5–6.2 wt. %), and the samples are mostly fractionated, as evidenced by their mg# (15–54) and concentrations of Ni (7–28 ppm), Cr (34–493 ppm) and Co (20–50 ppm). The chondrite-normalized REE diagrams show considerable enrichment in LREE (La/SmCN: 2.3-3.7, La/YbCN: 7.0–11.2) and fractionation of MREE over HREE (Tb/YbCN: 1.7–2.0). A negative Eu anomaly is not observed. In primitive mantle-normalised diagrams, the profiles exhibit a distinct negative inclination and are characterised by positive Nb-Ta anomalies, coupled with slight, non-systematic Zr-Hf and Ti negative inflections. The N-MORB-normalized profiles of the studied rocks closely follow that of OIB showing overall enrichment in incompatible elements.

The application of several geochemical proxies, including Ti/V, Nb/Y vs. Zr/Y, Th/Yb vs. Nb/Yb, Zr/Nb, and La/Nb, suggests that the magma was generated from an enriched asthenospheric source, Presumably, it formed at depths corresponding to the garnet-facies mantle, but close to the garnet-spinel phase transition. They display typical within-plate–type enrichment (OIB-like) and affinity to the geotectonic setting of divergent plates. Their geochemical features do not suggest the presence in the source of components derived from supra-subduction zone activity, which is incongruent with the meta-mafic lithologies documented in the surrounding units of the Central Sudetes. Notably, the studied rocks exhibit notable geochemical affinities to the metabasites identified in the West Sudetes (e.g., Kozłowski et al., 2016). Further research is required to elucidate their relationships to Palaeozoic mafic magmatic events in the northeastern part of the Bohemian Massif.

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Sulfides from spherosiderites from the Gnaszyn clay pit (Poland) – preliminary data

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Bathonian clay sediments from the Gnaszyn area (Ore-Bearing Clay Formation in the Cracow-Silesia Monocline) show the presence of at least six spherosiderite horizons. These concretions are ellipsoidal, spherical, spheroidal, or flattened. Numerous concretions exhibit a septarian structure and remnants of fossils (bivalves, ammonites, belemnites). The Gnaszyn spherosiderites can be divided into (1) siderite and (2) phosphate-siderite concretions. They consist of siderite, calcite, clay minerals, and detrital grains represented by quartz and feldspars. The spherosiderites are also rich in organic matter of terrestrial origin (Lis et al., 2022). Phosphate spherosiderites also contain numerous grains of apatite and barite.

The Gnaszyn spherosiderites contain numerous sulfide grains, which occur in the rock matrix, in calcite veins intersecting the rock matrix, or on the internal surfaces of concretions containing voids. The sulfides are represented by pyrite, sphalerite, chalcopyrite, and galena. Furthermore, some samples show the presence of monazite. Pyrite occurs in two forms: as framboidal or eu/anhedral grains in the rock groundmass, or as euhedral or anhedral grains in calcite veins. It occurs as almost pure iron sulfide. Sphalerite from the Gnaszyn spherosiderites occurs as pure zinc sulfide or as zinc sulfide with an admixture (up to 4.2 wt. %) of iron.

The occurrence of framboidal pyrite is supposedly related to sedimentation on the bottom of a shallow marine basin during the Bathonian. The relatively small size of the pyrite framboids (up to 5 μm in diameter) from Gnaszyn suggests their syngenetic nature (cf. Zatoń et al., 2008). The other sulfides (eu- and anhedral pyrite, sphalerite, chalcopyrite, galena) and monazite are likely phases that formed during sediment diagenesis and concretion formation. The most probably sources of metals (Zn, Pb, Fe, Cu) for the sulfides in the spherosiderites from Gnaszyn are surrounding mudstones.

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Submicron-scale constraints on zircon growth and alteration under ultrahigh-pressure, eclogite-facies metamorphic conditions

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This study explores the growth and alteration processes of zircon under ultrahigh-pressure (UHP) metamorphic conditions, using transmission electron microscopy (TEM) for submicron observations. Six zircon grains from two eclogite samples were chosen based on our previous study (Jaranowski et al., 2023). The samples were chosen based on inconclusive geochronological records obtained from LA-ICPMS U-Pb isotope dating, suggesting irregular zircon growth episodes during eclogite-facies metamorphism. Fifteen foils were prepared using focused ion beam (FIB) to investigate on the submicron-scale changes affecting zircon's growth under UHP conditions and impact of potential alteration processes.

The TEM investigations revealed that metamorphic zircon is predominantly homogeneous in composition. In some FIB-foils structural defects were observed, potentially caused by stress either during UHP metamorphism or exhumation of the eclogites. In all cases, nanoscale observations recorded point defects in the crystallographic structure, indicating damage from the metamictization of zircon due to the radiogenic decay of U and Th. The FIB-foils from the IK13-077 eclogite, cut out from the transition zone between the zircon's core and rim, displayed a distinct diffraction contrast between the homogeneous metamorphic rim and core domains with linear growth zonation. However, any compositional changes between the two, if present, were below the detection limits of the EDX and EELS detectors. In the case of FIB-foils from the MB17.01E eclogite, several euhedral crystal inclusions of apatite were embedded at various orientations within the metamorphic zircon, suggesting that apatite was present during the zircon's growth during the metamorphic events.

The TEM results indicate that the zircon grains from the two investigated eclogites have not been subjected to the alterations that could cause the compositional changes, and proved that there is no evidence that could suggest any impact to the U-Pb isotopic system that might have affected the age record in the zircon grains.

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Behavior of Ni and Cr during mineral carbonation of ultramafic rock: an X-ray absorption study

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Mineral carbonation is a natural process by which silicates react with CO_2 and transform into carbonates. It is being scaled up from the experimental stage and deployed on a pilot scale in the industry. Ultramafic rocks (UMRs) appear to be ideal materials for mineral carbonation, due to their high content of divalent alkaline earth metals, particularly Mg and Ca. It should be noted that UMRs also contain elevated concentrations of metallic elements (especially Ni and Cr). Understanding the fate of these elements during carbonation is important both for environmental safety and potential resource recovery.

We characterized UMRs (dominated by olivine and serpentine with up to 2000 $mg \cdot kg^{-1}$ Ni and 3000 $mg \cdot kg^{-1}$ Cr) before and after single-stage carbonation experiments. Magnesite was the main carbonation product and did not incorporate Ni or Cr. Instead, newly formed hydrated Mg-silicates enriched in Ni were identified, accounting for approximately 50 % of the Ni budget. This indicates that Ni was mobilized during carbonation but remained in the system through crystallization of secondary phase(s) (Cieślik et al., 2025).

To further investigate the behavior of Ni and constrain the behavior of Cr, we applied X-ray absorption spectroscopy (XANES/EXAFS) at their K-edges (ASTRA beamline, SOLARIS) for samples before and after carbonation experiment. Significant spectral changes were observed for both elements, indicating their mobilization during carbonation and subsequent incorporation into new phases. These results provide insights into the redistribution of Ni and Cr during mineral carbonation and its implications for CO_2 storage and metal recovery.

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Alum Shale of the Scandinavian Caledonides: integrating mineralogy, petrology, and geophysics to assess critical raw material resources

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Renewed interest in the Alum Shale Formation stems from its enrichment in critical raw materials such as vanadium, molybdenum, phosphate and rare earth elements, in addition to elevated concentrations of uranium, zinc, nickel, and copper. Its prospective potential is further enhanced where tectonic repetition within the Scandinavian Caledonides increases the shale's thickness to several hundred meters, most notably in the Tåsjö area at the Caledonian Front (Gee, 1972). This new focus builds on extensive exploration carried out in the 1960s–70s, when numerous drill holes and regional studies established a first geological framework that continues to serve as a key reference.

Recent studies show that regional greenschist facies metamorphism and associated deformation can be correlated with the enrichment of uranium and REE in the phosphoritic shales (Lecomte et al., 2019; Sordyl et al., *in prep*). Our current work builds upon previous studies by integrating mineralogy, petrology, and geophysics. Petrological studies examine the impact of greenschist facies metamorphism on the mobility of trace metals and the transformation of organic matter. Raman spectroscopy is used to characterize the degree of graphitization, serving as a proxy for metamorphic grade and providing constraints on the temperature conditions necessary for fluid mobility. Additionally, it explores potential future applications of carbonaceous matter, such as serving as a precursor material in the battery sector.

In parallel, pilot seismic surveys test reflection, refraction, and ambient noise methods to image shale boundaries and internal structure. Ambient noise tomography and anisotropy analysis, in particular, hold promise as tools for tracing metamorphic grade in organic-rich sediments, although their applicability remains to be fully evaluated.

This combined approach offers a renewed perspective on Alum Shale as both a critical metal and carbon resource.

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Metamorphic evolution of the eclogite-hosting augen gneisses from the Richarddalen Complex, Svalbard

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High-pressure (HP) rocks provide key insights into subduction-related processes. While most studies focus on eclogites, their host rocks can also yield valuable information. Here, we study the HP Richarddalen Complex, exposed in NW Svalbard. It comprises bodies of eclogite enclosed in orthogneisses. We combine inclusion thermobarometry with in-situ Lu-Hf dating of garnets and Rb-Sr of micas for the host rocks to further constrain its evolution.

Augen gneiss contains two garnet (Grt) generations, feldspar, plagioclase, quartz, biotite, chlorite, and rutile. Grt-I occurs as a few-cm big porphyroblasts, with a composition of $Alm_{72}Pyr_{23}Grs_{3}Sps_{2}$. Grt-II forms coronas at biotite–plagioclase contacts or small (~200 µm) grains overgrowing Grt-I, with zonation from $Alm_{57}Pyr_{22}Grs_{20}Sps_{1}$ in the core to $Alm_{50}Grs_{33}Pyr_{17}Sps_{0}$ in the rim. Mylonitic orthogneiss also contains two Grt generations, white mica, biotite, plagioclase, feldspar, quartz, and rutile. Grt-I forms large porphyroblasts with a composition of $Alm_{64}Pyr_{17}Grs_{16}Sps_{3}$. Grt-II occurs as smaller grains or overgrows Grt-I, showing zoning from $Alm_{59}Pyr_{16}Grs_{24}Sps_{1}$ to $Alm_{52}Pyr_{14}Grs_{34}Sps_{0}$. Inclusion thermobarometry (Zr-in-rutile and quartz-in-garnet) indicates HP conditions consistent with estimates for eclogites of Elvevold et al., 2014 (~2 GPa, 730 °C). In-situ Lu-Hf dating of Grt-I yields Tonian ages: 967 ± 44 Ma for augen gneiss (MSWD = 0.79, n = 60) and 959 ± 28 Ma for mylonitic orthogneiss (MSWD = 1.4, n = 86). Grt-II in mylonitic orthogneiss provides a younger age of 477 ± 98 Ma (MSWD = 1.1, n = 110), although low Lu in Grt-II limit precision. Rb-Sr dating yields 472.7 ± 3.6 Ma for biotite from augen gneiss (MSWD = 6.8, n = 100) and 470 ± 12 Ma for white mica from mylonitic orthogneiss (MSWD = 2, n = 117).

These results provide new age constraints for the Richarddalen Complex. Grt-I records the Tonian protolith, consistent with U-Pb zircon data (Pettersson et al., 2009), while Grt-II supports Paleozoic HP metamorphism. The Rb-Sr ages are interpreted as reflecting fluid influx (e.g., biotite chloritization) during post-HP decompression. Together, our data support the model of Mazur et al. (2022), suggesting that the Richarddalen Complex represents rocks derived from a subducted microcontinent.

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Mantle source heterogeneity and magmatic evolution recorded in Late Cenozoic basalts of Central Vietnam

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Late Cenozoic basaltic volcanism in central and south-central Vietnam occurs in scattered outcrops, including Ly Son and Small Ly Son islands and the mainland localities of Pleiku, Tuy Hòa, and Hòa Lộc. The investigated basaltic rocks are fine- to medium-grained and locally contain xeno-/phenocrysts of olivine, clinopyroxene, and rarely plagioclase. They are dominantly alkaline to mildly sub-alkaline basalts, trachybasalts, and basaltic andesites, with subordinate tephrites/basanites. Multi-element diagrams normalized to primitive mantle exhibit slightly positive Nb–Ta anomalies and Pb depletion. Rare earth element patterns show LREE enrichment, with $(La/Yb)_N$ of 5–16.

Mineral chemistry reveals not only contrasts between xeno-, phenocrysts and groundmass phases, but also systematic differences among localities. Clinopyroxene xenocrysts exhibit the highest Cr and Mg contents. Phenocrysts are generally Mg- and Cr-rich but poor in Ti and Al, whereas groundmass clinopyroxenes show lower Mg# and Cr but elevated Ti and Al contents. Olivine xenocrysts record the highest forsterite content. Phenocrysts generally show slightly lower Fo but higher Ni, while groundmass olivines are the most Fe-rich and Ni-poor. Plagioclase phenocrysts and groundmass grains mostly range from andesine to bytownite, rarely extending to sodic varieties. Some feldspar phenocrysts locally exhibit sanidine composition. Rare orthopyroxene groundmass grains (Ly Son) are resorbed, rimmed by clinopyroxene, with decreasing Mg# and increasing Ca content from core to rim.

Whole-rock geochemistry exhibits OIB-type signatures (Pearce, 2008), consistent with derivation from a heterogeneous, metasomatized asthenosphere containing enriched (EM1, EM2) and HIMU-like components. Compositional differences in mineral chemistry indicate early crystallization of phenocrysts from primitive melts at higher temperatures, followed by late-stage crystallization of more evolved residual melts at shallower levels. Olivine and clinopyroxene xenocrysts likely originate from lower crustal cumulates incorporated into the ascending magma. Our data highlights the interplay between mantle source characteristics and fractional crystallization in generating the diversity of Late Cenozoic basalts in Vietnam.

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Effect of water availability on heat-related layer charge changes in smectites

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Bentonites, which are smectite-rich rocks, are commonly used as barrier materials in various designs of radioactive waste repositories. In such an environment, bentonites would be subjected to elevated temperatures due to the decay of radioactive waste over prolonged periods. Furthermore, the hydration state of the material is expected to change over time, from undersaturated immediately after contact with the waste canister to fully water-saturated in the long term in the repository. As heat is known to introduce changes in the layer charge (LC) of smectite, which in turn may change its performance as a barrier, precise knowledge of smectite LC changes under such conditions is important.

The aim of this study was to determine LC changes in four smectites, each in four different cationic forms, representing various LC magnitudes and locations within the structure after heating for an extended period of time under oven-dry and hydrothermal conditions at 100 °C and 200 °C. The magnitude of LC changes was determined with the spectrometric OD method (Kuligiewicz et al., 2015). The reversibility of the LC changes was tested by cation-exchange and hydrothermal treatments.

Heating under hydrothermal conditions introduced more LC changes than in the oven-dry conditions. The LC of Mg^{2+} and Fe^{2+}-exchanged samples decreased. In the case of Fe^{2+}-exchanged samples treated hydrothermally at 200 °C, the formation of kaolinite was observed, and collapsed “illite-like” interlayers were detected for K^{+}-exchanged samples at the same reaction conditions. Hydrothermal treatment was able to restore LC to its original values for samples that were dry-heated at 100 °C, and partly but not fully for those treated at 200 °C.

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Th-U-Pb dating of monazites in garnet-biotite gneiss from borehole Kybartai 38 – a record of the complex Proterozoic evolution of the SW West Lithuanian Granulite (WLG) domain

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The studied garnet-biotite gneiss sample originates from borehole Kybartai 38 (Kb 38), located in the southwestern segment of the West Lithuanian Granulite (WLG) domain, part of the Amberland crustal assemblage (Bogdanova et al., 2015). This retrogressed rock is characterized by almandine-rich garnet, Ti-rich biotite (up to 5 wt. % TiO_2), labradorite plagioclase ($An_{50–55}$), quartz, K-feldspar, zircon and monazite. Monazite, a key chronometer for metamorphic and magmatic events, reveals two populations: (1) fine-grained (≤3 μm), homogeneous, and euhedral, and (2) larger (≤100 μm), zoned (Fig. 1), and anhedral crystals.

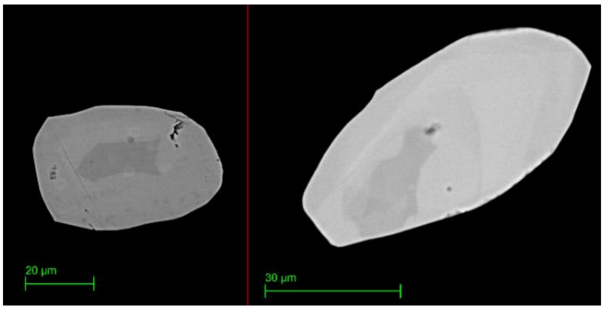

Figure 1. BSE images of 2 selected monazites exhibiting clear zonation, acquired using SEM.

The monazite crystals were imaged in BSE mode using SEMs; EDS mapping and imaging were performed. Five representative crystals were analysed using EPMA to reconstruct the metamorphic history of the gneiss. BSE imaging and WDS mapping revealed compositional zonation that records four distinct geological events. Chemical Th-U-Pb ages from zoned stripes within monazite crystals reveal the following sequence of geological events: ~1.86 Ga – records the protolith formation (magmatic/metasedimentary protolith age), ~1.64 Ga – interpreted as crystallization during the metamorphism associated with the TIB-2 or Gothian orogeny, ~1.56 Ga – thermal overprint related to Mazury intrusions, ~1.42 Ga – late-stage tectonic and metamorphic overprint, most likely associated with the Danopolonian or Telemarkian orogenies, and coeval with the emplacement of ~1.45 Ga granitoids in central Lithuania and Sweden. These ages reveal the dynamic history of the WLG domain, closely linked to the regional tectonic and thermal events recorded on the Baltic shield.

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Preliminary analysis of the influence of thermal maturation on organic matter transformations and organic acid generation in source rocks

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Organic acids generated from kerogen during diagenesis and early catagenesis can have important implications for, e.g., the deep biosphere, mineral reactions and the creation of secondary porosity. Yet little is known about the quantity and composition of such acids released from source rocks. To investigate the generation of organic acids immature shale samples with different kerogen types were subjected to hydrous pyrolysis (HP). Samples from the Green River Formation (USA, type I kerogen), Boquillas Shale (USA, type II) and Menilite Shale (Poland, type II/III) were heated in water for 72 hours at 240 °C, 270 °C, 280 °C, 295 °C, 310 °C and 320 °C. Organic acids in the reactor water were subsequently identified and quantified via ion chromatography, while residual rock samples were studied by Rock-Eval pyrolysis, FTIR, and micro-FTIR, to investigate organic matter structural changes in the different types of kerogens.

Organic acid concentrations varied significantly based on kerogen type and temperature. The highest yield of 33.2 mg/g TOC at 320 °C was obtained from Menilite Shale sample with kerogen type II/III. Kerogen type I (Green River Fm.) produced up to 16.9 mg/g TOC (320 °C). The lowest yield was recorded for kerogen type II (Boquillas Shale), which produced a maximum of 6.80 mg/g TOC (320 °C). The detected products were predominantly short-chain unsaturated monocarboxylic acids in the C_1–C_5 range, dominated by acetic acid (C_2). Organic acid quantities increased with pyrolysis temperature, but in each series of samples, a decrease in acid content was observed within the 295–310 °C temperature range, possibly indicating a geochemical shift point where kerogen transformation dynamics change. The analysis of the types and quantities of organic acids indicate that type II/III kerogen was the most productive, likely due to its higher initial oxygen content. In contrast, kerogen type II was the least productive, correlating with its lower oxygen content.

