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„Rhyolite – Rock of the Year 2026”

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31st Meeting of the Petrology Group of the Mineralogical Society of Poland

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of the Mineralogical Society of Poland



Krotoszyce Palace – the venue of the 31st Meeting of the Petrology Group
of the Mineralogical Society of Poland

Ladies and Gentlemen,

It is my great pleasure to present the 54th volume of Mineralogia Special Papers, which brings together the abstracts presented at the 31st Meeting of the Petrology Group of the Mineralogical Society of Poland. The contributions gathered here reflect the diversity of our research, spanning petrology, mineralogy, and geochemistry and taking us from the rocks beneath our feet to Mars and beyond.

The abstracts collected in this volume reflect the broad scope of the meeting and are organized around three main themes. Foremost among them is ***Rhyolite: Rock of the Year 2026****, focusing on rhyolitic rocks and the diverse processes involved in their generation, evolution, emplacement, and alteration. The contributions highlight why rhyolite is fascinating from multiple perspectives: rhyolitic magmatism is associated with climatically significant eruptions, important mineral resources, and key records of the magmatic processes involved in the evolution of the continental crust. Moreover, rhyolitic supereruptions capture the imagination and provide a powerful gateway for public engagement with Earth sciences.*

The second theme, ***Mantle Fascinations****, celebrates the 70th birthday of Jacek Puziewicz, founder of the Petrology Section, who has devoted a large part of his scientific career to the study of the mantle and mantle xenoliths. The session brings together contributions inspired by research on the mantle and mantle-derived rocks. These two thematic sessions are complemented by a General Session, reflecting the broad scope of contemporary mineralogical and petrological research, with contributions ranging from metamorphism and magmatic processes to environmental mineralogy.*

I hope that the contributions collected in this volume will stimulate lively discussions, exchange of ideas, and new scientific collaborations. Above all, I hope that the meeting will provide an enjoyable opportunity to share our fascination with rocks and minerals, meet old friends, make new ones, and spend a few inspiring days together.

Yours truly,
Anna Pietranik

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Marek AWDANKIEWICZ, Michael S. PETRONIS, Sam POPPE, Stanisław MADEJ, Anna PIETRANIK, Piotr SARUL, Norbert SZCZEPARA
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Rhyolite – Rock of the Year 2026



The Organy Wielisławskie quarry (photo: Marek Awdankiewicz)



The Organy Wielisławskie quarry (photo: Marek Awdankiewicz)

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MINERALOGICAL SOCIETY OF POLAND

Permo-Carboniferous volcanism in the Sudetes

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Regional context

The collision of continents in late Palaeozoic times resulted in the assembly of the Pangea supercontinent and the formation of orogenic belts, including the Variscides in the collision zone between Laurussia and Gondwana. During the evolution of Variscides, the collision-related processes were followed by the gravitational collapse of the Variscan Belt and later by continental rifting. Starting in the Carboniferous, many sedimentary basins developed, including several intramontane troughs within the Variscan Belt and, in its northern foreland, the Central European Basin System. The sedimentary fill of these basins includes thick intercalations of volcanic rocks (Mazur et al., 2021 and references therein).

In Central Europe the volcanic rocks, mainly rhyolites and rhyolitic tuffs, occur over an area exceeding 1 million km^2, locally exceed 2 km in thickness and are linked to the development of a felsic-dominated large igneous province (Paulick & Breitkreuz, 2005). However, most of these volcanic rocks are buried under a thick Mesozoic cover and surface outcrops are mainly found in the intramontane troughs of the Variscan Belt. The Sudetes (Figure 1), in the eastern part of the Variscides, expose volcano-sedimentary succession in two such inverted basins: the Intra-Sudetic Synclinorium (ISS) and the North-Sudetic Synclinorium (NSS). Sedimentation in the ISS began in the late Early Carboniferous and in the NSS in the Late Carboniferous. In both basins, extensive sedimentation occurred within the continental intramontane valleys, predominantly in alluvial fan, alluvial plain, and ephemeral lake environments. These deposits developed under a warm and humid climate during the Carboniferous, which later became warm and arid during the Permian. The siliciclastic sedimentary rock sequence, up to 10 km thick in the ISS, consists of conglomerates, sandstones, mudstones and shales with Carboniferous coal intercalations and thin Permian lacustrine limestone beds. The Permo-Carboniferous sequences are partly covered by Lower Triassic and Late Cretaceous deposits with regional hiatus spanning the Upper Triassic, Jurassic and Lower Cretaceous (e.g., Kozłowski, 1963; Kozłowski & Parachoniak, 1967; Nowakowski, 1968; Dziedzic, 1980; Wojewoda & Mastalerz, 1989; Baranowski et al., 1990; Dziedzic & Teisseyre, 1990).

This contribution provides a synthetic overview of the Late Palaeozoic volcanism in the Sudetes, covering the age of volcanism, emplacement processes of the volcanic and subvolcanic rocks, resulting volcanic centers, geochemistry of the volcanic rocks, magma origin and differentiation. Selected aspects and localities will be discussed in more detail during the conference field trip (Awdankiewicz et al., this volume) and in other conference presentations (Petronis et al., this volume; Poppe et al., this volume).

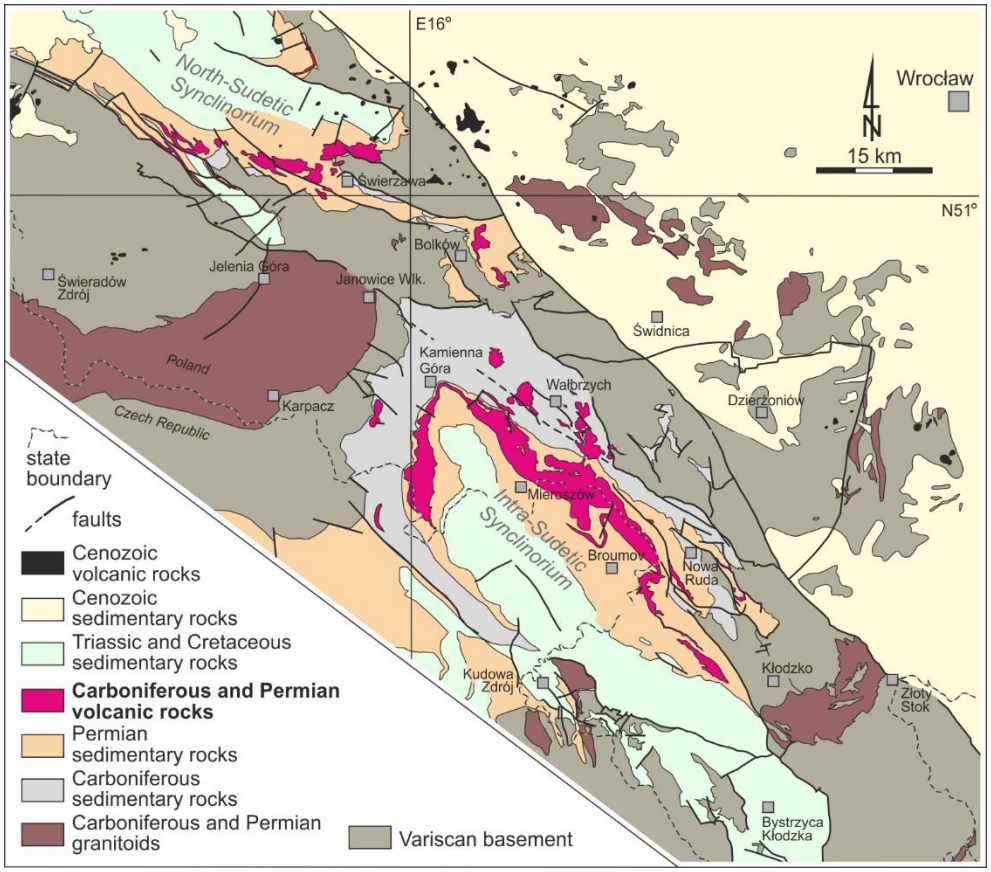


Figure 1. Geological map showing the North-Sudetic Synclinorium and Intra-Sudetic Synclinorium and the distribution of Carboniferous and Permian volcanic rocks in the Sudetes (modified from Kodym et al., 1967; Bossowski et al., 1981; Sawicki, 1988; Milewicz et al., 1989).

Evolution of volcanism

Volcanic rocks form relatively sparse intercalations in the Carboniferous of the ISS and much more extensive and continuous complexes in the Permian of both the NSS and the ISS (Awdankiewicz, 1998, 1999, 2006). U-Pb SHRIMP zircon dating indicates that volcanism occurred in several episodes, beginning at about 313 Ma. Volcanic activity peaked around the Carboniferous–Permian boundary (300–299 Ma) and during the early Permian, before waning by 287 Ma (Awdankiewicz et al., 2014, 2025; Awdankiewicz, 2022). The Carboniferous volcanic rocks in the ISS near Wałbrzych in the basin centre are rhyodacites with minor andesites and basaltic andesites. The rocks were emplaced mainly as subvolcanic intrusions (sills, laccoliths) and occasionally as cryptodomes, which are transitional between laccoliths and lava domes. The magma ascent can be linked to the activity of the Intra-Sudetic Fault (a major regional tectonic boundary) and the subvolcanic emplacement processes can be attributed to the thick Carboniferous basin fill, which hampered surface eruptions. However, in the southwestern part of the ISS, explosive rhyolitic volcanism produced the Křenov ignimbrite, dated at 312.39 ± 0.10 Ma (Opluštil et al., 2016). Along the eastern margin of the ISS, the Rusinowa–Grzmiąca belt comprises diatremes filled with rhyolitic

tuffs, accompanied by intrusive rhyolites and trachyandesites. The Rusinowa–Grzmiąca belt is of poorly constrained Carboniferous and/or Permian age and reflects explosive phreatomagmatic eruptions of silicic magmas rising through unconsolidated wet sediments (Nemec, 1981; see Awdankiewicz 1998 and references cited there).

The main, Permian stage of volcanic activity in the ISS and NSS occurred in several volcanic centers. In the western part of the ISS effusive eruptions (and associated subvolcanic activity) of basaltic trachyandesite and rhyolite lavas formed extensive lava fields/small shield-type volcanoes. There, the largest rhyolite complex of Góry Krucze / Vrani Hory rhyolites is dated at 297.11 ± 0.04 Ma (Opluštil et al., 2016). A major volcanic event at ca. 299 Ma (Awdankiewicz et al., 2025) was the eruption of the Góry Suche rhyolitic tuffs, which were emplaced predominantly as extrusive deposits, mainly as non-welded to welded ignimbrites, across the ISS. This activity is tentatively linked to a caldera 15 km in diameter in the central part of the ISS. The Góry Suche ignimbrites and Góry Krucze rhyolites are partly eroded and overlain by volcanogenic sedimentary rocks rich in rhyolitic lithic fragments. The post-ignimbrite activity comprised: 1) emplacement of trachyandesite and rhyolite sills and laccoliths along the NE margin of the Góry Suche caldera, dated at 298.4 ± 1.5 Ma and 292.6 ± 1.9 Ma (Awdankiewicz et al., 2025; see also Poppe et al., this volume) and 2) explosive phreatomagmatic to effusive eruptions of andesite magmas inside the caldera, forming tuff ring with associated intrusions and lavas (Awdankiewicz et al., 2014 a). Effusive eruption and subvolcanic emplacement of basaltic andesites further south-east terminated the Permian volcanism in the ISS.