Menilite Shale sample (kerogen II/III) was the most susceptible to transformations, showing significant aromatization of carbon bonds, while type I and II kerogens exhibited slower transformation rates and retained a much higher hydrocarbon generation potential. Micro-FTIR analyses of individual macerals suggest that the rate of transformation and the timing and amount of generated organic acids were influenced by the presence of oxygen bonds with varying strength, ranging from weaker carboxyl groups to stronger ether linkages.

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Glaukosphaerite - the first occurence in Poland

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The first samples of glaukosphaerite in Poland were collected by Krzysztof Łobos in 2023 from dumps at abandoned chromitite mine located on Czernica Hill, in the vicinity of Tąpadła, Ślęża massif, Central Sudetic Ophiolite (50°49’40.57”N, 16°41’52.63”E). The mineral usually occurs there as green spherules, with a maximum diameter of 0.3 to 0.5 mm, composed of radially arranged strongly elongated fibers, or it forms less or more unoriented fiber masses. It appears as encrustations on open fractures walls, in veinlets or interstitially within the chromitite and is accompanied mainly by green and/or purple-red clinochlores, serpentine group minerals, magnesite, calcite and hyalite.

The pXRD pattern interpretation confirms that green material separated from cracks in chromatite contains glaukosphaerite with diffraction pattern closely corresponding to the ICDD reference (PDF 04-013-2653). Associated minerals in analysed sample are clinochlore, serpentine and magnesite. Rietveld refinement of pXRD data provides unit cell parameters of the glaukosphaerite as follows: a = 12.082(3) Å, b = 9.342(4) Å, c = 3.1277(9) Å, beta = 98.27(4)° and calculated cell volume = 349.4(2) Å^3.

The Raman spectrum of the analysed mineral shows pattern similar to the glaukosphaerite analysed by Frost (2006) with bands at 1499, 1456, 1365, 1092 and 1060 cm^{-1} assigned to the (CO3)$^{2-}$ stretching vibrations and intense band at 3380 cm^{-1} within hydroxyl stretching region

EPMA results confirm that cationic positions of analysed mineral are mostly occupied by Cu^{2+} and Ni^{2+}. The results show chemical variation with CuO ranging from 49.76 to 57.09 wt. % and NiO from 11.90 to 17.44 wt. %. Maximum Cr_2O_3 and FeO contents are at 0.59 and at 0.38 wt. %, respectively whereas ZnO, CoO and MgO concentrations are below their detection limits or very close to them. Globular aggregates of glaukosphaerite display concentric chemical zoning. From the core to the rim the Cu content decreases while the Ni increases.

Secondary minerals of the supergene zone from the chromite deposit in the vicinity of Tąpadła have not been described so far in details. The occurrence of significant amounts of glaukosphaerite as a secondary phase is, according to the authors, evidence for the presence of primary Cu and Ni sulphides in unaltered chromitite ore as a potential sources of these elements necessery for that mineral growth.

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The ^{57}Fe-Mössbauer study of cryoconite from Spitsbergen glacier

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The ^{57}Fe Mössbauer spectra of cryoconite (CR) were measured for the first time. The spectra contain several components, including doublets belonging to divalent (ferrous) and trivalent (ferric) iron, and magnetic sextets. The main spectral component can be assigned to Fe^{2+} in such silicates as: hornblende, phengite/muscovite, chlorite. The contribution of Fe^{2+} increases down the glacier. The well-defined sextet belongs to Fe^{3+} in hematite, but the second magnetic component with wide spectral lines can be assigned to nanoparticles of iron oxides and/or oxyhydroxides. The contribution of magnetic components is higher for samples from the upper part of the glacier. The ratio of ferrous to ferric iron (Fe^{2+}/Fe^{3+}) is 0.8 for cryoconite from the upper part of the glacier and increases to 1.7 down the glacier. This indicates change in redox conditions along the glacier, in particular more oxidizing conditions in the upper part. The mineral dust in form of granules found in cryoconites appears to be primarily of volcanic origin due to high ferrous iron content in hornblende and its subsequent weathering to ferric iron. The Fe^{2+}/Fe^{3+} ratio can be an indicator of the weathering progress of cryoconite and therefore an indicator of its age. The weathering appears to have occurred over a longer period of time or more rapidly in the cryoconites from the upper part of the glacier.

The spectra of ice-marginal deposits (A samples) are dominated by Fe^{2+}, and the lack of magnetic sextets indicates the absence of iron oxides/oxyhydroxides. The Fe^{2+}/Fe^{3+} ratio are much higher for A than for CR samples. Therefore, the main source of ice-marginal material is the strongly reducing and anoxic environment occurring in the glacier bedrock. This indicates that this material was being pushed out under pressure from under the glacier or that the glacier retreat.

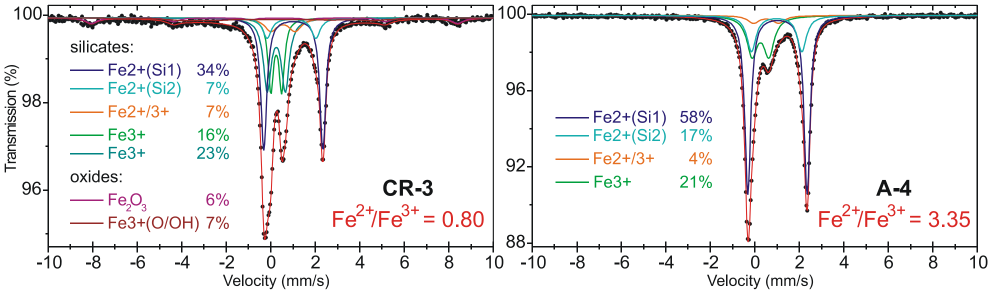

Figure 1. ^{57}Fe Mössbauer spectra (at RT) for cryoconite sample (CR) and ice-marginal deposits sample (A). The relative contribution of spectral components and the ratio of ferrous to ferric iron are shown.

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Eocene tectonothermal event recorded by in situ Rb/Sr biotite geochronology in the Western Tatra Mts.

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We dated biotite and muscovite in 3 samples of garnet-bearing metapelites from the Lower Unit of the crystalline core of the Tatra Mountains using the in situ Rb/Sr technique. The samples were selected based on the degree of secondary alteration, expressed mainly as chloritization of biotite. Chloritization is evinced by chemical changes and BSE contrasts between strongly and weakly chloritized biotite zones. The metasomatically overprinted zones yield consistent Rb/Sr isochron dates, clustering around 56-50 Ma, with a weighted mean of 52 ± 3 Ma. Weakly altered biotite zones provide dispersed dates, up to ca. 300 Ma. Interestingly, muscovite does not appear to be altered, and Rb/Sr dating of muscovite provides a Variscan signal at ca. 300 Ma. Altogether, it is apparent that biotite becomes reactive during the Eocene tectonothermal event, whereas muscovite remains intact. The latter, together with the type of biotite alteration reaction, suggests that the Eocene event has not exceeded greenschist facies conditions. Assuming the upper plate locus for the Tatric Superunit during the Alpine Tethys closure, the dated chloritization reaction may either reflect fluid release from the downgoing plate or overthickening of the upper plate itself. Alternatively, the Tatric Superunit may have been part of the downgoing plate. Notwithstanding the tectonic position of the Tatric Superunit (at least the Tatra Mts. portion of it), it is clear that the crystalline core of the Tatra Mts. was thermally altered/metamorphosed during the Alpine orogenesis.

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Searching for the missing Eastern Antarctica-Western Australia connections in SE Bunger Hills: the tale of three rocks

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The polyorogenic high-grade metamorphic terrane of Bunger Hills, East Antarctica (BH) is inferred to be a key region in understanding the ancient connections between East Antarctica and Western Australia. Here, we present preliminary insights from the previously unexamined Gantela Lake area in the SE of BH. Three different specimens were selected for this study: metamafite, paragneiss and pegmatite. Metamafite is two pyroxene metagabbro geochemically resembling back-arc tholeiite. High Th/U cores of fragmented, magmatically resorbed zircon yielded concordia ages of ~1.8 Ga. Banded garnet-cordierite-ilmenite-spinel-quartz-feldspathic paragneiss most likely derives from volcano-sedimentary protolith. Detrital zircon which preserved igneous morphology yielded ages of ~2.15, ~1.76, and ~1.67 Ga. Recrystallised metamorphic zones cluster between ~1.3-1.15 Ga. The pegmatite and its zircon grains show spectacular textural features of fluid-aided alteration. The concordia age of altered zones is ~1.18 Ga, however a few older (1.4-1.3 Ga) dates were preserved. The zircon ages of 1.9-1.6 Ga in the metamafite and in the paragneiss overlap the timing of polyphase mafic to felsic arc magmatism in the Biranup zone of the Yilgarn Craton (Hartnady et al., 2019) suggesting a likely linkage between BH and the Albany-Fraser Orogen (Tucker et al., 2020). The ages of ~2.15 Ga for detrital zircon correspond to Archean-early Paleoproterozoic continental margin magmatism recorded in Lutzow-Holm Complex in EAn (Takahashi et al., 2018). Zircon alteration in the pegmatite is coeval with the peak of Neoproterozoic (1.22-1.18 Ga) granulite-facies (800-960 °C, 5.5-7.1 kbar) event (Tucker et al., 2020) implying pervasive metasomatism by high temperature brines. The granulite-facies conditions are recorded in the metamafite, in which cpx-opx assemblage gives T/P conditions of 870 °C ~7 kbar.

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Particle size effects on Ni and Cr mobilization during ex situ mineral carbonation of ultramafic rocks

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Ex situ mineral carbonation of ultramafic rocks is a promising method for CO_2 removal from the atmosphere. Partially serpentinized peridotites contain abundant Mg^{2+} (~40 wt. % MgO), making them good candidates for carbonation, but their high Ni and Cr contents may pose ecotoxicological risks if mobilized during carbonation (Cieślik et al., 2025). In the ex situ procedure, mechanical pretreatment is critical because the reduction of particle size increases specific surface area and thus enhances Mg-silicates dissolution (Santos and Van Gerven, 2011).

To evaluate particle-size effects on Cr and Ni mobilization during ex situ mineral carbonation, we conducted batch experiments on powdered, partially serpentinized peridotite from the Szklary Massif (2060 ppm Ni, 2950 ppm Cr). Three particle size classes were tested: 250–125 μm; 125–50 μm; <50 μm. The specific surface area ranged from 17.0622 $m^2 g^{-1}$ for fraction 125–250 μm, through 17.1895 $m^2 g^{-1}$ for 50–125 μm, to 17.9458 $m^2 g^{-1}$ for <50 μm.

Carbonation experiment was performed for 24 h at 185 °C and 100 bar pCO_2 in a 600 mL Hastelloy® vessel, using 20 g of rock and 200 mL of ultrapure water.

At this stage, the correlation between metal release and particle size fraction remains open to discussion. The experiments performed under the applied conditions may have been insufficient to dissolve a substantial portion of Mg-silicates, as suggested by the limited extent of carbonation and the absence of crystalline magnesite in SEM observations. These findings indicate the need for further work with adjusted reaction parameters to better assess the relationship between particle size and metal release. In the future, we plan to analyze the solid carbonation products by Electron Probe Microanalysis (EPMA) to identify secondary phases that could serve as sinks for Ni and Cr.

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Petrogenetic characterization of La Vasca alkaline complex: first report in Mexico of eudialyte-bearing agpaitic rocks

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Peralkaline and agpaitic igneous rocks with local eudialyte mineralization have been reported in the La Vasca alkaline complex (LVAC) but no detailed information on its age and relationship to the Eastern Mexican Alkaline Province (EMAP) has been available. We present petrological, geochemical, isotopic, and geochronological data from the LVAC and the surroundings, located in northwestern Coahuila. The main intrusion is composed of ferroan granitoids that are classified by their alumina saturation index into metaluminous and peralkaline. The metaluminous rocks are monzonite and syenite with post-collisional geochemical affinity. Middle Eocene zircon ages of these rocks range between 47.6 ± 0.3 Ma and 45.4 ± 0.3 Ma and are significantly older than other alkaline rocks from the EMAP. The peralkaline rocks are composed of syenite and eudialyte-bearing foid-syenite with intraplate geochemical affinity that probably coevolved with the metaluminous rocks. Both groups show minimal crustal contamination, with affinity to an Ocean Island Basalt mantle source. The LVAC is explained by a similar formation model than other rocks of the EMAP, suggesting its extension into northwestern Coahuila. Furthermore, the eudialyte foid-syenites represent the first occurrence of agpaitic rocks in Mexico.

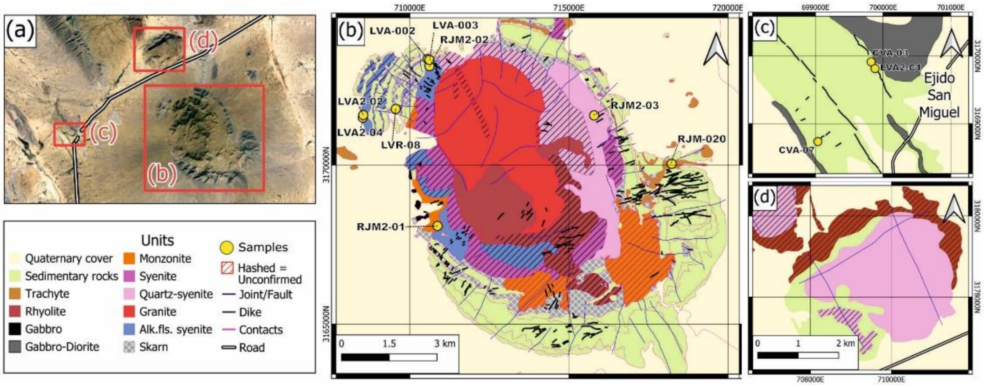

Figure 1. Photointerpreted geological maps. (a) Satellite imagery of the studied areas. (b) La Vasca Alkaline Complex, (c) Ejido San Miguel outskirts, (d) San José pluton.

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Using benzo[*ghi*]fluoranthene and benz[*a*]anthracene as a new proxy for assessing wildfire temperature

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Polycyclic aromatic hydrocarbons are widely used in reconstructing wildfire characteristics in geological periods starting from Paleozoic to recent times. Analyzed together with the fusinite reflectance they are a reliable tool in assessing the fire temperatures. In this study, we focus on investigating charcoal and fusinite-rich sedimentary rocks from the Late Triassic and Early Jurassic periods (Marynowski et al., 2025). In the Late Triassic, the burning plants consisted predominantly of conifers, while in the latter studied period the burned vegetation was diversified, covering almost all plant groups including lycopsids, horsetails, ferns, cycads, bennettitaleans, ginkgoaleans, and conifers. The detected wildfire temperatures are broader for the older period, and range from 272 °C to 742 °C corresponding to ground, surface and crown fires, whereas the Early Jurassic fires were mostly ground and surface ones. The main focus of this study was to develop a new wildfire temperature proxy using the distribution of benzo[*ghi*]fluoranthene (B[*ghi*]Fl) and benz[*a*]anthracene (B[*a*]A), which show different thermal stability. The B[*ghi*]Fl/(B[*ghi*]Fl + B[*a*]A) ratio shows a good correlation ($R^2 = 0.62$) with wildfire temperatures calculated from the measured fusinite reflectance. The novel formula, T [°C] = 664x + 117, where x represents the aforementioned ratio, is generally an effective temperature indicator when applied to unweathered immature samples. Additional research is needed to confirm and improve this approach, including combustion tests with contemporary plant material and broader sampling across various geological conditions, charcoal types, and temperature ranges.

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Identification of hydrothermally altered clastic rocks: geochemical and mineralogical approaches. Chrząstowice PIG-1 borehole profile case study

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The presence of hydrothermal alterations halos is attributed to many precious and base metal deposits, including porphyry Cu deposits. Although essential for targeting future discoveries of ore bodies, distinguishing the products of diagenetic, low-grade metamorphic, and post-magmatic hydrothermal alterations might be ambiguous. This study discusses the hydrothermal footprint observed in the profile of the Chrząstowice PIG-1 borehole, which was located near the Kraków-Lubliniec Fault Zone – a tectonic unit predestinated for porphyry-style mineralization.

The Chrząstowice PIG-1 borehole was drilled in 2023, aiming to investigate the crystalline basement of the Upper Silesian Block. The borehole penetrated 766.5 m of Early-Cambrian and Ediacaran sediments underlain by the Carboniferous succession. The clastic rocks of above mentioned strata are characterized by the presence of multiple network of veins and their mineral composition remains similar irrespective of wall rocks. The cross-cutting relationships of veins provide the evidence of probable mineralization sequences. An illite-chlorite assemblage seems to fill the oldest system of the veins formed at temperatures around 200 °C according to the Bourdelle's chlorite geothermomemeter (2013). The younger vein systems mostly exhibit minerals of low-temperature origin (e.g., calcite, ankerite, sphalerite, galena, barite). The temperature alone does not determine the origin of veins, so additional geochemical studies of sulphide mineralization were performed. The hydrothermal nature of galena might be inferred from the elevated concentration of Te (up to 300 ppm), being related to the lattice substitution for S. Also, the average Co/Ni ratio found at 1.4 in vein-hosted pyrite is consistent with specimens of hydrothermal origin as defined by Reich et al. (2016). Future evidence of hydrothermal processes comes from the presence of quartz crystals of "Marmarosh diamonds" genetic type found at the contact of Ediacaran and Carboniferous strata (overthrust zone). Although the presence of hydrothermal processes seems to be well documented, the timing of veins formation and their relation to the Variscan magmatic activity remains the open question.

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Trace elements and mineral inclusions in scheelite: an example from the Szklarska Poręba ore mineralization, Poland

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Due to the increasing interest in critical raw materials, this study examines trace elements and mineral inclusions in scheelite from the NYF-type granitic pegmatite of the Szklarska Poręba Huta quarry using EPMA and LA-ICP-MS. This pegmatite exhibits complex, multistage mineralisation, including W–Sn–Mo–Bi, U–REE, and Nb–Sc assemblages (e.g., Mikulski, 2007; Pieczka et al., 2023). Scheelite is typically found in association with wolframite, cassiterite, molybdenite, Bi-minerals, base-metal sulfides, Sn-bearing silicates, titanite, and other accessory phases (Mil et al., 2024). Two chemically distinct types of scheelite are identified: scheelite I appears as larger isolated grains up to 0.3–0.4 cm, while scheelite II forms intergrowths within wolframite. Scheelite I is relatively pure, containing up to 350 ppm REEs (with HREE>LREE), 200 ppm Nb, and 100 ppm Mo. It contains no mineral inclusions, shows a negative Eu anomaly, low Sr/(Eu/Eu*) and high Y/Ho ratios, indicating advanced fractional crystallization. Scheelite II forms intergrowths with wolframite and contains more than 5000 ppm REEs and over 8000 ppm Nb. It contains inclusions of Sc-bearing minerals such as thortveitite, scandiobabingtonite, and kristiansenite, as well as smaller (≤ 20 μm) inclusions of nioboixiolite-(Mn^{2+}) and nioboixiolite-(Fe^{2+}) with up to 7.0 wt. % Sc_2O_3. In both types of scheelite, Sc content is very low, reaching only up to 10 ppm in single analytical spots. The low Sc content, despite the sometimes numerous inclusions of Sc-bearing minerals, is due to a geometric mismatch between Sc^{3+} and the Ca^{2+}-site in the scheelite structure (coordination, ionic radius). The wide variability of trace-element content in scheelite II indicates significant interaction with hydrothermal fluids and the induction of metasomatic processes associated with the dissolution of wolframite, which altered the original set of trace elements. Scandium likely originated from mafic rocks within the metamorphic envelope of the Karkonosze pluton, while F-, Cl-, and OH-bearing fluids increased its mobility and transport to the late- to post-magmatic granite system.

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Environmental effects of uncontrolled disposal of lithium-ion batteries: experimental insights into metal leaching under rhizospheric conditions

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The uncontrolled disposal of used lithium-ion batteries poses a serious threat to the environment due to their complex chemical composition and the presence of potentially toxic elements. The aim of this study was to assess the environmental risk of electrode powder (black mass) when in contact with rhizosphere.

Laboratory leaching experiments were conducted using black electrode powder with two grain size fractions (<250 μm and >1 mm). The material was exposed to artificial root exudates solution (ARE) and demineralized water at two pH levels (3.5 and 6.7) for 7 days. The concentrations of elements in the effluent were measured using the ICP-OES method. In addition, a pot experiment was conducted to assess the toxicity of battery powder to plants (*Brassica juncea* and *Festuca rubra*). Two variants were tested: uncontaminated soil and soil amended with 1, 2, and 5 wt. % of powder. Toxicity was assessed based on root length and above-ground biomass measurements.

It was found that an acidic environment and the presence of organic compounds significantly increase the mobility of metals, especially Al, Ni, Co and Cu, with extraction reaching up to 6 %. In ARE solutions with a pH of 3.5, the concentrations of many elements were an order of magnitude higher than in demineralised water. In some cases, the concentrations exceeded the threshold values for soils. The pot experiment demonstrated inhibited plant growth under exposure to battery powder, with higher doses causing more pronounced toxic effects.

We conclude that uncontrolled disposal of lithium-ion batteries poses a serious threat to the soil environment. The increased mobility of metallic elements and negative plant responses to electrode powder highlight the need to implement effective collection and recycling systems, develop metal recovery technologies, and extend environmental monitoring to prevent undesirable pollution.

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Ore mineralogy of the porphyry Mo-Cu-W Myszków deposit: recent advances and opportunities for the recovery of critical raw materials

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Porphyry deposits represent a major producer in the global copper and molybdenum supply chain, as well as key sources of gold and silver. Although they might host a diverse range of rare and critical metals, typical mining operations focus on the major base metals and gold, while potential by-products often end up in waste. Recently, the concept of multi-metal mining has begun to develop and appears to be on the horizon for the near future. For this purpose, LA-ICP-MS has become a technique of choice for achieving accurate and precise element content of minerals, including major sulphides. Hence, this work reports new findings on the chemical composition of selected ore minerals from the porphyry Mo-Cu-W Myszków deposit (unexploited yet) obtained *via* LA-ICP-MS and opens the debate on the new sources of supply for some rare and critical metals.

The mineralogy of the porphyry Mo-Cu-W Myszków deposit is very complex, although **pyrite** is the dominant sulphide mineral precipitated during several different mineralization stages. It contains a wide range of trace elements, including: As, Bi, Co, Ni, Se, and Te. Among them, cobalt attracts the greatest research interest due to its usefulness for tracking boiling horizons (prospecting tool) and its susceptibility to recovery during the metallurgical ore processing.

The porphyry Mo-Cu-W Myszków deposit is characterized by the common presence of **chalcopyrite** that was formed under different physicochemical conditions. Its trace element budget includes mainly: Ag, Bi, Cd, In, Se, and Sn, and their content varies with the temperature and redox conditions of ore-forming fluids.

Similar to pyrite and chalcopyrite, **molybdenite** precipitated during several different mineralization stages; however, it is not found in low-temperature veins of the post-ore period. It hosts traces of Nb, Re, Se, Te, and W, which occur as structurally-bonded elements. From an economic point of view, the presence of Se seems to be the most promising, while the content of Re is relatively low, probably due to the nature of parent magma, oxidation state of mineralizing fluids, and/or high-temperature crystallization environment.

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Pyrolytic products of naturally charred plants from wildfires

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Global wildfire incidents have been on the rise, driven by factors like climate change, land management practices, and human activities. The phenomenon has a significant environmental impact, such as air quality degradation (CO_2, CO, VOCs, and particulate matter emission), adverse effects on water systems (runoff contaminated with ash and charcoal containing polycyclic aromatic hydrocarbons (PAHs), nutrients, and trace element), and soil alteration (accumulation of recalcitrant organic matter, changes in pH and nutrients). Thus, wildfire products introduced to the environment require more extensive research to deepen our understanding of their complex effects. The aim of the research was to recognise a relationship between the chemical composition of wood and other plants tar contained in naturally charred plants, their reflectance, and burning conditions.

Charred plant, plant, and soil samples come from the wildfire at 2 sites – a forest located at a coal waste dump and a lake overgrowth (Sosnowiec, Poland). Their DCM extracts were analysed on a gas chromatograph coupled with a mass spectrometer (Agilent Techn.) with a HP-5 column. The reflectance was measured by reflected light microscopy.

The extract yield was variable, from 0.07-36.67 wt. %. It depended on the sample type, with the highest values found for partially burned grass and canes. Low values for soils (~0.25 wt. %) may be caused by high temperature, which led to evaporation of lighter organic compounds. A wide range of compounds was formed during the thermal degradation of the organic matter. The main types included 1) volatile compounds (light aldehydes, ketones, esters, ethers, terpenes, carboxylic acids), 2) (PAHs), 3) phenolic products of lignin pyrolysis, 4) fats and lipids, 5) heterocyclic compounds (indole, furan, pyrrole, and thiophene derivatives). From the environmental point of view, PAHs and phenolic compounds have the highest impact since they are produced in large quantities in pyrolytic conditions of wildfire and have adverse effects as allergens, mutagens, and carcinogens of variable potency. Among PAHs, 3-4 ring compounds predominated (60-85 % rel.), such as phenanthrene, fluoranthene, and pyrene. Heavier PAHs were minor components (a few % rel.). 2-ring PAHs (naphthalene, biphenyl, etc.) were emitted to the air during wildfire since they were absent in the extracts. Phenols composition depends on two factors, the lignin type related to the burned plant species and temperature. Plant remains highly altered by wildfire, with high reflectance of charcoal, show a distribution composed of few phenols, without lighter compounds such as cresols, due to their evaporation. Phenols distribution of plant remains not altered or slightly altered is also poor in compounds since lignin pyrolysis occurred to the small extend. The richest in phenols are samples moderately altered by fire, since lignin was subjected to pyrolysis, producing phenols, and evaporation was limited.

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UHP eclogites of the Śnieżnik Massif (Sudetes, Bohemian Massif): Geodynamic insights into the Variscan orogen

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Eclogites from the Orlica-Śnieżnik Dome (SW Poland) provide key insights into the deep crustal evolution of the Variscan orogen. The dome, considered part of the Saxothuringian or Moldanubian Zone of the Variscan orogen, exposes orthogneisses enclosing bodies of high- to ultrahigh-pressure (UHP) rocks, including granulites and eclogites. Although the metamorphic history of these rocks has been debated due to the scarcity of diagnostic assemblages, our identification of coesite provides the first direct evidence for UHP metamorphism in this unit.

To refine estimates of the metamorphic conditions, we employed a combination of classical petrological techniques: phase-equilibria modelling, conventional geothermobarometry, Zr-in-rutile thermometry, and quartz-in-garnet elastic barometry. The samples analysed come from two localities and can be classified into two types, distinguished by the presence or absence of phengite. Although petrographic differences exist, both varieties record a comparable pressure–temperature evolution. Peak conditions, constrained by the mineral association Grt + Omp + Ky + Rt + Coe ± Ph, indicate pressures of ~3.0–3.2 GPa at 750–850 °C. Subsequent isothermal decompression led to pressures around 2.0 GPa at 700–800 °C, reflected in amphibole overgrowths on garnet. Later retrogression produced symplectitic intergrowths of Cpx + Amp + Pl ± Opx. Quartz-in-garnet barometry yielded lower entrapment pressures of ~2.0 GPa at ~770 °C, which we attribute to post-entrapment modifications, such as viscous relaxation of garnet at high temperature.

These results provide robust constraints on the UHP evolution of the Orlica–Śnieżnik Dome. We discuss their implications in the context of published geodynamic models to evaluate plausible tectonic scenarios explaining juxtaposition of the UHP eclogites and their surrounding HP orthogneisses.

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Assessment of the efficiency of zinc and lead recovery from metallurgical slags

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Slags formed during lead fire refining exhibit varied chemical and mineral compositions and contain considerable amounts of various chemical elements, such as toxic metals. Consequently, slags from Zn-Pb metallurgy are both a source of environmental pollution and a potential secondary raw material.

This paper presents a detailed mineral and chemical characterisation of products (metallic sinter) and waste (the secondary slag and dross) of the experimental pyrometallurgical processing of refining slags. This characterisation forms the basis for assessing process effectiveness and will enable the identification of future directions for additional recycling approaches.

The chemical composition of the metallic sinter is markedly different from that of the secondary slags and dross, with PbO and SiO_2 dominating at average contents of several dozen percent and a dozen percent, respectively. The dominant chemical constituents of the secondary slag are Fe_2O_3, Na_2O, and CuO, whereas in dross, the dominant constituents are Fe_2O_3, SiO_2, and Na_2O. Additionally, the phase composition of the metallic sinter is dominated by metallic precipitates Fe + Pb and Fe + Pb + Cu, while the secondary slags consist primarily of amorphous glass and crystalline Na and Fe silicates.

The phase composition of secondary slags also differs from that of refining slags. The latter serves as the feedstock for the refining process, and its dominant constituents are crystalline silicates (ferripyrophyllite, γ-disodium catena-disilicate, ferrierite, quartz, and coesite), which exceed 28 % of the total composition. The proportions of the remaining phases (Fe sulphates, Fe, Cu, Pb sulphides, and Fe, Cu oxides) are much lower and do not exceed 12 %.

Experimental tests of the proposed processing method for refining slags revealed a significant zinc and lead yield, with a substantial reduction in charge mass (greater than 40 %). This change in charge mass is the result of multiple factors, such as lead oxide reduction, carbon and sulphur burning, the addition of limestone and possibly iron, as well as the formation of slags.

The laboratory-scale experiments described in this study have demonstrated the potential of the proposed process for efficient lead recovery from refining slags. However, further recovery tests utilising the proposed hydrometallurgical process are required in the case of zinc.

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Mobility and phytoavailability of Al and Zn in sandy and sandy loamy soils amended with household ashes

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Household ashes are byproducts of coal and wood combustion in houses. They contain crystalline phases that are the anthropogenic equivalents of naturally occurring minerals. Furthermore, household ashes are a source of both beneficial (i.e., Ca, K) and harmful (i.e., Cd, Zn) elements. Household ashes are classified as municipal wastes. Nevertheless, they are sometimes used in backyard gardens to fertilize soils. However, using household ashes in soils poses an environmental risk due to the enrichment of metallic elements in such wastes. This study, therefore, aimed to determine the effect of two types of household ashes on the mobilization and phytoavailability of metallic elements (Al, Zn) in two soils with different textures. For this study, two soils from the central part of Poland (A-1: sandy loam and B-1: sandy soils) were amended with 10 % household ashes (ASH 1; ASH 2) after coal-wood co-combustion in households. Control and ash-amended soils were then used in a pot experiment to cultivate *Raphanus sativus* and *Spinacia oleracea*. The soil and plants were subjected to mineralogical (XRD and FTIR) and chemical analyses (i.e., pH, CEC, digestion, and analysis using ICP-OES). Due to the important role of bacteria in processes ongoing in soils, experiments with *Pseudomonas fluorescens* were conducted to investigate the mobilization of metallic elements in soils.

The common mineral phases in both types of ashes were: calcite, anhydrite, hematite, and quartz. Furthermore, portlandite was noted in ASH 2. Sandy and sandy loamy soils, in turn, were characterized by the presence of quartz, feldspars, and mica. In the clay fraction of sandy loam soil, kaolinite and mica-smectite mixed-layered clay minerals were noted. Testing the effect of two household ashes in two types of soils on the growth of *R. sativus* and *S. oleracea*, established that the impact of the household ashes on the biomass of *R. sativus* is generally irrelevant. In contrast, the studied household ashes increased the biomass of *S. oleracea* regardless of the soil tested. Moreover, an increase in the Al and Zn uptake was generally visible in cultivated plants in the ash-amended soils relative to the control soils. Furthermore, the increase in Al and Zn yield was notable, especially in *S. oleracea*, with a translocation factor higher than 1 observed in this plant species. An experiment involving bacteria revealed that metallic elements can be mobilized in household ash-amended soil by *P. fluorescens*. However, this process can be partially limited due to biofilm formation and the presence of Ca-bearing minerals (i.e., calcite) in household ashes, which control the biofilm formation. Based on the results and findings of this study, household ashes are not recommended for the fertilization of soils intended for food production, despite their ability to increase soil pH.

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Role of the sulfide-saturated pyroxenite melts in the metallogeny of the subcontinental lithospheric mantle

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Melts migrating through the upper mantle interact with host peridotite, triggering metasomatism and refertilization, and resulting in mantle heterogeneity. However, the role of sulfides in this process has received little attention, and therefore, sulfide-driven refertilization is poorly constrained, limiting our understanding of the metallogeny of the subcontinental lithospheric mantle. To elucidate the role of the sulfide-saturated pyroxenite-forming melts in metal transfer, we investigated the exceptionally fresh pyroxenites hosted by the well-characterized Balmuccia massif (NW Italy), a mantle body exposed at the Earth's surface. The sulfide-focused investigations of pyroxenite-peridotite transects showed that mantle pyroxenites constitute a critical metal reservoir for subcontinental lithospheric metallogeny and should be accounted for in global metal budget calculations.

We demonstrated that Balmuccia pyroxenites are enriched in magmatic sulfides and sulfide-loving elements compared to the hosting Balmuccia mantle peridotites. Sulfides occur mainly as polyphase grains, mostly irregular and angular in the interstitial positions (>95 %) to silicates. The Balmuccia peridotite-hosted sulfides are dominated by pentlandite (on average 71 %; n = 27), whereas the contribution of pyrrhotite and chalcopyrite gradually increases, associated with a decrease in pentlandite proportion, towards the pyroxenite dykes. Consequently, pyroxenites contain up to 8 times more Cu (avg. 227 ± 58 ppm; 1SD; n = 8) than mantle peridotites (29 ± 20 ppm Cu; n = 20). The same trend is expressed by Ag and S, which are low in peridotites (avg. of 7 ± 4 ppb Ag and 150 ± 81 ppm S; 1SD; n = 20), and relatively high in pyroxenites (avg. of 62 ± 27 ppb Ag and 917 ± 384 ppm S; 1SD; n = 8). These elements exhibit strong correlations: $R^2 = 0.98$ for Cu vs. Ag and 0.96 for Cu vs. S.

The effective metal transfer throughout the lithospheric mantle and crust is a critical process controlling upper crust metallogeny. We calculated that the reported sulfide enrichment in mantle pyroxenites contributes up to 26 % of Cu and Ag in the local-scale metals budget. These findings also help estimate pyroxenites' role in global-scale extrapolations, contributing 12 % to 42 % of the Cu and Ag inventory. Thus, accurate spatial recognition of the Cu and Ag endowment in the lithospheric profile has key implications for ore exploration.

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Is zircon a problem when it comes from a solution: dating of hydrothermally altered zircon from the Organy Wielisławskie rhyolite

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Dating of rhyolites is important for understanding the timing of silicic magma generation and large-volume eruptions, including caldera-forming events. Although zircon geochronology provides high analytical precision, the interpretation of age distributions in volcanic rocks can be complex. In some cases, zircon populations show a wider range of ages than expected based on analytical uncertainty alone. This may result from extended crystallization timescales, the incorporation of slightly older zircon grains into younger magmas, or interactions with post-magmatic fluids. Understanding the origin of such age variations is important for reconstructing the geological history of silicic magmatic systems and for the accurate use of zircon ages in regional correlations. In this study we selected a rhyolite from Organy Wielisławskie for high-precision dating and ion-probe dating of chemically abraded zircon because it represents a well-characterized and geochemically homogeneous volcanic unit (Awdankiewicz et al., 2014).

Our observations of zircon from the studied unit revealed a broad range of internal structures and compositions, including evidence for extensive post-magmatic modification. In particular, grains with oscillatory zoning—commonly interpreted as magmatic—sometimes contained domains enriched in trace elements such as Ca, Al, and REEs, suggesting interaction with hydrothermal fluids. Our analyses revealed that such hydrothermally altered domains can survive chemical abrasion, including Ca- and LREE-rich cores. TIMS dating yielded a weighted mean $^{238}U/^{206}Pb$ age of 298.2 ± 0.3 Ma, while abraded SHRIMP data gave 296.6 ± 1.2 Ma. The slight age offset between the oldest grains (ca. 300 Ma) and the main population may imply of a short time gap (>1 Ma) between magmatic crystallization and hydrothermal overprint, though alternative explanations such as lead loss or inheritance cannot be excluded.

Our results show that hydrothermally altered zircon could be more widespread in Permo-Carboniferous silicic rocks than previously recognized. If overlooked, it can bias geochronological interpretations and mislead stratigraphic correlations. Mapping Ca by electron microprobe can help identify such zircon, though Ca-free variants may also form and require other ways to identify them.

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The petrological reinterpretation of the Pusztaföldvár Basement High, Hungary, and its spatial correlation in the basement of the Great Hungarian Plain

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The basement of the Great Hungarian Plain is composed of buried crystalline highs characterised by a complex, mosaic-like structural pattern and overlain by a thick Neogene sedimentary sequence. Although previous integrative models summarised the lithology, structural framework, and spatial correlation of these metamorphic units (M. Tóth et al., 2021), the Pusztaföldvár Basement High (PBH) has not been included. In this comprehensive study, we present the petrographic characterisation of the PBH along with estimating the peak metamorphic temperature using Raman Spectroscopy of Carbonaceous Material (RSCM) (Lünsdorf et al., 2017). Based on these data, we reconstruct the P-T-d-f-t evolution of the unit by integrating the mineral composition, texture, fluid alteration reactions, and previously published geochronological constraints (Lelkes-Felvári et al., 2003). The M1 metamorphic assemblage in the garnet-biotite paragneiss comprises garnet, biotite, and muscovite, followed by an M2 paragenesis that includes albite, tourmaline, and secondary muscovite. Subsequent pervasive hydrothermal fluid activity, likely associated with the M2 contact event, modified the mineral assemblage and led to the crystallisation of chlorite, hydrothermal rutile, siderite, hematite, and dickite. Graphite thermometry indicates a peak metamorphic temperature of approximately 545 °C (IQR: 514–566 °C), corresponding to progressive amphibolite-facies conditions. However, in highly deformed samples, the accuracy of the estimate decreases due to the method's sensitivity to the degree of graphite crystallinity, which is affected by deformation (Barzoi, 2015). The metamorphic evolution of the PBH unit closely resembles that of the rock units within the Algyő–Ferencszállás–Kiszombor Basement High, (AFKBH), Hungary, located along the same strike as the corresponding Cretaceous nappe, suggesting a genetic link. Furthermore, the rock unit displays petrological similarities with the Aranyosbányai Nappe in the Apuseni Mountains, Romania.