In the NSS rhyolitic volcanism is dated at 297 Ma (Mikulski & Williams, 2014), as well as 294 ± 3 to 292 ± 2 Ma, with the youngest ages (least reliable?) of ca. 287 ± 4 Ma (Awdankiewicz et al. 2014 b). The main outcrop of rhyolites in the NSS, the Różana Rhyolites (Szczepara, 2018) is a complex of lava flows, partly underlain by rhyolitic tuffs, significantly eroded and partly covered with volcanogenic sandstones and conglomerates. The eruptive vents of these rhyolitic lavas are linked with the Wieslawka rhyolite cropping out nearby (Awdankiewicz et al. 2014 b) which is interpreted as a partly eroded laccolith or cryptodome (see Petronis et al. this volume and Awdankiewicz et al., this volume). Another rhyolite outcrop in the eastern part of the NSS near Bolków represents a laccolith (Skórzewski, 1981) or a complex of lavas and densely welded ignimbrites with other associated pyroclastic flow and fall deposits (Pańczyk, 2003). The Bolków rhyolites are overlain by volcanogenic sedimentary rocks containing abundant rhyolitic clasts, as observed elsewhere in the region. The mafic volcanic rocks of the NSS (mainly basaltic andesites) are considered younger than the rhyolites based on geological field relations (Awdankiewicz, 2006). These rocks occur as lava flows (up to 7 stacked lava sheets at some locations) as well as shallowly emplaced sills. The location of their feeders/eruptive centers remains poorly constrained.

Petrological aspects

Similar to other ancient volcanic successions, the Sudetic Permo-Carboniferous volcanic rocks show evidence of widespread post-magmatic and/or diagenetic alteration. Petrographic evidence includes pervasive alteration and/or complete recrystallization of volcanic glass, common pseudomorphs of clay minerals and carbonates after mafic minerals, and replacement of primary plagioclase by albite, clay minerals, and carbonates. Geochemical evidence includes high values of LOI (up to 15-20% in post-magmatic carbonate and clay-rich mafic rocks) as well as, in most altered samples, scattered patterns of mobile elements such as Ba, Sr, Rb (e.g., Awdankiewicz, 1998, 1999, 2006). However, lava flows and subvolcanic intrusions in their central parts often preserve unaltered to weakly altered rocks,

e.g. the basaltic trachyandesites or andesites with primary magmatic, calcic plagioclase (labradorite-oligoclase), augite and /or enstatite. The petrogenetic interpretation of geochemical and mineralogical data required selection of most fresh specimens and caution.

Two suites of volcanic rocks are distinguished in the ISS (Figure 2). The older, Carboniferous volcanic rocks represent a calc-alkaline suite of rhyodacites with minor andesites and basaltic andesites. This suite shows trace element signatures similar to convergent margin lavas. The younger, Permian volcanic rocks tend to be mildly alkaline; this suite is dominated by rhyolites with less widespread trachyandesites (grading to andesites) and basaltic trachyandesites (grading to basaltic andesites). Trace elements indicate within plate geochemical affinities with gradation to convergent margin affinities in silicic rocks. The Permian volcanic rocks of the NSS are geochemically distinctive and represent a bimodal, high-K suite, with mafic rocks of basaltic andesite and basaltic trachyandesite composition, and felsic rocks of rhyolite composition. Their trace element affinities are gradational between within-plate and convergent margin volcanic rocks.

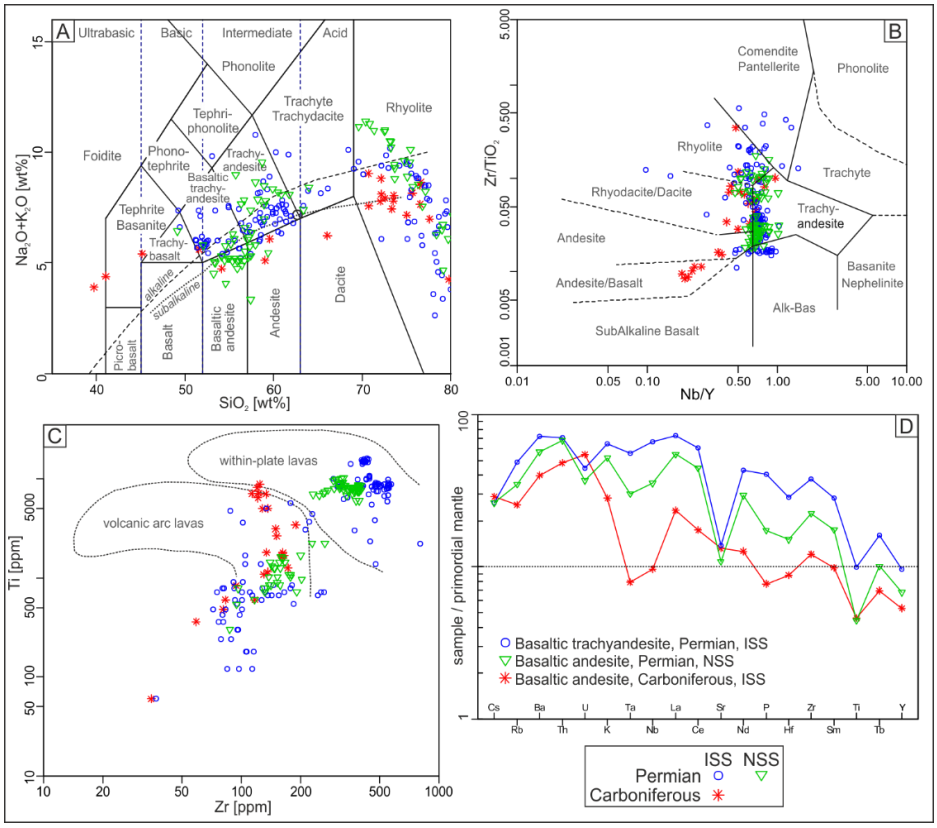


Figure 2. Selected diagram illustrating the classification and geochemical characteristics of the Carboniferous and Permian volcanic rocks of the Sudetes (237 samples; ISS – Intra-Sudetic Synclinorium, NSS – North-Sudetic Synclinorium; data from Awdankiewicz, 1998, 1999, 2006; Szczepara, 2018, and unpublished results). A. The total alkalis – silica (TAS) diagram (after Le Maitre et al., 2002). The boundaries of the alkaline and subalkaline series after Irvine & Baraggar (1971; dashed line) and after Kuno (1966; dotted line). B. The Zr/TiO_2-Nb/Y diagram (Winchester & Floyd, 1977). C. Ti-Zr discrimination plot (Pearce, 1983). D. Primordial mantle-normalized plots of least evolved samples from the main volcanic suites (normalization after Wood et al., 1979).