In contrast to previous interpretations that attributed the PBH to the Codru Nappe System (Tisza Megaunit), the spatial correlations presented here support its reinterpretation as part of the Biharia Nappe System (Dacia Megaunit) within the current basement framework of the Great Hungarian Plain.

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The principles underlying the dissolution of metal-bearing phases exposed to bacterial metabolites and biofilms

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The disposal of metallurgical wastes involves complex (bio)weathering interactions which can mobilize contaminants bound to specific phases and facilitate their transfer to the environment. Weathering conditions are dynamic and strictly modified upon microbial activity. Here, the foundational tenets of the most common biotic influence is questioned and noticed that the volumetric exposure of phases to bacteria implicates the efficiency of metals leaching.

The incubation experiments under semi-open flow-through configuration with the heterotrophic bacterium *Pseudomonas fluorescens* were conducted to compare the dissolution of individual phases incorporated in metallurgical slag and sulfide-rich matte. Experiments were accompanied by non-biotic experimental variants involving sterile solution and water. The deteriorative effects of both, bacteria and its siderophore were deciphered by means of (bio)leaching, while direct surface alteration was assessed using a scanning electron microscope and geochemical model.

The results demonstrated that microbial activity caused elements leaching at levels 2 to 92 times higher than the water or sterile solution did. It has been shown that bacteria not only dissolved elements, but also captured them within the biomass. The contribution of uptake varied among individual elements and was up to 23 times higher relative to dissolution process. Different weathering sequence was established for metallurgical wastes exhibiting various phase compositions. The Pb-bearing intermetallic phases of sulfide-rich matte reacted preferentially when exposed to bacteria, whereas Cu- and Zn -bearing phases of slag showed greater susceptibility to biotic dissolution.

Microbial interaction with metal-bearing wastes occurs through two primary weathering mechanisms: contact and non-contact. Under direct microbial contact with the waste, weathering is influenced by both microbial metabolites and biofilm formation. In contrast, non-contact weathering is driven solely by the action of microbial metabolites. To distinguish these two interaction modes, further use of dialysis membranes is essential to isolate the opposing effects of conditions that enhance dissolution from those that promote passivation.

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DFT calculations of iodine-bearing apatites for nuclear waste immobilization

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The safe management of radioactive waste remains a key industrial challenge in the sustainable use of nuclear energy, particularly as Poland begins its nuclear era. Among the critical fission products, iodine-129 is of particular concern due to its mobility, uptake in the biosphere, and extremely long half-life (1.57×10^7 years). Developing mineral-based host phases for its immobilization is therefore essential for long-term waste repository performance. Minerals of the apatite supergroup ($Me_{10}(AO_4)_6Z_2$), which are already widespread in natural systems and technologically adaptable, are increasingly recognized as potential industrial materials for radionuclide sequestration due to their structural flexibility, durability, and low solubility (Campayo et al., 2015; Jiménez-Arroyo et al., 2025; Laird et al., 2025).

In this study, we applied density functional theory (DFT, CASTEP) to calculate selected thermodynamic properties of theoretical chemical compositions of twenty iodine-bearing apatites with Me = Ca, Sr, Ba, Cd, Pb and A = P, As, V (Benisek & Dachs, 2018). Calculated formation enthalpies, Gibbs free energies, and solubility products were implemented into the PHREEQC database. Then, modeling of water–apatite equilibria under repository-relevant conditions was performed. The results reveal that Pb-iodoapatites, in particular, possess the lowest solubility constants and release negligible amounts of iodine to the aqueous phase, even in alkaline environments.

These findings highlight iodine apatites as promising candidates for engineered waste forms. They illustrate how predictive thermodynamic modeling of mineral systems can guide the design and assessment of durable materials for one of the most demanding resource and environmental challenges: the long-term immobilization of nuclear by-products.

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Thermal History, Rehydration, and Structural Evolution of Smectites: Implications for Bentonite Barrier Performance

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The rehydration behavior of smectite is a critical property influencing the long-term performance of bentonite barriers in deep geological repositories for radioactive waste. Smectites possess a unique ability to hydrate, dehydrate, and rehydrate, governed by their layer charge, interlayer cation composition, and environmental conditions such as temperature and relative humidity (RH).

This study examined how homoionic (exchanged with K^+, Na^+, Ca^{2+}, and Mg^{2+}) smectites and natural bentonites from diverse deposits worldwide regain water after heating. Rehydration experiments were conducted under controlled temperatures and humidity, monitored with in situ thermogravimetry (TG), Near-Infrared (NIR) spectroscopy and X-Ray Diffraction (XRD). The layer charge of smecitites was measured using the O-D method (Kuligiewicz et al., 2015). Relatively fast rehydration (20 min – 7 h, depending on the conditions) implied how quickly the buffer could regain its hydration capacity after thermal perturbations. Rehydration extent and rate were strongly cation-dependent - divalent cations promoted higher water uptake and nearly complete recovery after dehydration at 100 °C (Rybka et al., 2025). Higher dehydration temperatures caused partial collapse of smectite layers, especially in high-charge Mg-smectite, reducing rehydration and structural recovery. This highlights the need to constrain acceptable thermal loads during repository design. Structural changes were confirmed by shifts in the OH bands (NIR), decreased layer charge (O-D method), and incomplete basal spacing restoration (XRD). On the contrary, K- and Na-exchanged montmorillonite showed minimal basal spacing recovery, indicating largely irreversible interlayer collapse, consistent with thermogravimetric data. This implied that the cation composition is a critical parameter in selecting bentonite for buffer applications in repositories. Bentonite rehydration trends mirrored homoionic smectites but displayed a non-linear relationship with cation composition, highlighting exchangeable cations as the dominant factor over layer charge, cation exchange capacity, or impurities.

These findings provide key parameters linking smectite structure, interlayer chemistry, and thermal history, which can be directly integrated into models to improve predictions of bentonite performance under repository conditions.

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Melts evolution in the Kraków-Lubliniec Fault Zone (KLFZ)

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In the Kraków–Lubliniec Fault Zone (KLFZ) late Carbonifereous–Permian volcanic rocks mark the boundary between the Małopolska Block (thinned marginal sector of Baltica) and the Upper Silesian Block (a sector of the Brunovistulia composite Terrane). The Zone is a part of the major Hamburg–Kraków–Dobrogea transcontinental strike–slip tectonic zone separating the Laurussian craton and Gondwana blocks which came together to form it. The geochemistry of the volcanic rocks reflects the collisional nature of the tectonism. However, it also presents a signature compatible with extensional magmatism. The volcanic rocks present models of magma generation and evolution in what was a zone of alternating transpression and transtension. The magmatism in this zone of amalgamated terranes was related to two different sources: enriched mantle and primitive crust. This leads to the emergence of two groups of rocks with intermediate and acidic compositions. The lithospheric mantle beneath some blocks of the amalgamated terranes may have experienced enrichment processes during previous subduction events. The metasomatism may have also occurred as a result of crustal thickening during transpression followed by delamination, subsidence and melting. These metasomatised blocks reacted with decompressional melting. The melts that provide the basis for differentiation of intermediate rocks originate from low-degree melting of the metasomatized mantle. The mechanisms of melt evolution leading to the formation of acidic rocks are low-degree melting of crustal rocks, low degree of fractional crystallization and low-degree hybridization of crustal melts by intermediate melts. Our results show that magma generation and evolution in the zone seem to be not typical examples of late Carbonifereous–Permian magmatism, which is known from other locations throughout Central Europe.

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Zircon record of Crystal Mush Remobilization within rhyolitic Halle Volcanic Complex (Germany)

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High-silica magmatic systems can crystallize over a wide range of timescales, from hundreds of thousands to millions of years. This longevity likely reflects prolonged, low-temperature storage in crystal mushes that undergo episodic remobilization. Such extended durations contrast sharply with the short timescales often recorded in volcanic systems (e.g., through diffusion chronometry), raising the question of which stage(s) of magma evolution are actually recorded by zircon dating.

To address this question, we studied two rhyolitic laccoliths within the Permo–Carboniferous Halle Volcanic Complex: the fine-grained Petersberg and the coarse-grained Landsberg units. Careful petrographic observations in thin sections revealed that zircon commonly occurred in glomerocrysts, probably recording early mush crystallization. These grains were largely isolated from the rhyolitic melt responsible for final remobilization and laccolith emplacement—a detail that could have been overlooked without analyzing mineral associations in thin section.

By combining in situ high-precision U–Pb dating, Hf compositional mapping, and structural context, we reconstructed the evolution of the magmatic activity in the Halle Volcanic Complex. Our results indicate that the Landsberg (~299.5 Ma) and Petersberg (~299.0 Ma) laccoliths formed through at least three magmatic pulses from a shared source. This work highlights the value of studying failed eruptions such as laccoliths, which can preserve an undisturbed crystallization sequence and structural record, providing a robust basis for reconstructing pre-eruptive magmatic evolution.

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From Industrial Input to Biogenic Ore Formation: Fe, Pb, Zn, and As Redistribution in Anthropogenic Wetland Sediments

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A marsh wetland receiving mine waters from a Zn–Pb mine was studied to delineate mineral dissolution–precipitation processes and the resulting redistribution of Fe, Pb, Zn, and As. The wetland, covering 52 ha along the Biała River (a tributary of the Biała Przemsza), is on average 1 m thick and stores 3,927 Mg of Zn and 1,887 Mg of Pb in fine-grained dolomitic sediment (Wójcik et al., 2004).

Two 0.5 m long cores were collected 80 m apart, each consisting of dolomitic sediment overlain by a 17 cm organic-rich layer. The sites were densely vegetated by *Phragmites australis* and *Carex paniculata*. The cores were sliced into 2 cm intervals and analyzed for elemental composition, sulfur isotopes, mineral phases, and organic matter content. Selected samples were further investigated using electron microscopy (SEM, TEM), while sulfate-reducing bacteria (SRB) abundances and community structures were assessed using molecular techniques in both the mineral and organic-rich sections.

Detrital galena, sphalerite, and FeS_2 (pyrite and marcasite) make up 3-4 % of the dolomitic sediment and act as the primary hosts of Pb, Zn, and As, respectively. In the organic-rich layer, the relative abundance of galena and FeS_2 grains decreased compared to sphalerite. Trace elements were transferred from well-crystalline detrital sulfides into amorphous and nanocrystalline phases. Zn occurs mainly in nanocrystalline ZnS aggregates, Pb partitions between Fe (hydro)oxides and authigenic galena, while As was identified as a trace constituent in both Fe (hydro)oxides and authigenic sphalerite. Redox-driven transformations were further indicated by the occurrence of mackinawite, formed via the reduction of Fe (hydro)oxides, accompanied by Pb expulsion and incorporation as nanometric PbS inclusions. SRB communities were detected throughout the wetland, with abundances an order of magnitude higher in the organic-rich layer.

This study demonstrates the progressive transformation of wetland sediments under spatially and seasonally variable redox conditions. The observed mineral and microbial processes drive the redistribution and immobilization of trace elements, leading to the gradual formation of biogenic ore-like accumulations in anthropogenic wetland.

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From mineral chemistry to mineral exploration: novel pathfinders to concealed porphyry deposits

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The rapidly increasing demand for critical raw materials and relatively long lifetime of their applications means that even if the recycling strategies develop, primary resources mining will be still crucial in the near future. As a result, deposits of lower and lower grades of ore at greater and greater depths will be explored *via* expensive drilling programs. Geochemical campaign might provide benefits for prospecting by supporting the decision-making process in locating drilling sites.

Porphyry Cu deposits typically occur within an alteration halo with characteristic mineralogical and chemical zoning patterns, which reflects the decreasing temperature outward from a central heat source (e.g., Wilkinson et al., 2015). Similarly, some elements hosted in both barren and ore minerals show predictable pattern around cooling intrusion, e.g., Ti content in chlorites (Wilkinson et al., 2015), Ag, and Co content in pyrite (Rivas-Romero et al., 2021), as well as Sn and In content in chalcopyrite (Rivas-Romero et al., 2021) providing new proxies for targeting mineralization center. An alternative approach involves the spatial variations in isotope composition of porphyry-style sulphides (e.g., pyrite, molybdenite, chalcopyrite) in respect to the distance to mineralization center. Importantly, the recognizable footprint defined by chlorite compositions extends to at least 4.5 km and by $\delta^{34}S_{pyrite}$ values to at least 3 km (Naglik et al., 2025), significantly beyond the whole rock anomaly (≤1.5 km), and thus represents a powerful new exploration tool for detecting porphyry systems. The ore mineralization of the Myszków Mo-Cu-W porphyry deposit is characterized by a classic mineralogical zonality with four main alteration zones: potassic, propylitic, argillic, and phyllic, providing key mineral guides, e.g., chlorite, epidote, pyrite, etc. for ore prospecting (e.g., Ślósarz, 2001). Latest study performed here by Naglik et al. (2025) reported a gradual decrease in $\delta^{34}S$ of late-stage pyrite outwards from the deposit core (av. 3.95 ‰), through circum-deposit (av. +3.40 ‰) to distal zone (av. +3.05 ‰). Additionally, some elemental ratios of pyrite (e.g., Sb/Te, Co/Bi, Ag/Ni, Ag/Co) were found out as a proxies toward mineralization center. Future opportunities arise from the usage of Ti-in chlorite proximitor, which is planned in further research in this area.

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Origin of enigmatic leucocratic rocks at the orthogneiss/metasediment contacts (Lądek-Śnieżnik Metamorphic Unit, Sudetes) – geochemical and geochronological constraints

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A fundamental, yet still unresolved question related to the Lądek-Śnieżnik Metamorphic Unit (LSMU) is the relationship between its two constituent complexes — orthogneisses with a Cambro-Ordovician protolith, and Ediacaran-Cambrian volcano-sedimentary rocks, now mica schists and paragneisses with minor quartzites, marbles, amphibolites and leptynites. One potential origin is Cambro-Ordovician granite intrusion into Ediacaran-Cambrian volcano-sedimentary rocks; a second possibility is tectonic juxtaposition during Variscan orogenesis. An answer to this issue can be found at the contacts between two complexes.

In two LSMU localities, E of Międzygórze (MG) and S of Sienna (SI), layers of fine-grained leucocratic rocks, 10s of cm thick, have been observed. Optical microscope observations show these leucogneisses are composed of Qz+Kfs+Ab+Ol+Ms and have a moderately to well-developed metamorphic foliation. As the leucocratic layers are usually situated immediately between the metaigneous and metasedimentary rocks, they could represent aplitic veins or, alternatively, be products of Variscan ductile shearing between two juxtaposed complexes. Field studies did not allow a resolution between these alternatives.

WR geochemical analyses were obtained from three lithological types sampled at the contact zones in the MG and SI areas. Multi-element trace element (TE) and REE spider diagram patterns show that leucocratic rocks have closer affinity to the orthogneisses than to the metasediments, e.g., they show distinct Eu anomaly and are devoid of LREE enrichment observed in the metasediments. The leucocratic rocks are characterised by lower TE contents than the orthogneisses. However, a mylonitized gneiss from a shear zone within the metagranitoids shows a similar trend in TE content depletion.

U-Pb dating of zircons from two pairs of MG and SI orthogneisses and leucocratic rocks yielded Cambrian (~500 Ma) crystallisation ages for their protoliths. An age of 482±6 Ma was obtained for the MG orthogneiss. Precise emplacement age for the other samples is difficult to determine due to Pb-loss, likely during Variscan metamorphism. However, most zircons exhibit evidence for a magmatic origin, including high ΣREE and Y and strong HREE enrichment. The MG leucogneiss probably crystallised from the most REE-enriched melt, possibly due to a late-stage melt evolution or partial melting of an enriched crustal source. Zircons with discordant U-Pb ages tend to have lower Yb/La and Th/U, and less pronounced REE anomalies, indicating metamorphic overprinting, alteration, or partial recrystallisation. Similarities between TE patterns are even stronger when comparing rock pairs from the same locality, which suggests a common origin of the orthogneisses and leucocratic rocks.

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The good, the bad and the slow - the ambiguous effects of EDTA, citric, acetic and oxalic acids on monazite dissolution in HNO_3

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Supply of Rare Earth Elements (REE) is limited, and the demand is constantly growing due to high-tech industries pressure and limiting geopolitical factors. To answer this demand, new sources and efficient, inexpensive extraction methods are needed. REE-bearing apatite mine waste piles have been studied recently as new economically feasible material for REE extraction. The recovery of rare earth elements from this type of material mainly involves acid leaching, the effectiveness of which can be increased by the addition of organic acids. Monazite is the most common accessory mineral accompanying REE-rich apatites.

This study was set to determine the effect of EDTA, citric, acetic and oxalic acids on dissolution of natural monazite $(Ce,La,Th)PO_4$ in nitric acid. Two types of experiments were conducted: (1) batch experiments with powdered monazite that were sampled periodically and (2) whole crystal dissolution experiments with Atomic Force Microscopy (AFM) Scanning Electron Microscope (SEM) ex-situ imagining of reacted surface. Powders or crystals were treated with 1:1 HNO_3 (control experiment) and with HNO_3 containing organic acids in concentrations: 1 mM or 10 mM EDTA or 100 mM for other organic acids. The extent of dissolution was monitored by PO_4 content determined by UV-Vis spectroscopy in periodically sampled solutions over the course of 1200 hours. In case of AFM ex-situ experiments, the crystals were taken out of the solution, washed, air-dried, analyzed by SEM and AFM and returned to the solutions. This was repeated every 40 hours, over the course of 600 hours.

The addition of organic acids increases the solubility of monazite. The highest solubility of monazite of 620 mg/l was observed (close to equilibrium) in HNO_3 with the addition of EDTA (compared to control experiment where the solubility close to 370 mg/l was achieved). However, the presence of organic acid additives prolongs the time needed to reach a state close to equilibrium from 500 to even 1300 hours. AFM experiments have shown that the dissolution of monazite crystals proceeds through the evolution of existing surface forms rather than through the formation of new etch pits or other dissolution features. The formation of a precipitate layer on the surface of monazite was locally observed as the dissolution experiments progressed. Preliminary studies indicate that this is most likely a rhabdophane $(REE)PO_4 \cdot nH_2O$. Its presence may limit the solubility of monazite. Further studies are needed to determine the potential industrial applications.

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Pb-modified zeolite as a novel material for rapid arsenate removal from water through mimetite $Pb_5(AsO_4)_3Cl$ formation

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Arsenic is a persistent contaminant that poses serious health risks, creating an urgent need for effective water treatment technologies. In nature, arsenic is immobilized by precipitation, adsorption, or ion exchange—processes often replicated in treatment systems. Among these, precipitation of low-solubility arsenate salts is attractive for its simplicity and low cost. Mimetite ($Pb_5(AsO_4)_3Cl$), an apatite-like mineral with high stability and very low solubility, has been proposed for arsenic immobilization in water, soils, and wastes. Its formation requires controlled addition of Pb and Cl, following the reaction:

$$5Pb^{2+} + 3AsO_4^{3-} + Cl^- \rightarrow Pb_5(AsO_4)_3Cl\downarrow.$$

This study presents an innovative method for using lead-modified zeolite as an environmentally safe source of Pb necessary to induce mimetite precipitation. The experiments consisted of two stages: (1) preparation of Pb-modified clinoptilolite and (2) reaction of Pb-clinoptilolite with synthetic and real solutions contaminated with As.