The convergent margin-like trace element signatures in the mafic volcanic rocks of the ISS and NSS, most pronounced in the Carboniferous basaltic andesites and andesites, suggest that their parental magmas were derived from subduction-modified, metasomatized mantle sources with less significant crustal contamination during fractionation of magma (Awdankiewicz 1999, 2006). It is further considered that such supra-subduction zone signatures in the post-orogenic volcanic rocks represent a specific "echo" of subduction processes preceding the Variscan collision that resulted in mantle metasomatism. These subduction-related signatures, however, waned with time and the younger, Permian mafic rocks of the ISS show more pronounced within-plate characteristics. These geochemical trends can be further linked to the gradual change of geotectonic regime with time, from late/post-orogenic in Carboniferous to extensional, within-plate in Permian, with related change of magma source in the mantle.

All the volcanic suites show evidence of rather advanced differentiation, such as the lack of primitive basaltic rocks and the predominance of evolved, silica-rich compositions. Based on trace element geochemistry, Awdankiewicz (1998, 1999) linked differentiation of magma in the ISS with fractional crystallization (hydrous mineral assemblages in the Carbonifeous, anhydrous in Permian), with some influence of crustal contamination and magma mixing. Ulrych et al. (2004), using isotope geochemistry on samples from the Czech part of the ISS suggested significant role of continental crust and assimilation-fractional crystallization (AFC) processes. The Permian mafic rocks of the NSS show distinctive differentiation trends interpreted as the result of fractional crystallization coupled with mafic replenishment and crustal assimilation in the advanced stages (Awdankiewicz 2006). The rhyolitic magmas in the NSS originated due to fractional crystallization and intense crustal assimilation (Pańczyk, 2003; Szczepara, 2018). A significant involvement of continental crustal sources in the rhyolitic magma genesis can also be suggested by analogy with Permian rhyolites in adjacent areas (Pietranik et al., 2013; Słodczyk et al., 2018).

Summary

The Late Palaeozoic volcanism in the Sudetes spanned 20-25 Ma between 313 and 287 Ma and reached its peak close to the Carboniferous - Permian boundary, coinciding with the regional "magmatic flare-up" in the felsic-dominated large igneous province of Central Europe (Breitkreuz & Kennedy, 1999; Paulick & Breitkreuz, 2005). The geotectonic setting of volcanism evolved from late- to post-orogenic conditions towards intracontinental extension. This transition was accompanied by changes in magma source and a shift in the geochemical signature of the volcanic rocks from supra-subduction-like to within-plate affinities. Emplacement of the mantle-derived magmas through thickened continental crust favored advanced differentiation and resulted in the predominance of silica-rich volcanic rocks. Differentiation processes included fractional crystallization, mafic replenishment as well as crustal assimilation, especially in the most evolved compositions. Magmas erupted through thick siliciclastic successions in the continental Intra-Sudetic and North-Sudetic basins from several volcanic centers of various types (large rhyolite extrusions, mafic lava fields / small shield volcanoes, lava domes, maars and tuff rings) and formed also numerous subvolcanic intrusions (sills, laccoliths). A major explosive eruption (ca. 100 km^3 of magma) of the Góry Suche rhyolitic tuffs at ca. 299 Ma deposited ignimbrites across the Intra-Sudetic basin and likely resulted in the formation of a caldera in this basin centre, whereas voluminous rhyolite extrusions at other locations formed intrabasinal elevations. Volcanism strongly influenced paleoenvironment and sedimentation patterns in the basins: intrabasinal rhyolite and ignimbrite highs underwent post-eruptive erosion and supplied volcanogenic detritus, whereas the ignimbrite caldera acted as an intrabasinal depositional centre. Several

aspects of the Permo-Carboniferous volcanism in the Sudetes require further studies, such as, in several areas, basic geologic mapping to constrain the outcrop geometry and rock types, deciphering emplacement processes of volcanic rocks, precise dating and correlation of volcanic events, constraining magma origin and differentiation in more detail.

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Miocene large explosive volcanic eruptions of Si-rich magmas in the Carpathian-Pannonian Region

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The formation and evolution of the Pannonian basin as part of the Mediterranean region was accompanied by eruptions of compositionally diverse magmas during the Neogene to Quaternary. The long-lasting magmatic activity started with the most voluminous silicic eruptions in Europe for the last 20 Myr, resulting in more than 4000 km^3 of tephra during a period of major lithospheric extension. It was associated with formations of a wide range of ignimbrites from unwelded to strongly welded facies. The pyroclastic flows could have even a long run, almost over 100 km distance. Zircon U-Pb geochronology indicates that the volcanism occurred between 18.2 and 11.6 Ma and involved several major eruption episodes. The silicic volcanism in the Bükkalja volcanic field was a response to the extension of the continental lithosphere, whereas that in the Tokaj Mts. took place close to the assumed subduction zone, where lithospheric extension was triggered by slab roll-back, slab verticalization before detachment. Volcanic glass, zircon, and bulk rock chemical data show distinct features yielding specific geochemical fingerprints of these eruptions. They indicate the development of different silicic magma types, thus, these fingerprints help to correlate the eruption products even with scattered distal occurrences over large distances. Distal ash materials related to these volcanic eruptions are recognized around the Pannonian basin and more than a thousand kilometers away in Germany and Italy. These pyroclastic units serve as key-horizons in the lithostratigraphy of the Carpathian-Pannonian Region and the surrounding areas as well as in Paratethys stratigraphy. The silicic magmatism had a major influence on the state of the continental crust due to the contemporaneous existence of large-volume (several thousands of cubic kilometers) silicic magma reservoirs and could have contributed to the effective crustal stretching beneath the Pannonian basin.

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The Permian Organ Pipes at Wielisławka Rhyolite, Poland: Integrating Anisotropy of Magnetic Susceptibility, Rock Magnetic, and Paleomagnetic Data to Reconstruct the Emplacement History

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The Organy Wielisławskie Natural Monument in the North-Sudetic basin of southwestern Poland exposes the spectacular columnar-jointed Wielisławka Rhyolite, a volcanic complex whose emplacement history has been debated for more than a century (Kozłowski & Parachoniak, 1967, and references cited there). The rhyolite was emplaced during post-Variscan felsic volcanism and yields a zircon U–Pb age of 292.8 ± 2.1 Ma (Awdankiewicz et al., 2014) and 297.5 ± 2.8 Ma (Mikulski & Williams, 2014). The preserved outcrop pattern represents roughly the lower half of the original rhyolite body, with much of the upper portion removed by erosion (Fig. 1). Exposure is largely restricted to road and river cuts, scattered higher-elevation outcrops, and steep hill slopes, limiting the continuous tracing of macroscopic structures through the intrusion. We combine field and aerial mapping, rock magnetic, anisotropy of magnetic susceptibility (AMS), and paleomagnetic data to constrain magma emplacement processes, cooling history, and post-emplacement modification of the rhyolite. The rock magnetic data help determine what minerals carry the magnetization and the geologic stability of the magnetic record. The physical magnetic fabric produced by magma flow and strain yields an AMS fabric, while paleomagnetic data record the direction of Earth's magnetic field, ideally during the time of emplacement. In the well-exposed central part of the rhyolite, columnar joints dip outward to the northwest and southeast on opposite sides of the ridge crest, defining a simple, symmetric dome cooling geometry. The absence of nested domes or cross-cutting cooling surfaces argues against emplacement of multiple magma pulses. Rock magnetic experiments include hysteresis, first-order reversal curve distributions, and Curie point estimates. The data provide constraints on the magnetic grain size, domain state, concentration, and composition of the magnetic phase(s) present in the sample. The results indicate that a minor amount of single-domain magnetite likely carries the geologic characteristic remanent magnetization (ChRM) in most samples, while some sites have a mixture of magnetite domain sizes and hematite. The AMS fabrics are considered weak ($0.1E^{-3}$ SI), the degree of anisotropy is low at 1.3%, with both prolate and oblate fabrics present. The AMS fabric(s) are defined by the direction and magnitude of the three principal susceptibility axes: the maximum K_1 (lineation), intermediate K_2, and minimum K_3. The magnetic lineation direction is defined by the K_1 axes and the magnetic foliation is defined by the strike and dip of the K_1-K_2 susceptibility plane. The magnetic fabrics vary spatially

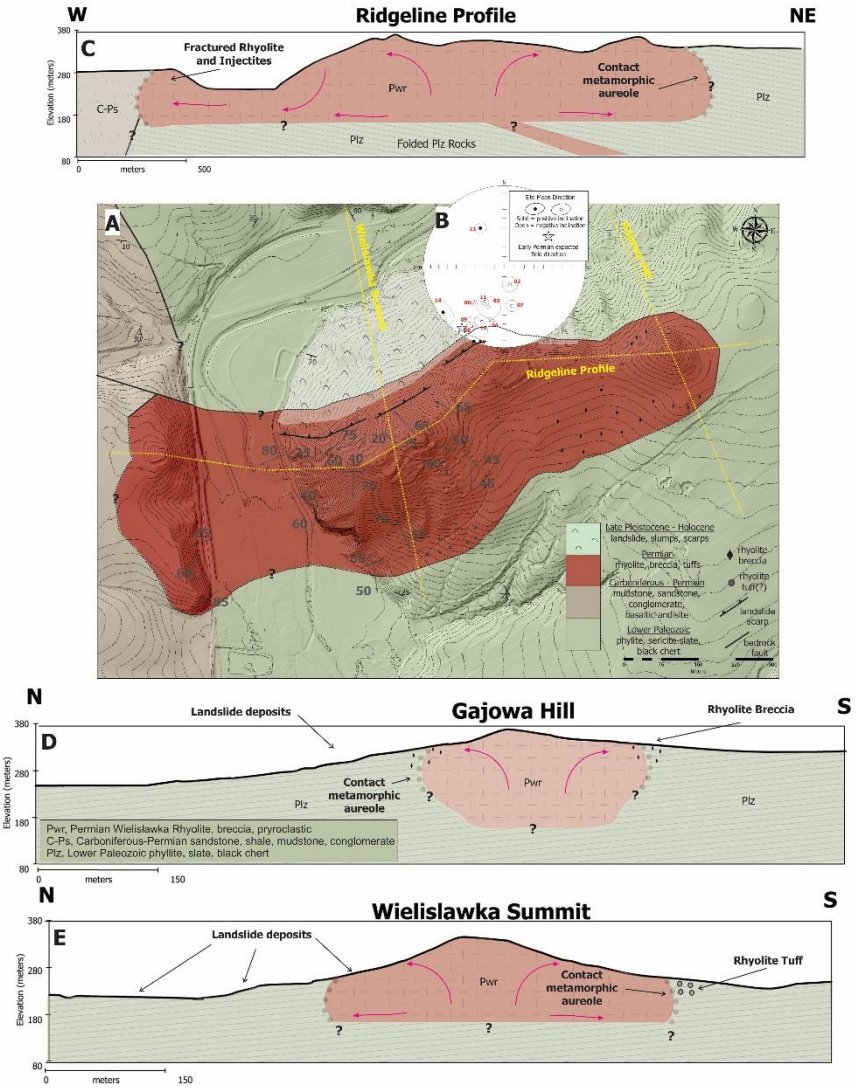


Figure 1. Bedrock geologic map (modified from Zimmermann & Kühn, 1918; Frąckiewicz, 1958; Milewicz & Kozdrój, 1995), paleomagnetic directions, anisotropy of magnetic susceptibility (AMS), and inferred magma flow of the Wielisławka Rhyolite. A) Geologic map of the Wielisławka Rhyolite showing the strike and dip of the macroscopic flow foliation and the trend and plunge of columnar joints. Yellow dotted lines indicate the location line of sections C-E. B) Lower hemisphere equal-area projection of the paleomagnetic site mean results. Star indicates the expected Permian field direction. C-E) Topographic profiles with idealized geologic interpretation of the subsurface and the inferred magma flow directions (magenta arrows). C) The cross-section line of section follows the ridgeline trail atop Wielisławka hill. The location of the magma ascent conduit is speculative; possible ascent pathways include a central pipe-like vent, a fissure vent parallel to the rhyolite outcrop, or a pre-existing fault or fracture zone. D) Line of section crossing Gajowa hill at the eastern part of the exposed rhyolite. E) Line of section crossing Wielisławka summit. Explanation: Pwr, Permian Wielisławka, CPs, Carboniferous-Permian sandstones, shales, mudstones, conglomerates; Pz, Lower Paleozoic phyllite, slate, black chert.