Natural Ca-clinoptilolite was converted to Na form, loaded with Pb^{2+} via 24-hour ion exchange, and washed to remove excess lead (~70 g Pb/kg remained strongly bound). It was then reacted with arsenate solutions (0.1-50 mg/L As(V)) with 20 mg/L Cl^- at pH 2-8 for up to 7 days.

Results show rapid arsenic removal via mimetite precipitation, with up to 99 % removal achieved within 2 hours at pH 6 and 8, and negligible Pb^{2+} release under these conditions. At pH 2, removal efficiency decreased due to reduced mimetite stability and arsenate speciation effects. X-ray diffraction confirmed the formation of crystalline mimetite, while SEM-EDS imaging revealed its occurrence as both incrustations on zeolite surfaces and free needle-like crystals between grains.

In tests with real and synthetic contaminated waters, Pb-zeolite reduced arsenic in a natural water sample from Złoty Stok (pH ~7.5) to below detection limits within 1 hour. In synthetic acid mine drainage (40 mg As/L, pH ~2), no removal occurred without pH adjustment; however, raising pH to 4 enabled a reduction to ~1 mg As/L within 1 hour, with mimetite formation confirmed. The performance was sustained in the presence of competing cations (K^+, Mg^{2+}, Ca^{2+}, Al^{3+}, Mn^{2+}, Cu^{2+}, Ni^{2+}, Zn^{2+}, Cd^{2+}) and anions (F^-, SO_4^{2-}, PO_4^{3-}).

Pb-modified zeolite rapidly and stably immobilizes arsenate across diverse water chemistries, performing best at near-neutral to alkaline pH and showing resilience to competing ions, making it promising for field-scale treatment.

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Magma Storage and Crystallization Depths in the Cenozoic Strzelin Volcanic Field: Insights from Raman Spectroscopy of CO_2 Inclusions

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The Strzelin Volcanic Field in southwestern Poland, a part of the Central European Volcanic Province (CEVP), is composed of nephelinites, basalts and trachybasalts that are found as lava flows and scoria cones. These rocks represent intraplate alkaline basaltic volcanism associated with lithospheric extension, asthenospheric upwelling, and interactions between mantle-derived melts. The parental magmas were derived from relatively depleted mantle sources and underwent a limited fractional crystallization, but the depths of magma storage and crystallization remain insufficiently constrained (Awdankiewicz et al., 2016). To address this issue, we analyzed CO_2-rich fluid inclusions in olivine in nephelinite using Raman spectroscopy. This technique exploits the Fermi diad of CO_2, two bands near 1285 and 1388 cm^{-1}, where the peak separation is proportional to fluid density and thus to entrapment pressure. Combined with estimates of crystallization temperature, Raman data provide an effective means of reconstructing magma storage and ascent conditions, and magmatic system architecture (Yamamoto & Kagi, 2006). A total of 65 inclusions were examined, including 14 hosted in a peridotite xenolith. The olivine phenocrysts vary from anhedral, through subhedral to euhedral. Most inclusions were measured in the subhedral grains; these inclusions record the broadest spectrum of crystallization depths. The densities vary between 0.1 and 0.91 g/cm^3. Assuming crystallization temperatures of ~1100–1200 °C, the highest values correspond to pressures of 6.5–7 kbar, or depths of ~23–24.5 km, indicating the onset of olivine crystallization in the deep magma reservoir. The lowest densities (~1 km) may reflect upper-crustal crystallization or partial re-equilibration of inclusions during magma ascent. Importantly, the greatest depths coincide with a major seismic boundary between the upper and the middle crust (Majdański et al., 2006), interpreted as a principal magma storage horizon. Preliminary data from the xenolith record CO_2 densities of 0.23–0.80 g/cm^3, consistent with depths around 17.5 km and shallower, likely reflecting re-equilibration after incorporation into the nephelinite magma and further rise through the crust.

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Tectonometamorphic history of supracrustal formations revealed by phase equilibria modelling and quartz-in-garnet geobarometry: The Orlica-Śnieżnik Dome (Sudetes, Bohemian Massif)

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This study reconstructs the tectonometamorphic evolution of supracrustal rocks in the Orlica–Śnieżnik Dome (Sudetes, Bohemian Massif) by integrating phase equilibria modelling, conventional geothermobarometry, quartz-in-garnet elastic barometry, and structural analysis. The new data improves our understanding of the internal structure and geodynamic evolution of this Gondwana-derived crustal fragment involved in the assembly of the Variscan orogen.

Structural investigations were carried out in supracrustal formations of the Bystrzyca Massif (western part of the dome) and the southern part of the Śnieżnik Massif (eastern part of the dome). Three planar structures — S_{0+1}, S_2, and a composite S_{2+3} foliation — are associated with three distinct metamorphic episodes. Nine representative garnet-bearing, Al-rich metapelites and metapsammites from both parts of the dome were analysed. Three successive metamorphic assemblages were identified. The earliest (M1), marked by phengitic white mica, albitic plagioclase and rutile, likely formed under high-pressure conditions, although their exact P–T estimates remain poorly constrained. The best preserved metamorphic assemblage (M2), comprising garnet, low-Si white mica, plagioclase of mostly oligoclase composition, biotite, chlorite and locally staurolite and rutile, reveals prograde P–T paths with two contrasting trends: (1) near-linear, higher-pressure trajectories reaching up to 12.5 kbar in the Młynowiec and Wyszki Formation paragneisses, and (2) lower-pressure paths (up to 7.7 kbar) with decompression segments in the Stronie Formation mica schists. A retrograde assemblage (M3), dominated by chlorite, documents exhumation during the post-collisional stage.

The combined structural and metamorphic data suggest that the Orlica–Śnieżnik Dome may comprise juxtaposed tectonic slices with contrasting metamorphic histories, emplaced along cryptic thrusts and later refolded. The dome's composite structure likely evolved through nappe stacking, large-scale folding, and extrusion of deep crustal rocks in front of the Brunovistulian terrane.

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Nanotextures of altered zircon from Bancroft (Ontario, Canada)

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Zircon grains from Bancroft (Ontario, Canada) were described to be cut by unique finger-like textures as a result of fluid-induced alteration (Nasdala et al., 2010), which inspired further micro- to nanoscale evaluation of these features on similar grains from that region. In this study, zircon grains from the quartz core of a pegmatite display various textural micro-domains, which include an oscillatory zoned primary zircon, cut by finger-like textures of secondary Ca- and Na-enriched zircon, a different crystalline zircon at the edges of the grains, and patchy zoned domains which occasionally partially replace the core. Transmission electron microscopy (TEM) evaluation of these domains revealed a homogeneous, amorphous primary zircon. The crystalline zircon, predominantly present at the rim of the grains, displays a nanostructure with a moderate degree of radiation-damage. The finger-like textures are composed of a Na-bearing amorphous zircon matrix and accumulated crystallites of Ca-bearing zircon at the nanoscale. The transitions of the primary zircon into the finger-like texture, and between the Na-bearing and Ca-bearing zones are sharp and are a product of coupled dissolution-reprecipitation processes (Putnis, 2002). The patchy zoned domains, which partially replaced the core of some grains, displayed the most heterogeneous features with significant element mobilization resulting in U- and Th-rich inclusions, and metallic Pb-inclusions at micro- and nanoscale. The nanotextures provide new insights on submicron alteration mechanisms of the zircon grains, which have been subject to multiple alteration events: (i) at a late magmatic stage that resulted in a partial replacement of the primary zircon by a crystalline zircon along the rim at ca. 1064 Ma, and (ii) hydrothermal alteration induced by Na- and Ca-enriched fluids at ca. 240 Ma. Nanoscale observations are important for interpretation of textures at the microscale, but they also require careful evaluation of the microscale to understand the whole picture of zircon alteration from the rock through the mineral down to the single atoms.

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Experimentally altered xenotime-(Y) and zircon with alkali-, alkaline-rich fluids and an Fe-rich environment

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Xenotime-(Y) and zircon are considered robust geochronometers for a wide range of geological settings. Their chemical stabilities have been tested in various experiments, which demonstrate the effectiveness of alkali-alkaline fluids interactions with zircon and xenotime-(Y), resulting in element mobilization and disturbance of the geochronological record. In this study, experiments involved a mixture of solids including xenotime-(Y), zircon, albite, sanidine, muscovite, biotite, magnetite, and SiO_2 with different fluids, i.e. 2M KOH, 2M NaOH, 2M $Ca(OH)_2$, $CaCl_2$ + H_2O, that replicated a granitic alkali- and Fe-enriched environment in four Au capsules. Purpose of the experiments was to evaluate the chemical stability of xenotime-(Y) from Datas (Brazil) and zircon from Plešovice (Czech Republic), and effects to their U-Pb age records, in close proximity to each other under 200 MPa, 650 °C, and 7 days utilizing autoclaves at the hydrothermal line.

The xenotime-(Y) and zircon were altered at various degrees in the presence of all used fluids. The experiment with KOH resulted in the lowest degree of xenotime-(Y) and zircon alteration, which includes partial dissolution, developed minor porosity and limited compositional alteration, whereas the U-Pb ages are mostly undisturbed. Experiments with 2M NaOH and 2M $Ca(OH)_2$ resulted in a moderate degree of alteration with well-developed porosity and partial dissolution of xenotime-(Y) and zircon that include compositional alteration, formation of secondary phases at their rims, and partial dissolution of magnetite indicating enrichment of fluid in Fe during the experiments. The U-Pb ages of zircon are significantly disturbed resulting in reverse discordance, where the eldered ages are mostly concordant. Xenotime-(Y) U-Pb ages are mostly undisturbed. The experiment with $CaCl_2$ + H_2O was the most effective considering alteration of the entire mineral assemblage in the capsule. Xenotime-(Y) and zircon are strongly altered, with xenotime partially replaced by secondary britholite-(Y). They both show significantly disturbed U-Pb ages.

The experimental results provide new insights to our understanding of xenotime-(Y) and zircon interactions with alkali- and alkaline-rich fluids that result in moderate to significant alterations. The particular importance is that of the "oldering" of U-Pb ages in compositionally altered zircon, expressed by shifting data along concordia curve, which may be related to the high Fe-content in the system due to dissolution of magnetite.

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Fluid-assisted melting of amphibolites at low-medium pressure in the High-Grade Metamorphic Complex of the Sardinian Variscan Belt (Asinara Island, Italy)

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Partial melting processes during orogenesis can involve a wide variety of protoliths and take place over a wide range of pressure. Petrological studies dealing with partial melting of natural mafic rocks at low-medium pressure are however limited. Amphibolites, amphibolitic gneisses and mafic granulites from the High-Grade Metamorphic Complex (HGMC) of the Asinara Island (Sardinia, Italy), southern Variscan Belt, are a perfect target for studying these processes. In the Punta Scorno area, they occur as lenses and fragments, surrounded by granites and migmatitic metapelites. There are two varieties of amphibolites, one is massive, composed mostly of hornblende, plagioclase and biotite with minor quartz, zoisite, K-feldspar and muscovite, the other is banded and contains grunerite, garnet, plagioclase, hornblende and biotite. Amphibolitic gneisses and mafic granulites have overall the same mineral assemblage as the banded amphibolites but different modal proportions. Evidence of former melt, such as melt pseudomorphs and melt inclusions, is observed in banded amphibolites and amphibolitic gneisses. The mineral chemistry is similar throughout the different lithologies. Plagioclase composition is variable, with $X_{An} = 0.29 – 0.96$. The amphibole occurring as larger crystals is classified as magnesio-/ferrohornblende with variable $X_{Fe} = 0.46 – 0.68$, whereas the one occurring on the grunerite rims is tschermakite with $X_{Fe} = 0.62 – 0.73$. Grunerite has $X_{Fe} = 0.52 – 0.64$. Biotite is also Fe-rich ($X_{Fe} = 0.48 – 0.64$). Si in muscovite reaches 3.10 apfu. Garnet in banded amphibolites is $Alm_{69-72}Grs_{11-14}Prp_{7-9}Sps_{8-10}$, whereas in amphibolitic gneisses is slightly higher in almandine. Pressure-temperature conditions of metamorphism have been preliminarily estimated to be ca. 0.6 GPa and 730ºC with the Ti-in-amphibole thermometer (Liao et al., 2021) and Perple_X program (Connolly, 2005). Such a low melting temperature for a mafic protolith requires that partial melting took place in presence of a water-rich fluid which lowered the solidus of the system (Weinberg & Hasalová, 2015). The occurrence of partially melted amphibolitic rocks, together with granites and metasediments, suggests interactions between mafic and felsic crust. This topic will be the subject of further research, as this study is an introduction to investigations of the processes recorded in the rocks of the HGMC.

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Pyrometamorphism products from coal waste dumps of Nowa Ruda coal district – preliminary studies

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Pyrometamorphism, also known as combustion metamorphism, occurring in burning coal waste dumps (BCMD), is a typical process in many mining regions around the world (e.g., northern France, the Chelyabinsk coal basin in Russia, Silesia in Poland). Most of the research on pyrometamorphic formations in Poland has been conducted within the Upper Silesian coal basin (Parafiniuk & Kruszewski, 2009; Gawęda et al., 2012; Ciesielczuk et al., 2014).

This scientific work is focused on pyrometamorphism products from the Nowa Ruda mining area. Analyzed samples come from three waste dumps: Nowa Ruda 'Miasto' (Piast shaft), Nowa Ruda Słupiec (Nowy shaft), and Przygórze (Bolesław shaft). Thin sections were prepared from selected samples, which were further analyzed under an optical microscope. XRD analyses were performed in the Laboratory of Electron Microscopy, Microanalysis, and X-Ray Diffraction at the Geology Faculty, UW. The samples represent partially thermally altered sedimentary rocks with preserved original texture (Nowa Ruda 'Miasto' and Nowa Ruda Słupiec), as well as paralavas and clinkers (Przygórze). The most interesting samples, in comparison with previous research, seem to be those from Przygórze.

In the case of the Przygórze heap, a complete 'profile' of pyrometamorphic formations can be observed, including pyrometamorphic breccia composed of clasts of thermally altered material bound by ferruginous paralava, clinker, and partially altered rocks located at the edges of the combustion zone. The composition of the clinkers, which are the main element of the altered zones of the Przygórze heap, is quite typical for this lithology type, including quartz, feldspar, tridymite, rutile, and hematite. A distinctive feature, which is a result of the protolith properties, is the presence of porcelainite, a rock with a structure similar to that of man-made porcelain (sample PG-07). This sample is dominated by clay minerals (mainly illite) and mullite ($Al_{4+2x}Si_{2-2x}O_{10}$). The large quantity of clay minerals or products of their thermal transformation is characteristic of products of pyrometamorphism processes in the Przygórze coal waste dump, despite the clearness of local coal.

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Garnet and rutile dating of eclogite records post-peak high-temperature reequilibration in high-pressure Tjeliken lens, Seve Nappe Complex, Caledonides

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We present new geochronological data from eclogite in the Stor Jougdan area (N Jämtland, Sweden), the Tjeliken lens of the Seve Nappe Complex. The rock's peak-pressure metamorphic assemblage consists of garnet, omphacite, phengite, quartz and rutile, with peak metamorphic conditions estimated at ~3.5 GPa and 800 °C (Klonowska et al., 2016). The Lu-Hf isochron yielded an age of 448.6 ± 2.2 Ma. Although the Lu-Hf system in garnet is known for its ability to withstand temperatures as high as 900 °C, Lu diffusion is significantly faster in fine grains, particularly during slow cooling. Consequently, the Lu-Hf closure temperature (Tc) may fall below 700 °C (Ganguly, 2021). This is consistent with the observation that the zonation patterns of both major and trace elements in dated garnet are diffused, most likely the original growth zonation was erased during post-peak high-temperature conditions. Therefore, we interpret the obtained age as that of the post-peak high-temperature overprint. Zr-in-rutile thermometry indicates growth near the peak conditions at temperatures of around 760 ± 20 °C. The weighted average U-Pb age of rutile is 442.2 ± 6.8 Ma, which is slightly lower than the garnet age. However, the Tc of Pb in small rutile grains (<1 mm) is considered to be below 600 °C. Thus, we interpret the U-Pb age of rutile as the age of rock cooling below this temperature.

This interpretation aligns with previous geochronological studies which suggest the peak conditions of eclogite facies metamorphism in the region occurred ca. 460 Ma (e.g., Andersson 2015; Fassmer et al., 2017), while ages of ca. 450 Ma indicate the timing of the final thermal relaxation following high-pressure conditions (Jaranowski et al., 2023) and the onset of cooling.

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Resource potential of hazardous waste incineration bottom ashes: phases composition and metal leachability

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Controlled waste incineration provides substantial volume and mass reduction of the waste feed, disintegration of most of organic pollutants and additional advantages such as heat and energy generation. During the waste incineration metals and metalloids are redistributed into different incineration residues, such as bottom ashes (slags-like particles deposited on the bottom of boiler). Depletion of natural metal resources along with attempts to move into the circular economy model and to mitigate environmental pollution promotes a development of the leaching-based metal extraction from industrial by-products.

Geochemical and mineralogical investigations of bottom ashes from a hazardous waste incineration facility were conducted. Bulk elements composition was obtained by acid digestion coupled with ICP-OES/MS, while SEM-EDS and EPMA were used to understand solid-phase speciation of elements of interest within specific phases.

Elevated bulk concentrations of metals such as Cu (up to 6715 ppm), Ni (up to 8022 ppm), Cr (up to 3598 ppm), Zn (up to 1.36 wt. %), V (up to 2521 ppm) and Mo (up to 1007 ppm) were found in the studied bottom ashes.

Nickel and Cu co-occur with Fe, forming sulfides and metallic particles, but were detected to lesser extent also in Fe oxides. Chromium and Zn are predominantly concentrated in oxides (up to 31.67 wt. % and 11.24 wt. % respectively). Vanadium occurs in silicates and Fe oxides, reaching concentrations up to 1.79 wt.% and 5.76 wt. % respectively. Molybdenum is concentrated within Fe sulfides (up to 0.48 wt. %), metallic Fe (up to 1.55 wt. %) and Fe oxides (up to 1.39 wt. %).

Initial pH-static leaching tests provided insight into leaching properties of bottom ashes. Acidic pH values support extraction of Cu, Ni, V, Cr and Zn, while Mo exhibits better mobility in alkaline range of pH. Based on the results, proper recovery procedures using different leaching agents (either inorganic or organic) should be proposed and evaluated in the future.

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Bacterial-mineral interactions: biohydrometallurgical potential deciphered from black shale bioleaching experiment using dialysis bags

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The activity of microorganisms can substantially affect the features of mineral phases, leading to extensive minerals dissolution coupled with the release of various elements. Although our understanding of microorganisms-mineral interactions has grown over the last few years, many issues remain unsolved. One of them is the exact role of microbial attachment to mineral surfaces and how it affects weathering/leaching processes.

A bioleaching experiment was conducted on copper-bearing black shale using siderophore-producing bacterium *Pseudomonas fluorescens*. To assess the role of microbial attachment two experimental setups were applied:

(I) indirect bioleaching, where dialysis bags separated shale grains from bacterial cells, enabling only dissolution mediated by microbially-secreted compounds and no microbial attachment
(II) direct bioleaching, without dialysis bags, where bacterial attachment was not restricted.

Additionally, different amounts of organic nutrient (succinic acid) were applied, to assess its impact on overall bioleaching efficiency.

The experiment demonstrated higher effectiveness of indirect bioleaching, where bacterial contact with shale was restricted, rather than direct bioleaching. Copper extraction under indirect bioleaching was improved by 9.3–32.9 % compared to direct bioleaching. Furthermore, higher amount of succinic acid promoted overall metal leaching compared to its absence, improving copper extraction by 18.3–43.8 %. However, an intermediate amount of succinic acid had comparable influence on metal leaching as its maximal content with the latter improving leaching effectiveness by only up to 13.5 %.

This experiment emphasizes how biohydrometallurgical process can be optimized by adjusting key parameters such as the growth medium composition (organic nutrient content) or reactor settings (presence or absence of bacteria inside reactor). These adjustments may be crucial for optimizing lab-scale results and upscaling them to industrial applications.

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Lithology and origin of the Hvannhagi Fm., Faroe Islands

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The Faroe Islands represent a unique geological laboratory for studying volcanic and paleoenvironmental processes associated with the opening of the North Atlantic Ocean Rift. The Faroe Islands Basalt Group (FIBG) comprises 7 formations, predominantly basaltic in composition, representing pre-breakup and syn-breakup phases and documenting ~6 Ma of environmental evolution related to the development of the oceanic continental margin (Passey & Jolley, 2009).

Within this framework, the Hvannhagi Fm. constitutes a syn-eruptive unit formed during a phase of reduced volcanic activity within the North Atlantic Igneous Province (NAIP) at the Paleocene–Eocene transition. Unlike the thick basaltic successions that dominate the FIBG, this relatively thin unit provides a rare record of volcanic-sedimentary interactions within a lacustrine–palustrine setting under highly dynamic conditions. To reconstruct its depositional history and lithological variability, 16 rock samples were collected from four outcrops in the Hvannhagi Valley on the island of Suðuroy. Analytical methods included geochemistry, petrographic analysis, X-ray diffraction (XRD) and SEM–EDS.

The results reveal three lithogenetic series. The basal pyroclastic series comprises poorly sorted tuffs and lapillistones with palagonitized basaltic glass, hematite, and zeolite crystallization (analcime, chabazite), reflecting low-temperature alteration under oxidizing conditions. The intervening epiclastic series represents sedimentary deposits, characterized by the absence of glass, zeolites, and hematite, but enriched in smectite group clays and displaying prominent sedimentary structures, indicating deposition in a shallow lacustrine system during a volcanic quiescence. The upper pyroclastic series indicates renewed volcanism, comprising scoria-rich, welded tuffs and lapillistones with glass fragments.Intense zeolitization (analcime, philipsite, thomsonite, natrolite), suggesting higher-temperature hydrothermalalteration and diagenesis.

The facies architecture and alteration patterns reflect complex interactions among phreatomagmatic activity, intense rainfall, and fluctuating hydrological regimes within an isolated archipelago. These findings refine the depositional model of the Hvannhagi Fm. and highlight its significance as a key archive for NAIP volcanism–environment interactions and post-eruptive alteration under subtropical conditions during the Paleocene–Eocene Thermal Maximum (PETM).

The characteristic red coloration of the Hvannhagi Fm. deposits contrasts sharply with the otherwise monotonous landscape of the Faroe Islands. Although, there is no direct evidence of historical use of these sediments as a pigment source, the red sandstones are currently utilized by local artists for ceramic production.

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Reassessing terrane provenance and collision-related metamorphism in the Lapland-Kola Orogen, northeastern Fennoscandian Shield

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The Lapland-Kola Orogen (LKO) is a ca. 800 kilometer-long collisional orogen comprising Paleoproterozoic and late Archean rocks across northernmost Norway, Finland and Russia's Kola peninsula. Since Eskola's classic study of the Lapland granulites (Eskola, 1952), the orogen has provided a natural laboratory for studying Paleoproterozoic orogenesis. Yet, its tectonic setting and the processes that drove heating in the Lapland Granulite Belt (LGB) remain debated (Cagnard et al., 2011). We present new whole-rock geochemistry, zircon U-Pb ages, and Lu-Hf isotope data from igneous intrusions across three key LKO units: the Tanaelv Migmatite Belt (TMB), LGB, and Inari Arc, together with preliminary P-T estimates from LGB metasediments. Across all three units, the intrusions show characteristic arc-type geochemical signatures: Nb-Ta depletion with elevated large ion lithophile element concentrations, consistent with subduction-related magmatism. The igneous intrusions formed between 1962 ± 6 Ma and 1916 ± 9 Ma and were metamorphosed at 1912 ± 3 Ma. Zircon Hf isotope data reveal contrasting crustal sources: Inari and TMB intrusions yield median two-stage model ages of 2.7-2.2 and 3.4-2.3 Ga, indicating derivation from or interaction with Archean substrates, whereas LGB intrusions show no evidence of Archean input. Quartz-in-garnet elastic thermobarometry and Ti-in-biotite thermometry indicate relatively low-pressure, high-temperature peak metamorphic conditions in the LGB. Trace element zoning in garnet differentiates between solid-state prograde growth followed by melt-present growth with oscillatory zonation in phosphorous and finally retrogression of garnet (almandine-rich rims) associated with the growth of retrograde biotite and cordierite. These results imply that the LKO terranes represent arc systems assembled during the ca. 1920-1900 Ma Lapland-Kola Orogeny, with the LGB distinguished by limited crustal inheritance and high-temperature metamorphism.

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Wildfires in the Frasnian: Evidence from Petrography and Geochemistry during the Punctata Event

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Wildfires are now widely recognized as a significant disturbance in Paleozoic ecosystems. This study provides new petrographic and molecular evidence from Frasnian sedimentary successions, specifically targeting the Punctata Event. The analyzed assemblages indicate that the burning vegetation was dominated by higher-plant biomass. This is supported by dimethylphenanthrene ratios, with 1,7-DMP/(1,7-DMP+2,6/3,5-DMP) and (1,7-DMP+2,6/3,5-DMP)/(1,7-DMP+2,6/3,5-DMP+1,2-DMP) values consistently falling within a narrow range of 0.50–0.85, consistent with higher-plant-derived fuels. While 1,7-DMP/1,2-DMP values range from 0.78 to 2.15, indicating predominantly higher-plant input with some minor mixed contributions. Benz[*a*]anthracene-based ratios further support a pyrogenic origin of PAHs; most B*a*A/(B*a*A + Chr) values exceed 0.35, with only a few samples falling below this threshold, suggesting a dominant combustion source. In contrast, B*a*A/(B*a*A + Chr + Trip) values show fewer samples above 0.35, which may reflect occasional mixed contributions or dilution effects from Trip. Cross-plots of (B[*ghi*]Fl + B*a*A)/(B[*ghi*]Fl +B*a*A + Chr + Trip) against 1,7-DMP/(1,7-DMP + 2,6/3.5-DMP) show that most samples fall in the wood combustion fields, with a subset trending toward mixed sources. Wildfire temperatures calculated from fusinite reflectance range from 250 to 695 °C, encompassing ground, surface, and crown fire regimes. In addition, applying the molecular proxy T [°C] = 664× + 117; where x = B[*ghi*]Fl/(B[*ghi*]Fl + B[*a*]A) value (Marynowski et al., 2025) yields estimated temperatures of (129–426 °C). The differences in temperature observed in the reflectance of fusinite and PAHs could be due to fine fusinite particles being transported by wind during crown fires. At the same time, smoke carried PAHs (prevalence of low-molecular-weight PAHs) because the dominant wildfires were low-temperature ground and surface fires. These results provide robust evidence for recurrent wildfire activity during the Punctata Event, highlighting the role of fire in Late Devonian ecosystems and its potential links to climatic and ecological perturbations.

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Various forms of lead nanostructures in experimentally heated zircons

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Taking zircon nanostructures into account is very important for a reliable dating because nano-scale disturbance of the U-Pb isotopic system in zircon ($ZrSiO_4$) has an influence on U-Pb geochronology. The process of Pb mobilization leading to the formation of metallic Pb nanospheres has been documented in ancient zircons from the Napier Complex (East Antarctica, Kerala Khondalite Belt (Southern India), Jack Hills (Western Australia) and the Acasta Gneiss Complex (Northwestern Canada). Pb oxide nanoclusters have been discovered in seismically deformed zircons from Ivrea-Verbano Zone (Northern Italy).

To understand the process of Pb nanostructure formation, heating experiments with zircons were performed. For these experiments zircon grains from a Cambro-Ordovician orthogneiss (the Central Iberian Zone, Spain) were selected. Zircons were heated at 1400 °C for 30, 90 and 180 days in a horizontal furnace at 1 atm.

The analyses of the nanostructure of zircon were performed using Transmission Electron Microscopy (TEM) and mobilization of Pb was documented in > 2.2 Ga inherited cores of zircons. Nanostructures containing Pb in different oxidation states: Pb^0, Pb^{2+} and Pb^{4+} were observed. In pristine zircons only metallic Pb nanospheres have been found. During the heating process, Pb in nanospheres was oxidized, and after 30 and 90 days of heating zircon grains, metallic Pb nanospheres co-existed with Pb oxides: PbO, Pb_3O_4 and Pb_2O_3. Additionally, PbO_2 was present in only one specimen. After 180 days of zircon heating, no more metallic Pb nanospheres occured, only nanoinclusions of Pb oxides were present. The occurrence of Pb nanostructures was observed in the presence of other inclusions (e.g., feldspars) in zircon, what might be an important factor for Pb oxidation during heating.

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In situ Rb/Sr and K/Ca mica geochronology of the Mosselhalvøya Group, West Ny-Friesland Terrane, Svalbard

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The Svalbard Archipelago is a composite of terranes that were assembled during the Caledonian Orogeny. *In-situ* mica Rb/Sr and K/Ca geochronology was performed on four rocks in the Mosselhalvøya Group of the West Ny-Friesland Terrane to constrain the timing of its juxtaposition against the Nordaustlandet Terrane along the Eolussletta Shear Zone, forming the terrane boundary. The rocks comprise garnet micaschists, micaschist and metagranitoid, and were sampled along an E-W transect through the northern part of Mosselhalvøya Peninsula. The variably dipping prograde foliation in the rocks is overprinted by a N-S trending, pervasive secondary foliation that becomes more prevalent eastward towards the Eolussletta Shear Zone.

The *in-situ* Rb/Sr and K/Ca geochronology was performed on biotite and white mica highlighting both metamorphic fabrics. The calculated Rb/Sr isochron dates of muscovite in all four samples are at ca. 420-400 Ma. For two samples, the Rb/Sr isochron dates of biotite were calculated and yielded 419 ± 12 Ma and 408 ± 5 Ma. K/Ca white mica geochronology was performed on two samples from the western part of the Mosselhalvøya Group, where grain size allowed the analysis. Both samples yielded identical K/Ca inverse isochron dates of 480 ± 4 Ma. The obtained results suggest that the Rb/Sr system in white mica was completely reset at ca. 420-410 Ma, which can be interpreted as the age of strike-slip motion along the Eolusletta Shear Zone. The ca. 480 Ma K/Ca ages of white mica may reflect an early prograde metamorphic event, as they predate garnet growth at ca. 444 Ma, constrained by monazite geochronology (Bazarnik et al., 2023).

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Automated mineralogy application (TIMA system) in exploration and economic geology – examples from Polish targets and deposits

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Automated mineralogy techniques have been developed intensively in recent decades, including technical and software improvements. It is a very fast and robust method utilized by both academia and industry in many stages along the value chain of the mineral raw materials. During mineral exploration it is used for fast and thorough rock characterization (ore minerals identification, mineral associations-alterations, visualization of textures and structures, etc.), in active mines for ore quality control and recognition of mineralogy and chemistry of the newly developed part of the deposits, during mineral processing stage it is indispensable as grain size and shape, mineral liberation, mineralogy and chemistry of a large set of samples can be measured in a very fast and efficient way.

The TIMA automated mineralogy system is used at AGH University of Krakow in cooperation with the TESCAN company since 2020. It has been employed in several EU founded projects (EIT RM MinExTarget, Horizon Europe AVANTIS), internal research projects, and student master thesis. A few conclusions from those projects are presented here.

Analyses of the Heavy Mineral Concentrates (HMC) from recent river sediments from the Karkonosze Izera Massif were tested as a tool for tracking tin mineralization. Fast samples scanning allowed to identify the mineral composition of HMC, which helps with cassiterite grain selection for further EMPA and LA-ICP-MS analyses. A brief interpretation of the rutile chemistry confirmed several rutile generations. Analyses of size and shape of selected heavy minerals help with interpretations of sources and transportation patterns.

The processing of the Fe-Ti-V ores from Krzemianka deposit is demanding and one of the reason why the deposit is currently considered uneconomic. Application of the TIMA system for the analyses of the products of the selective fragmentation of the Krzemianka ore allowed to quantify how efficient each technique (e.g., Selfrag, HPGR) is and to track the element deportment. The data illustrates in very simple way mineral liberation and size of the fragmented ore, that helps to choose the most efficient method of fragmentation (included mineral liberation ratio, energy efficiency, etc.).

Besides many advantages of this method the most important conclusion is that the quality of the obtained data highly depend on data interpretation and in this sense the process of data acquisition is “automated” but the quality of the result is highly depend on the skills and the experience of the operator.

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30th Meeting of the Petrology Group of the Mineralogical Society of Poland

Field trip guide

An open-pit mine of Upper Triassic Keuper clays in Patoka (northern Lubliniec district; photo: P. Wojtulek).

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Pre-conference field trip:
The Częstochowa ore-bearing region: Jurassic sedimentary iron deposits

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The Cracow – Silesia Monocline and the Ore-Bearing Clay Formation

The Cracow-Silesia Monocline is part of the Polish Basin, which stretched from NW to SE during the Mesozoic (Feldman-Olszewska, 1997). This basin was covered by a sea during the Jurassic and subjected to intensive sedimentation. The marine sedimentary successions in this area reach a thickness of 300 m in the distal parts of the basin to about 1 km in the central part, the Mid-Polish Trough (Dayczak-Calikowska, 1997). Sedimentation began with a marine transgression related to the Tethys Ocean in the late Aalenian (Dayczak-Calikowska, 1997). The sediments of the Cracow-Silesia Monocline (Lower, Middle, and Upper Jurassic) constitute the southern part of the Polish Basin and currently dip in the NE direction. The Lower Jurassic is characterized by sandy and mudstone deposits, the Middle Jurassic is dominated by thick clay deposits known as the Ore-Bearing Clay Formation (Matyja and Wierzbowski, 2000 and references therein), while the Upper Jurassic is marked by the presence of thick sequences of marine organogenic limestones (Leonowicz, 2016 and references therein).

The Ore-Bearing Clay Formation is a lithostratigraphic unit with a Late Bajocian (*Garantiana* ammonite zone) to Late Bathonian (*Discus* ammonite zone: Leonowicz, 2015) age. The sediments of this formation were deposited in the marginal, shallow part of the sea that covered the Polish Basin during the Jurassic. This area shows 7 transgressive-regressive cycles, which resulted in the deposition of very fine-grained clay material (Feldman-Olszewska, 1997). Iron-rich rocks (spherulitic and/or bedded siderites) form horizons within the clay succession of the Ore-Bearing Clay Formation were historically mined for iron production.

The Częstochowa Ore-Bearing Region

The Częstochowa region is the largest area of occurrence and former exploitation of siderite rocks within the Jurassic formations, besides the Holy Cross Mountains and Łęczyca regions (Maliszewska et al., 2018). Jurassic rocks containing siderite deposits are also found in the West Pomerania region, known from boreholes carried out near Kamień Pomorski (Dayczak-Calikowska, 1959). The last siderite iron ore mine in the Częstochowa region, Wręczyca, was closed on June 30, 1982, due to a decision by the authorities of the Polish People's Republic. This decision was dictated by the transition to iron and steel production in Polish smelters based on BIF-type ores from the Zaporizhzhia Basin in Ukraine. In total, 46 million tons of ore were extracted in the Częstochowa Basin between 1945 and 1982, while the remaining unexploited resources are estimated at 426 million tons (Fig. 1; Adamski, 1994).

The Częstochowa region covered 27 deposits. It is a zone about 130 km long and up to 20 km wide, extending from the vicinity of Zawiercie to Wieluń. The siderite rocks in this area are associated with the middle period of the Mesozoic Era (Middle Jurassic, Bathonian - formerly known as Dogger). The ore occurs in two forms: as spherulitic siderite (oval concretions with an iron content of up to 41 % Fe) and as bedded ore, which was the main wealth of the Częstochowa deposits, with an average thickness of 0.15 – 0.35 m and a content of up to 33 % Fe. The ore substance in both cases is iron carbonate ($FeCO_3$), mixed with clay minerals and carbonates of calcium, magnesium, and quartz. The ores were extracted by deep mining, for which mining shafts and galleries were drilled. The largest and most modern mine at that time, *Szczekaczka*, located near the village of Wrzosowa near Częstochowa, had a mining shaft with a depth of 73 m. It was one of the deepest operating mining facilities in the Częstochowa region.

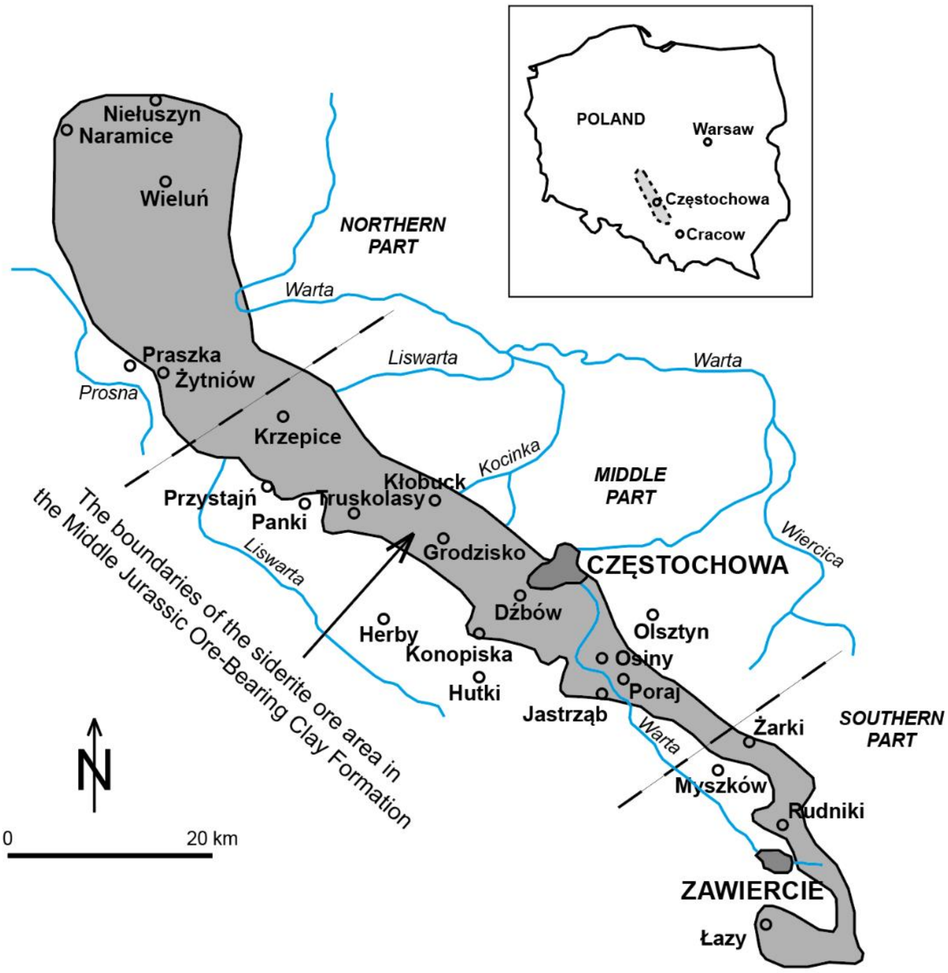

Figure 1. Schematic map of the distribution of Ore-Bearing Clay Formation rocks containing siderite ores in the vicinity of Częstochowa (central Poland). Modified from Adamski (1994).