across the rhyolite and are carried by a mixture of silicate and magnetic grains. It is probable that Fe-Ti oxide grains, likely of a pseudosingle to multidomain grain size, control the AMS fabric. The AMS results reveal three distinct fabric domains. The western terminus or "nose" region exhibits flattened fabrics consistent with strain localization during interaction between the advancing magma and country rock. The central region (around the Organ Pipe quarry) contains shallow K_1–K_2 fabrics, suggesting subhorizontal magma transport during inflation, and a "roof" domain (along the ridgeline of Wielisławka Hill) that displays steep K_1–K_2 fabrics consistent with subvertical flow. Paleomagnetic analysis involved both thermal and alternating field demagnetization experiments to isolate the ChRM. The results indicate that the samples contain geologically stable magnetic grains of a moderately high coercivity indicative of fine-grained magnetite, likely of a pseudo-single-domain (PSD) or single-domain (SD) grain size. The rhyolite preserves a stable ChRM of southwest declination with two separate inclination populations. One population is of southwest declination with a shallow negative or positive inclination. The second population yields a similar southwest declination with inclinations that are moderate to steep (>-40). The shallow inclination population plot near the expected early Permian field direction; however, the remaining sites are considerably steeper than the expected field. Spatially, we do not see a correlation between the inclination and location across the rhyolite. The anomalously steep inclinations may reflect post-emplacement localized tilting (preferred), high-amplitude geomagnetic field behavior, or partial remagnetization. Remagnetization is considered unlikely based on rock magnetic characteristics indicating preservation of primary magnetic mineral assemblages. We can not rule out the possibility of an anomalous geomagnetic field direction. The steep inclinations may reflect localized post-emplacement tilting, given the lack of spatial organization in the anomalous directions. Collectively, our results indicate that the rhyolite preserves a primary Early Permian remanence carried by geologically stable, fine-grained single-domain magnetite. Some sites record inclination values steeper than the expected amount, yet the absence of a systematic spatial pattern suggests localized internal tilting rather than block-scale rotation or regional tilting of the rhyolite. The preservation of a primary Early Permian remanence and the absence of regional tilting indicate that the AMS fabrics predominantly reflect primary magmatic emplacement fabrics, with only localized post-emplacement tilting. In conclusion, our data provide complementary constraints on the emplacement, cooling, and post-emplacement evolution of the Wielisławka Rhyolite. The identification of a primary Early Permian remanence demonstrates that the AMS and macroscopic fabrics largely record primary magma flow. These observations support the interpretation of emplacement of the Wielisławka Rhyolite as a shallow cryptodome or laccolith that inflated beneath the surface and cooled as a simple domed body.

Plain Language Summary

The spectacular rock columns of the Wielisławka Rhyolite in southwestern Poland formed about 293 million years ago from cooling magma. Using field observations and magnetic measurements, we reconstructed how this magma body formed. Our results show that it developed as a shallow dome-shaped intrusion, with magnetic fabrics preserving the record of magma movement and only minor deformation after emplacement.

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Zircon petrochronology in magmatic systems: Opportunities and limitations

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Zircon, a widespread accessory mineral in silicic igneous rocks, is an unparalleled witness of magmatic processes. Thanks to its durability and resistance to resetting, it holds promise of providing snapshots of magma properties (via its composition) at a range of times (given by U–Th–Pb geochronology) and across multiple addresses within a magma reservoir.

Originally, zircon geochronology and magma geochemistry were interpreted in separation. This is because the temporal resolution achievable by U–Th–Pb zircon geochronology limited the interpretation of zircon dates to a single event (e.g., eruption age, emplacement age). However, continued methodological improvements have now increased the accuracy and precision of this geochronometer to a point where an extended record of zircon crystallization can often be resolved in single rock samples. Zircon crystals are commonly found to predate the eruption or final solidification of a magma body by tens of thousands to as much as over a million years. If individual zircon dates are interpreted to accurately represent their crystallization ages, then we can leverage their spread and compositional properties to start tracking the conditions of zircon crystallization (and by extension conditions in, and geochemical properties of, the magma system) through time. Some call this approach *petrochronology*.

In this talk, I will discuss (1) the analytical resolution of zircon U–Th–Pb geochronology as related to the lifetime of a magmatic system (in situ vs whole-grain geochronology), (2) new opportunities offered by resolving an extended record of zircon crystallization in a single rock (e.g., reconstructing the recharge/cooling history, but also improved eruption or emplacement age interpretation), (3) additional insights afforded by combining zircon crystallization ages with their elemental or isotopic composition. These advances have provided a new resolution in studies of silicic magmatic systems, but they create just as many new questions about the fate of zircon in magma.

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From magma mobilization to rare-metal mineralization: The role of fluids across the lifespan of silicic magmatic systems

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Fluids exert a first-order control on the evolution and eruptibility of silicic systems. Far from passive byproducts of crystallization and magma ascent, a volatile phase modulates magma compressibility, rheology, heat transfer and elemental transport across the lifespan of silicic reservoirs, from melt extraction and mush rejuvenation to pegmatite formation and hydrothermal alteration. Here, we synthesize observations from thermomechanical models and diffusion experiments with field studies of Li-rich pegmatite and granite systems to investigate the role of fluids in silicic reservoirs.

Thermomechanical models demonstrate that volatile exsolution and resorption can fundamentally alter the stability of silicic magma chambers. In systems undergoing voluminous recharge, volatile resorption may accelerate pressurization by reducing magma compressibility, thereby expediting destabilization and eruption onset. Such feedbacks illustrate how fluids regulate eruption frequency and magma remobilization in long-lived crystal-rich reservoirs. Constraining fluid transfer rates remains challenging, but diffusivity contrasts in fluid-mobile elements and isotopes, like Li, provide a promising avenue for quantifying fluid transport timescales.