Iron ores are found at three levels (Fig. 2; Adamski, 1994):

- The **roof level** is the highest and most often consists of two ore beds with a thickness of up to 15 cm (C level in Fig. 2);
- The **middle level** occurs at a depth of 30 – 50 meters below the roof level. It is characterized by variable thickness, and usually, 3 levels of ore beds be distinguished within it (B level in Fig. 2);
- The **bottom level**, the most important from a mining perspective, lies at a depth of 75 m below the middle level. It consists of several ore beds with a thickness of up to 0.4 m (A level in Fig. 2).

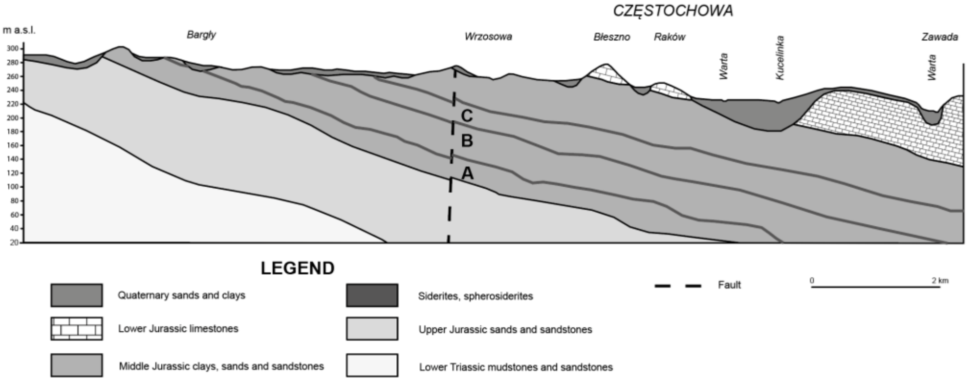

Figure 2. Schematic geological cross-section through the Częstochowa area showing the geological position of the siderite and spherosiderite levels (modified from Nowe Przedsiębiorstwo Geologiczne w Częstochowie, published in Muzeum Górnictwa Rud Żelaza. Przewodnik do wystawy stałej. Częstochowa 2009).

Stop no.1 – Gnaszyn Open-Pit Clay Mine

(50.79913°, 19.04571°)

The *Gnaszyn* open-pit clay mine is located in the SW part of the city of Częstochowa. Mining has been carried out here since the 1940s. The mine is currently owned by the *Wienerberger* Group, and the clay rocks extracted here are used for brick production. The Gnaszyn mine is currently the best location to find relatively fresh outcrops of siderite rocks.

The *Gnaszyn* open-pit mine is located within relatively monotonous Middle Jurassic sediments, including the upper part of the rock formations of the Ore-Bearing Clay Formation, dating from the Lower to Middle Bathonian (Gedl and Kaim, 2012). These deposits are represented by dark gray, calcareous mudstones (classified as silty claystones and clayey siltstones) with six main horizons of siderite concretions (Fig. 3; Leonowicz, 2012). The clay rocks primarily contain illite and kaolinite (approximately 20 and 10 wt. % of clay minerals, respectively), as well as minor amounts of chlorite and glauconite. The mineral composition of these sediments is uniform throughout the succession, and they also contain quartz, potassium feldspar, calcite, gypsum, and anhydrite (Dudek, 2012). The clay rocks of Gnaszyn are rich in fossils of Jurassic fauna, including ammonites, belemnites, bivalves, and small gastropods (Leonowicz, 2012).

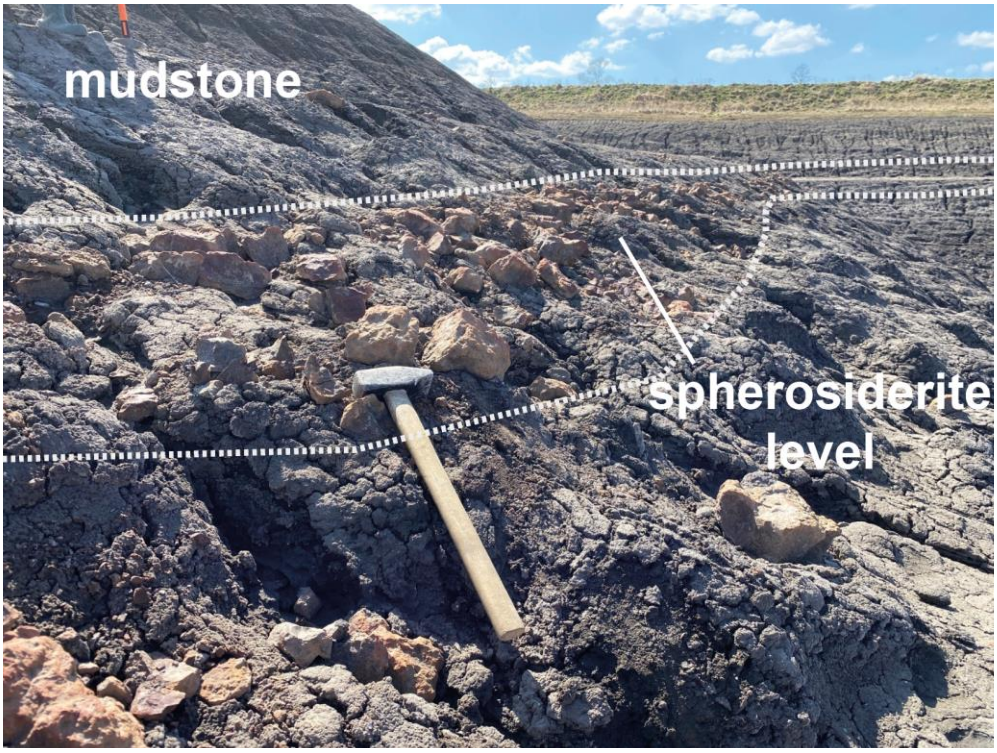

Figure 3. Spherosiderite level within mudstone succession in the Gnaszyn clay-pit.

The succession of clay rocks in Gnaszyn, although seemingly monotonous, records numerous changes in the paleoenvironment. It was formed in a coastal environment with an intense supply of terrestrial material. The depositional conditions in this environment varied, partly due to fluctuations in sea level, which in turn caused changes in salinity and nutrient availability (Gedl et al., 2012). The relatively rapid accumulation of sediments led to oxygen-depleted conditions, which favored the deposition of organic matter remains.

The spherulitic siderite concretions in Gnaszyn can be divided into two types: (1) sideritic and (2) phosphate-siderite concretions. These concretions vary in size and shape, from small (up to several cm in diameter) to large (up to 60 cm in length), and can be ellipsoidal, round, spheroidal, or flattened. They often show septarian structures. The concretions within a single horizon show similarities in their mineral composition and the fossils they contain. The first type of concretion is dominated by siderite, while the second type contains apatite in addition to siderite. The concretions, beside clays, are rich in detrital minerals: quartz, feldspar, muscovite, and calcite (Fig. 4; Witkowska, 2012). A characteristic feature is the presence of terrestrial organic matter remains (wood; Marynowski et al., 2007) within them, typical of type III kerogen (Lis et al., 2022). The presence of this matter contributed to the formation of local anoxic conditions, a process associated with microbial activity. The activity of microorganisms in reducing iron and/or sulphates became the dominant biodegradation reaction, introducing Fe^{2+} and HCO^{3-} ions into the system. Negative $\delta^{13}C$ values in the cortex of the analyzed concretions indicate that the bicarbonate consumed in siderite precipitation was supplied by this microbial activity. The reducing microenvironments that developed in the sediment and wood fragments acted as nucleation sites for siderite precipitation (Lis et al., 2022).

The spherulitic siderite concretions in Gnaszyn also contain numerous sulfide minerals: pyrite, marcasite, sphalerite (usually rich in iron), and galena. The ore minerals occur in the siderite matrix, in cracks that are either unfilled or filled with calcite. The iron, zinc, and lead that make up the ore minerals in the Gnaszyn spherulites came from the surrounding clay rocks.

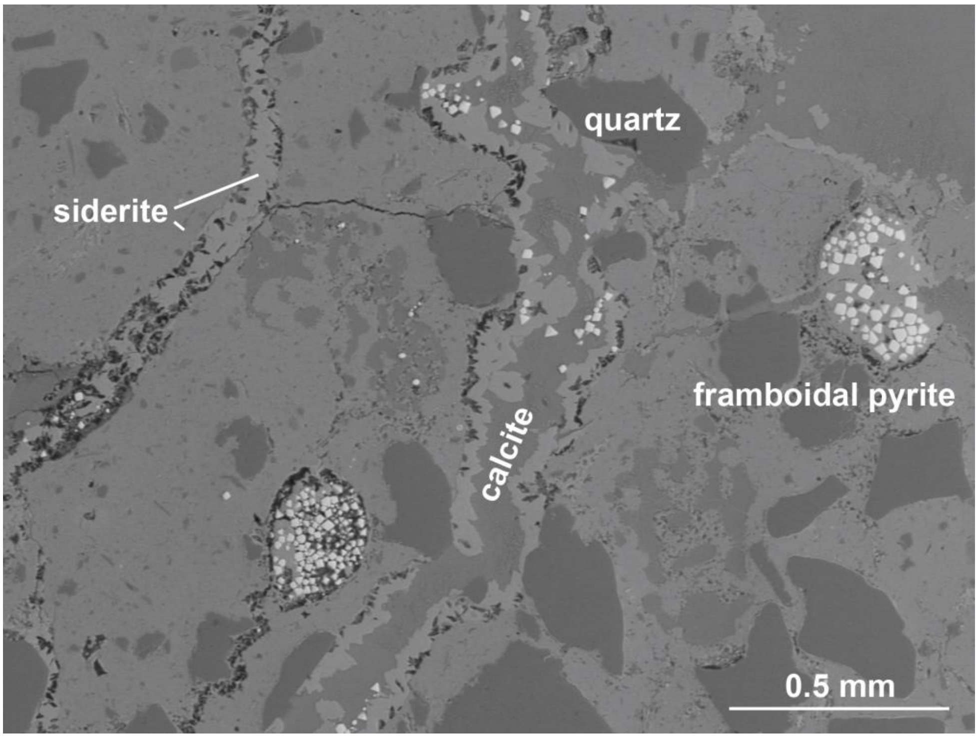

Figure 4. Spherosiderite in the BSE image, showing the presence of various types of carbonates, detrital grains and probably syngenetic pyrite.

Stop no.2 – The Museum of Iron Ore Mining in Częstochowa

(50.81098°, 19.10031°)

The Museum of Iron Ore Mining was created in underground tunnels drilled between 1974 and 1976 in Stanisław Staszic Park in Częstochowa. The museum first opened in 1980 at the *Szczekaczka* mine in the Poczesna near Częstochowa commune. The museum was inspired by the government's decision to close the siderite iron ore mining plants in the Częstochowa region (the siderite mine in Łęczyca, in the Łódź Voivodeship in central Poland, survived longer, until 1989). Difficulties in maintaining the exhibition at the former *Szczekaczka* mine, including problems with dewatering the shafts, led to the exhibition being moved near Jasna Góra, the medieval monastery of the Pauline Fathers in Częstochowa, where new corridors were prepared for this purpose in the limestone rock.

The museum's exhibition presents original exhibits from the iron ore mines of the Częstochowa region, particularly from the liquidated *Szczekaczka* mine. Original supports from this mine were used to reinforce the ceilings of the workings. Visitors can also see pumps used for dewatering the workings, as well as railway rolling stock and tracks.

The exhibition is divided into three parts. The first part covers the geology of the Częstochowa Iron Ore Basin. It presents the types of iron ores mined in the region (Fig. 5), a geological cross-section through the iron ore deposits, and the fossil assemblages found in the former siderite mines. It also discusses the geological conditions of mining operations, including the thickness of the exploited seams.

The second part is dedicated to the construction of the workings, including their safety and the transport system used in the mines. This section explains the methods of mining operations, from the extraction of the mineral at the working face to its transport from the face to the shaft or transport incline.

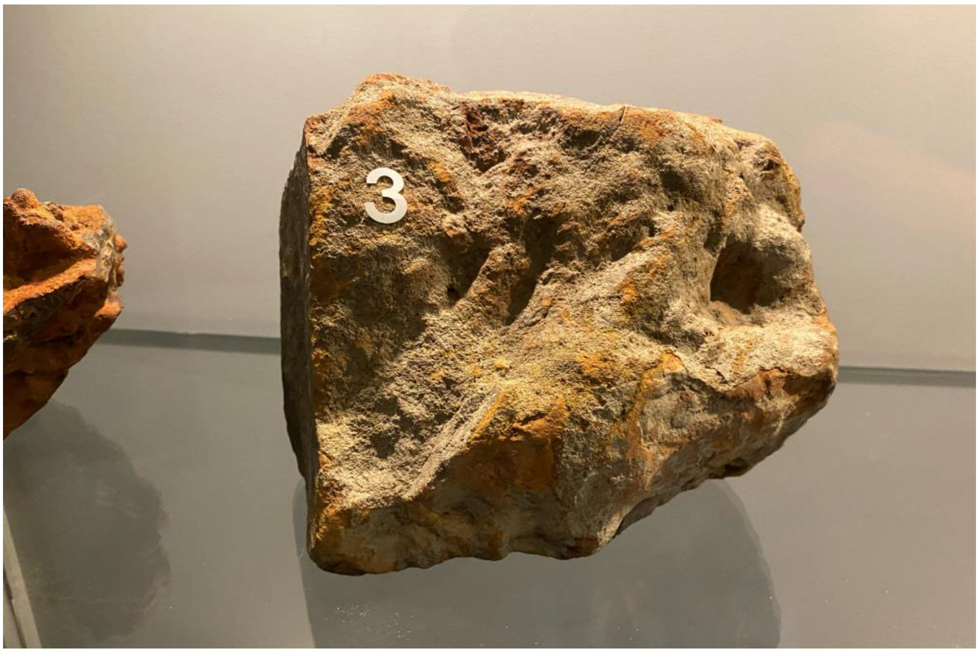

Figure 5. A sample of bedded siderite ore from the Szczekaczka iron ore mine, exhibited at the Museum of Iron Ore Mining in Częstochowa.

In the third part, visitors can learn about the old methods of obtaining iron ore, especially those from the pre-industrial era (for example, the construction of wells with windlasses), and the changes in ore exploitation styles associated with the development of mining technology. The exhibition presents a rich collection of pumps used for dewatering the workings. A separate part of the exhibition is dedicated to the systems for protecting miners from mining hazards, particularly the oxygen apparatuses used in the past.

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Post-conference field trip:
MVT Pb-Zn-Ag deposits of Upper Silesia and Małopolska in the Tarnowskie Góry region

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The Cracow – Silesian Monocline and MVT Pb-Zn Deposits: General Characteristics

The lead-zinc deposits of the Silesian and Małopolska regions are hosted within the Triassic carbonate rocks of the Kraków – Silesian Monocline (to a lesser extent also in the surrounding Devonian rocks and small veins found in Jurassic carbonates – Sutley et al., 1999). This monocline is composed of various Triassic and Jurassic units, and it overlies the northern part of the Moravian-Silesian fold belt, the northern and NE parts of the Upper Silesian Basin, the Kraków – Lubliniec Fault Zone, and the SW margin of the Małopolska Block (Żelaźniewicz, 2011). The monocline's basement is highly tectonized: the main system of faults, extending in a NW-SE direction and known as the Kraków-Lubliniec Fault Zone, is part of a larger, transcontinental Hamburg-Kraków Fault Zone (Dadlez, 1994). It is accompanied by local fracture zones: the Tarnowskie Góry fault zone and the Upper Silesian fault (Morawska, 1997). Among the Triassic sediments of the Kraków-Silesian Monocline, a complex of clastic rocks associated with a terrestrial environment (sandstones, conglomerates, claystones) of Upper Triassic age (formerly known as *Buntsandstein*) is distinguished, along with a complex of Middle Triassic carbonate rocks (formerly known as *Muschelkalk*), and a complex of Upper Triassic terrestrial sediments consisting of land-based mudstones formed in a swamp environment, together with the Woźniki palustrine limestones. The thickness of the Middle Triassic carbonate sediments in the Pb-Zn ore district is approximately 200-400 m. These carbonates are limestones and early diagenetic dolostones deposited in a shallow marine environment (Sass-Gustkiewicz & Dżułyński, 1998; Sutley et al., 1999).

Host Rocks and Ore Bodies

Within the Middle Triassic carbonate rocks of the Kraków-Silesian Monocline: the Gogolin, Górażdże, Karchowice, and Boruszowice formations are identified, as well as the *terebratulida* and *diplopora* limestone units (Bogacz et al., 1972; Kowal-Linka, 2008). The primary host rock for the Pb-Zn ore minerals is ore-bearing dolomite. The dolomitic rocks within the Kraków-Silesian Monocline occur within unaltered Triassic limestones and were formed at their expense through dolomitization processes that took place during the Triassic period (Sass-Gustkiewicz & Dżułyński, 1998). This process is considered to have preceded the formation of the Pb-Zn ores within the dolomite.

The ore bodies are tabular, lenticular, or nestlike (Sutley et al., 1996). They contain the following ore minerals: sphalerite, galena, marcasite, pyrite, and in smaller quantities, wurtzite and rare Pb-sulfosalts. The gangue minerals co-occurring with the Pb-Zn ores are dolomite, calcite, clays, and barite. It is emphasized that the crystallization process of the Pb-Zn ore bodies was related to the creation of spaces for the migration of metal-bearing fluids resulted from the formation of karst voids, which may have occurred during the initial introduction of ore-forming fluids but prior to the deposition of sulfides (Leach et al., 1996).

Mineralization and Age

The formation of MVT-type ore mineralization was a multi-stage process, though two main ore-forming stages can be distinguished (Fig. 1). The first stage involved the precipitation of the first generation of galena (Gn1), followed by light and dark brown varieties of sphalerite (Sph1) exhibiting a colloform texture, and the second generation of galena (Gn2). The second stage involved the formation of pyrite and marcasite in conjunction with the second generation of dark brown sphalerite (Sph2) and the third generation of galena (Gn3; simplified after Viets et al., 1996). Fluid inclusion temperatures measured for the Upper Silesian Zn-Pb sulfide ores range from 45 to 130 °C (Kozłowski et al., 1980).

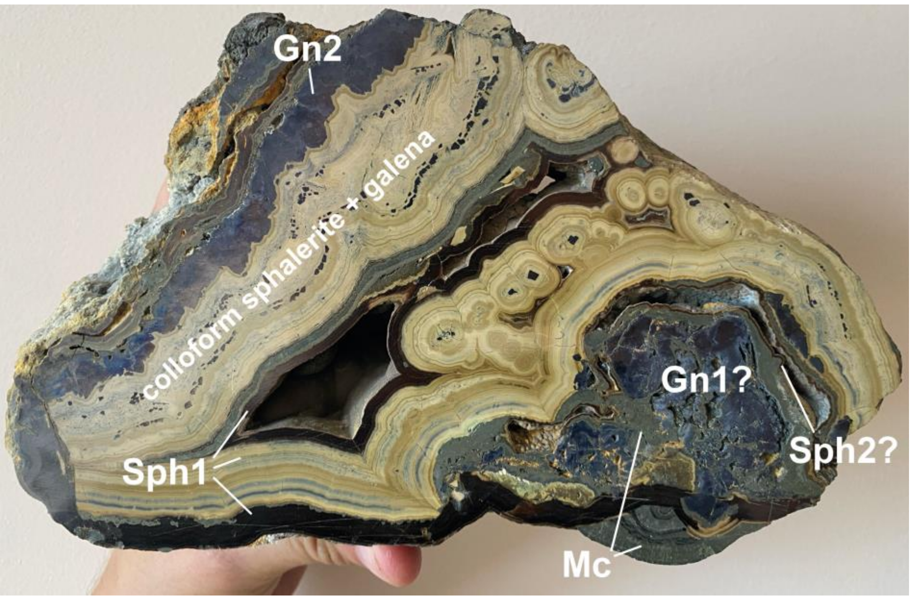

Figure 1. Typical MVT Pb-Zn ore from the Pomorzany mine in Bukowno with various generations of ore minerals.

There is a lack of data that unambiguously points to the age of the ore mineralization of the MVT deposits of the Kraków-Silesian Monocline (Mikulski et al., 2020). However, considering the general genesis of MVT deposits, which form in the forelands of developing orogens, some researchers suggest a possible coincidence between the formation of Pb-Zn mineralization in the Silesian – Małopolska region with intense closing stages of the Alpine orogeny in the Carpathian orogenic belt (Leach et al., 2001). Following this, Symons et al. (1995) proposed a mid-Tertiary age (currently Oligocene/Miocene) for ore deposition, coinciding with the closing stages of the Carpathian orogeny. In this stage, the uplift of the orogenic belt influenced the contractional deformation of the foreland of the orogenic belt. The flysch rocks of the Carpathians are mentioned as the source of the fluids (Symons et al., 1995; Leach et al., 2001).

MVT Lead-Zinc Mining in the Silesian and Małopolska Regions

The MVT lead-zinc deposits of the Kraków-Silesian Monocline are found in four distinct regions: (1) the western region, encompassing the areas around Tarnowskie Góry and Bytom; (2) the southern region, around Trzebinia and Chrzanów; (3) the eastern region, near Olkusz and Bukowno; and (4) the northeastern region, in the Zawiercie area (Fig. 2).

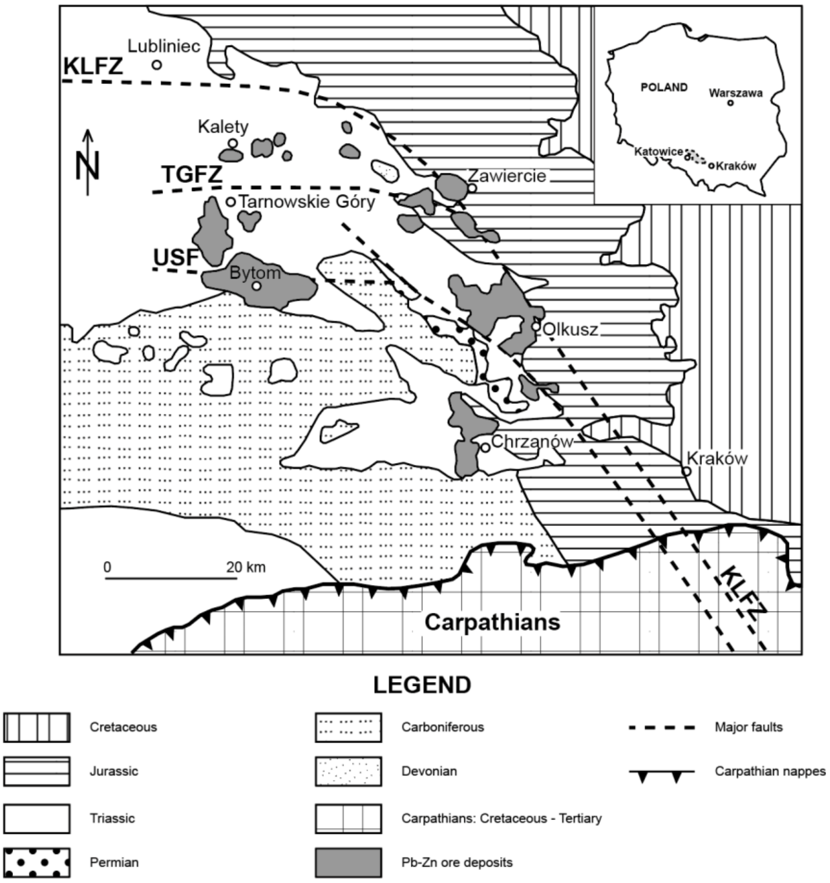

Figure 2. Distribution of the Upper Silesian Zn-Pb stratabound ores related to major Palaeozoic fracture zones in schematic geological map without Quaternary cover (based on Sass-Gustkiewicz and Dżułyński, 1998). KLFZ – Kraków – Lubliniec Fault Zone, TGFZ – Tarnowskie Góry Fault Zone, USF – Upper Silesian Fault

Mining for these ores, initially exclusively for lead, has a long tradition in these regions, likely dating back at least 1,000 years. A papal bull from 1136 mentioned the mining of these ores in the Bytom area for silver extraction. Furthermore, the exploration for lead and silver in the Silesian-Małopolska area was the subject of the first mining exploration license granted in Poland by King Casimir IV Jagiellon in 1448. The exploitation of Pb-Zn deposits in the Silesian-Kraków area intensified during the industrial era especially with the discovery of the element zinc and its increasingly widespread use. Mining operations extracted both sulfide zinc ores (sphalerite) and oxidized ores, known as "galmans" (a mixture of smithsonite – $ZnCO_3$ – and hemimorphite – $Zn_4[(OH)_2/Si_2O_7]xH_2O$).

The decline of zinc and lead mining in Poland occurred in three stages:

1. Just before the political transformation in 1990, the last zinc and lead mines in the western region were closed, including the Orzeł Biały mine in Piekary Śląskie.
2. In 2013, the Trzebionka mining plant (southern region) was liquidated.
3. In 2020, the last Polish zinc and lead mine, Pomorzany (eastern region), ceased operations.

Currently, the northeastern region (Zawiercie area) is considered to be a prospective area for MVT-type Pb-Zn ores in Poland; however, a mine has not been constructed there for economic and social reasons.

Stop no.1 – *Frederic* Lead and Silver Ore Mine in Tarnowskie Góry

(50.42602°, 18.84955°)

The Tarnowskie Góry deposit area includes the vicinities of Tarnowskie Góry, Miasteczko Śląskie, and Kalety. In this area, the ore mineralization is represented by lead sulfide ores and oxidized zinc ores, known as galmans. Zinc sulfide ores are not present here, except for small deposits in the northern part of the area (Miotek and Bibiela deposits). The main exploited mineral in the Tarnowskie Góry region was galena, with a silver content reaching up to 1.2 wt. %. Some deposits in the region show only Fe mineralization (Fig. 3; Żeglicki, 1996).

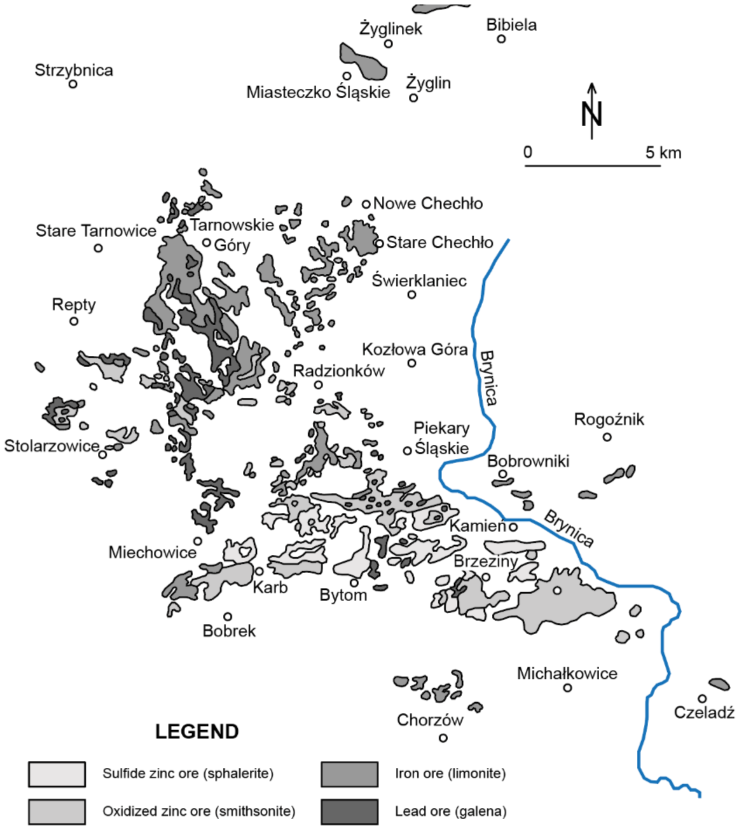

Figure 3. Distribution of Pb-Zn-Fe ores of the Tarnowskie Góry and Bytom region (based on Żeglicki, 1996).

The exploitation of lead and silver ores in the Tarnowskie Góry region dates to the Middle Ages. The development of mining in this area was made possible by a special mining ordinance issued by the Duke of Opole, Jan Dobry, in 1528, which regulated mining activities. In the 19th century, the exploitation of galman also began for zinc extraction. The most intensive period of mining in the Tarnowskie Góry region was the 19th century, after which local deposit resources began to be depleted rapidly. The local lead and silver ore mine, *Frederic,* established in 1784 by the Prussian government, was closed in 1912.

The Tarnowskie Góry region was known not only for the extraction of lead and silver ores but also for their host rock: the ore-bearing dolomite. The largest open-pit mine by area for extracting dolomite in the Tarnowskie Góry region was the Bobrowniki mine, located on the border of Tarnowskie Góry and Bytom, which was closed in 1998. The rocks that can be found in the underground *Frederic* mine in Tarnowskie Góry are ore-bearing dolomite, limestones, and clayey rocks containing iron minerals. The transitions between these lithologies and galena veins within the ore-bearing dolomite can be observed on the walls near the *Szczęść Boże* shaft (Fig. 4; Żeglicki, 1996). The ore bodies were located in the marginal parts of the so-called Tarnowskie Góry basin and thinned out towards its center. The lead and silver ores were also accompanied by rich limonite-type iron ores, consisting of iron oxides and hydroxides.

Among the minerals found in the Tarnowskie Góry region that form inclusions within galena, argentite [Ag_2S], freibergite [$(Ag,Cu,Fe)_{12}(Sb,As)_4S_{13}$], and stephanite [$Ag_5SbS_4$] may be also distinguished. Carbonate rocks contain also secondary lead minerals: anglesite [$PbSO_4$] and cerussite [$PbCO_3$]. A great mineralogical curiosity of the Tarnowskie Góry region was tarnowicite, formerly considered a mineral with the formula [$(Ca,Pb)CO_3$], which is aragonite containing an admixture of cerussite. The name for this former mineral was coined by A. Breithaupt, and its holotype was deposited in the Mineralogical Museum of the University of Wrocław. Tarnowicite is currently considered to be a variety of aragonite.

Figure 4. A typical excavation in the Frederic Pb-Ag ore mine in Tarnowskie Góry. Ore-bearing dolomite and galena veins are visible on the sides.

Stop no.2 – Washing Plant Spoil Heap

(50.41612°, 18.85449°)

The washing plant spoil heap, located in the southern part of Tarnowskie Góry, is a deposit of dolomite waste created during the operation of the underground *Frederic* Pb-Ag ore mine. This heap is 17 meters high and covers an area of 6.77 hectares. It is a protected reserve and, along with other mining sites in the region, was inscribed on the UNESCO list in 2017.

The deposition of post-mining waste at this site began in the 1830s, when a processing plant was built nearby for the ores extracted from the *Frederic* mine. The plant was designed by Rudolf von Carnall, a well-known local geologist who also authored the first geological map of Upper Silesia. Waste deposition here ceased with the closure of the Frederic mine in 1912.

As an anthropogenic object, the spoil heap is a subject of study regarding the environmental impact of zinc, iron, and lead mining waste. The heap has developed characteristic galman grasslands, which are overgrown by species of plants resistant to high concentrations of heavy metals in the soil (especially zinc and lead). These plants cover the northern part of the heap and include species like the calamine violet (*Viola calaminaria*) and large thyme (*Thymus pulegioides*). These native plants are primarily threatened by invasive species, mainly Japanese knotweed (*Reynoutria japonica*) and Canadian goldenrod (*Solidago canadensis*).

Stop no.3 – Dolomite quarry in Bobrowniki

(50.41622°, 18.86126°)

The dolomite quarry in Bobrowniki, a southern district of Tarnowskie Góry, is a significant site measuring 700 m in length, 500 m in width, and with a maximum depth of up to 50 m. Exploitation at the quarry was carried out between 1903 and 1998. Initially, iron ores were mined here, and after their depletion, dolomite extraction began. A remnant of the original ore mining is an excavation from the former underground iron mine, visible in one of the quarry walls.

In the quarry, ore-bearing dolomites and diplopora dolomites are exposed, and locally (in the northeastern part of the quarry), bright marly dolomites of the Tarnowice beds (Middle Triassic) are also visible. The ore-bearing dolomites are exposed primarily in the southern part of the quarry, and are locally mineralized with Zn, Pb, and Fe compounds. The *diplopora* dolomites, which form the main part of the exposed quarry walls, lie on top of the ore-bearing dolomites. The Triassic fauna is represented mainly by brachiopods, gastropods, bivalves, and crinoids. Fragments of reptile bones also occur sporadically.

Figure 5. The southern wall of the dolomite quarry in Bobrowniki, revealing the ore-bearing dolomite and *diplopora* dolomite.

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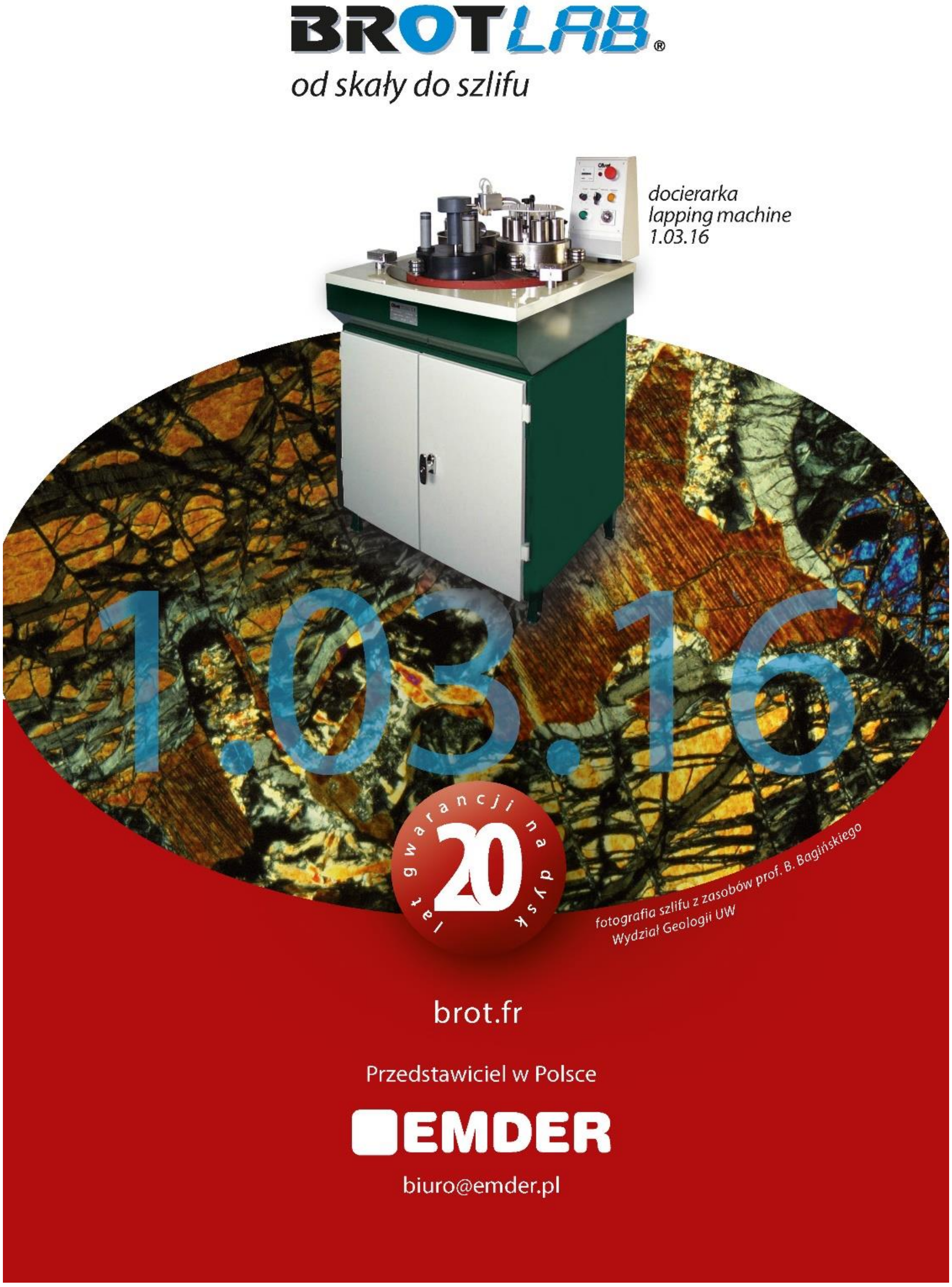

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Unlocking Value through Process Mineralogy: TIMA-powered Automated Characterisation of Raw Materials

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The TESCAN TIMA automated mineral characterization system has been widely adopted in geometallurgy and applied mineralogy over the past decade. This contribution outlines the measurements that support metallurgical assessment—modal mineralogy, grain-size distributions, liberation and association, textural classes, and elemental deportment—and explains how analyzing large particle populations at micron-scale resolution reduces uncertainty. Brief case studies will show how TIMA data locate value carriers, identify locking and penalty phases, and quantify loss pathways to tails, supporting options from exploration through plant optimization, including stockpiles and legacy tailings. Emphasis is on practical integration: outputs used as a common language between geology and metallurgy, and correlative workflows linking TIMA data with LA-ICP-MS, EPMA/microprobe, cathodoluminescence, and Raman to produce reproducible, decision-ready interpretations. Applied early in project development, TIMA-based mineral characterization provides rapid, repeatable evidence that reduces risk, compresses schedules, and focuses effort on critical elements and domains.