Fluid evolution is equally critical for rare-metal mineralization. High concentrations of incompatible fluid-mobile metals, e.g. Li in pegmatites, require carefully balanced timing between crystallization and fluid saturation. Early fluid saturation may flush incompatible metals from the system prior to extreme enrichment, producing unmineralized aplites and quartz veins, whereas excessively late fluid saturation can trap fluids within low-permeability crystal frameworks. Late hydrothermal alteration can further modify primary Li enrichment through muscovitization and chloritization. Together, these observations emphasize the role of fluids in coupling magma reservoir evolution, eruption initiation, and ore deposit formation across crustal scales.

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Syn-Emplacement Deformation Pathways in Silicic Welded Tuffs: How Lava-Like Ignimbrites are Made

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Silicic calderas and large igneous provinces are commonly associated with strongly to intensely welded tuffs. The overwhelming majority of these deposits are interpreted to be ignimbrites, the deposits of high-temperature pyroclastic density currents (PDCs). Syn-depositional fabrics in strongly to intensely welded ignimbrites are usually heavily overprinted by decametre-scale post-depositional folding and pervasive devitrification / recrystallization, obscuring their origins. Research on these types of 'lava-like' deposits has often focused on distinguishing them from silicic lavas and less on how they form a distinct part of ignimbrite welding-grade continuum. Studies of deformation in several ignimbrites across this welding spectrum in Europe, Mexico, and the western USA reveal that the formation of sub-horizontal shear zones within very strongly welded (<1% porosity) horizons are a pre-requisite for forming lava-like lithofacies. The colocation of such sub-horizontal shear zones within intensely welded horizons becomes inevitable and self-reinforcing as strain is localized to the weakest horizons and the glass transition temperature (T_G) is suppressed. This effect is so strong that such welding-shearing zones can nucleate at the PDC-deposit interface when the PDC is >>T_G. The presence of obsidian vitrophyres or their relics (e.g., perlitic texture) are records of this process.

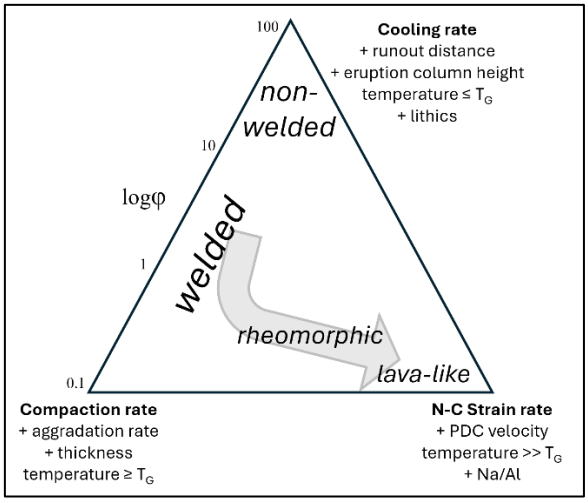


Figure 1. Controls on welding intensity in tuffs.

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Mafic Sheet Intrusion Propagation through Anisotropic Rhyolitic Ignimbrite: The Breiðuvík Caldera, Iceland

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The significance of magma sheet propagation in interpreting volcanic unrest and identifying potential eruption precursors is well established. However, the nature of propagation through the geologically heterogeneous subsurface makes direct study challenging on Earth and more so on other terrestrial planetary bodies. The interpretation of geophysical data, aided by computational modelling, is thus essential for understanding magma propagation mechanisms. Earlier models have often assumed a simple basaltic composition of upper planetary crust, whereas recent investigations on Mars indicate that pervasive fracture systems, and pyroclastic deposits of more evolved compositions may be more widespread in its shallowest stratigraphy. Earth analogues offer a means to understand geological processes on other planetary bodies such as Mars. We conducted detailed geological mapping of basaltic sheets that were intruded and arrested into welded rhyolitic ignimbrites in the Miocene-aged sequence of the partially eroded Breiðuvík caldera in Northeast Iceland. The area exposes a range of host rock types, such as silicic pyroclastic deposits, silicic and mafic intrusions, and fractured basaltic lava flows (Burchardt et al., 2022). At Hvítserkur mountain, we systematically characterized the structural properties of both the host rocks and intrusive bodies, documenting parameters such as strike, dip, intrusion geometry, and fracture-set characteristics. We performed Unmanned Aerial Systems (UAS) based photogrammetry to obtain high-resolution three-dimensional virtual outcrops. The resulting data was used to constrain host rock heterogeneity and intrusion tip geometry. On the virtual outcrop we mapped fracture networks and intrusion boundaries and calculated fracture attributes (length, orientation, spacing). We observed tip geometries varying from sharply bladed to double sigmoidal curves and recorded tip interactions. Tips were often observed to be associated with local fracturing parallel to the intrusion direction (leading fractures). These results will be further integrated into future numerical models developed in the ongoing DAGGER project. By integrating intrusion geometry, fracture system characteristics, and host-rock mechanical properties, this study provides insights into the interaction between propagating magma sheets and mechanically anisotropic crustal rocks. The outcome will enhance future interpretation of intrusive magmatism on Earth, Mars, and other rocky planetary bodies.

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Integrated volcanological, petrological, and structural analysis of the Iferda ignimbrites in the eastern Ougnat inlier (Anti-Atlas Mountains, Morocco)

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The Ougnat inlier in the Anti-Atlas Mountains (Morocco) is one of many inliers outcropping Precambrian rocks surrounded by Palaeozoic counterparts. At its northeastern edge, Precambrian ignimbrites, granodiorites, and surrounding Cambrian rocks are outcropping.

This study presents a detailed volcanological model for two distinct ignimbrite sheets identified in the mapping area, focusing on their depositional architecture, welding intensity, and paleoflow directions. A total of 11 cross-section profiles and 16 geological columns have been traced to document and reconstruct the contact faces between the ignimbrite units themselves and with the surrounding lithologies. The measured profiles distinguish several felsic ignimbrite units that vary in colour from pink to greenish-brown and contain differing proportions of lithic and juvenile fragments. Their mineral assemblages are dominated by feldspar and quartz, with subordinate ferro-magnesian minerals such as biotite. Individual units reach thicknesses of up to ~100 m and exhibit variable degrees of welding, accompanied by distinct textural and structural characteristics. Based on these features and their spatial distribution, the ignimbrites are preliminarily grouped into two main units: upper lithic-poor plateau ignimbrite (PI) and lower lithic-rich ignimbrite (compound cooling unit, CCU). In places, massive lithic breccia (mlBr) with large blocks outcrops alongside PI, indicating a proximal emplacement of the pyroclastic units. Complementary structural analysis documents joints, faults, and vein networks through systematic mapping of cross-cutting, trailing, and abutting relationships. These data constrain the post-depositional deformation history of the Iferda ignimbrites and are interpreted within the broader tectonic evolution of the Ougnat inlier in the Anti-Atlas. Ongoing petrological, textural, and geochemical investigations using SEM-based Mineral Liberation Analysis and electron microprobe analysis further refine the relationships between the ignimbrite bodies and aim to reconstruct the pre-eruptive conditions that governed their emplacement.

This work represents the first application of joint-relationship structural analysis to Precambrian volcanic rocks in the region. Field measurements reveal predominant joint orientations of steeply dipping NE–SW and NW–SE, together with subordinate shallow-dipping NE–SW trends. These structural data, combined with the volcanological and petrological observations, refine the geological history of the Ougnat inlier and contribute new insights into Neoproterozoic volcanism and deformation in the Anti-Atlas.

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Origin of the very large Los Chocoyos rhyolitic volcanic eruption in the Atitlan volcanic centre, Guatemala

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The Atitlan volcanic centre (AVC) in Guatemala is part of the subduction-related Central American Volcanic Arc (CAVA). The caldera-forming Los Chocoyos (LCY) rhyolitic pumice eruption of the AVC had a Volcanic Explosivity Index of 8 and a volume of erupted products of 510 km^3 dense-rock equivalent. This makes it the largest volcanic event in the CAVA in the past 75 ka, and one of the largest Quaternary eruptions worldwide. What conditions caused the LCY eruption to be so massive? Our study (Gilchrist et al., under review) places the LCY eruption in the tectonic framework of the CAVA and the local framework of the AVC. We compare LCY samples to other pre- and post-LCY eruptions of more mafic magma which formed large stratovolcano edifices, and to smaller local pre- and post-LCY pumice deposits of varied compositions.

Major and trace element compositions of a wide range of lavas, pumice and enclaves from the AVC have been analysed, as well as compositions of glass in anteliths which may represent unerupted portions of melt from crustal magma reservoirs. The most primitive magmas are basaltic andesites, which are the product of fractionation of subduction-related mantle-derived magma with minor assimilation at the base of the crust. The geochemical and petrographic data show evidence of the presence of high- to very high-K magmas which were involved in the mixing, together with andesitic recharge magmas. Many samples host anteliths and antecrysts which are suggestive of the presence of a crystal mush beneath the region prior to the LCY eruption.

Bulk-rock radiogenic isotope compositions show changes related to both time and space. Older AVC and CAVA eruptions further from the present-day subduction trench have higher $^{87}Sr/^{86}Sr$ and Pb isotope ratios, and lower $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ ratios, than the younger magmas erupted closer to the trench. These changes are related to rapid migration of the CAVA because of roll-back of the subducting Cocos oceanic slab beneath the region, and differences in the overlying crustal structure and composition.

We consider that the high rate of arc migration beneath the AVC (estimated at >9 km/Myr) was a major factor in the super-sized LCY eruption, but it was not the only one. Crustal thickening and high magma supply rates were also significant, together with the segmented nature of the CAVA controlled by strike-slip faulting. These factors combined to produce the perfect conditions for generation of the extremely large volume of rhyolitic magma erupted in the LCY event.

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Integrated SEM-Based Automated Mineralogy and GXMAP Imaging for High-Resolution Characterization of Early Pleistocene Pyroclastic Deposits from Kurtan, Armenia

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The Early Pleistocene pyroclastic sequence at Kurtan (Kechut Volcanic Province, Armenia) represents one of the most important tephra archives in the southern Caucasus, yet its fine-grained and fragile ash textures have long limited detailed characterization. This study applies an integrated workflow combining SEM-based automated mineralogy with high-resolution X-ray mapping (GXMAP) to resolve mineral assemblages, particle morphologies, and fragmentation signatures across three stratigraphic units (TP-13-1, TP-13-2, TP-13-3). Complementary granulometric and geochemical analyses provide additional constraints on depositional processes and magma evolution.

GXMAP-based granulometry significantly reduces preparation-induced fragmentation and yields more consistent particle-size distributions than traditional dry sieving, particularly for fine-ash fractions. Shape-parameter fields derived from BSE images reveal pronounced contrasts in concavity, elongation, and form factor, with TP-13-1 containing highly irregular compound fragments and the upper units dominated by deformed bubble-wall shards, or so-called simple ash. Most studied particles plot within the ductile fragmentation domain, reflecting dominant bubble-wall deformation and minor brittle breakage.

The SEM-GXMAP-based study reveals systematic variations in glass chemistry and mineral assemblages that reflect changes in crystallisation conditions and magma evolution. The three units display distinct mineralogical and morphological fingerprints: TP-13-1 is dominated by Bt-bearing rhyolitic coarse pumice-lapilli particles with heterogeneous textures, varying from highly vesicular, foam-like to simple ash fragments. In contrast, TP-13-2 and TP-13-3 consist almost entirely of Cpx-rich trachyandesite fine ash with more compact morphologies.

These results highlight the power of multi-approach analyses for characterizing composition, fragmentation, and depositional regimes in fragile pyroclastic deposits. The Kurtan sequence advances constraints on explosive volcanism in the Armenian Highland and offers a transferable framework for tephra studies worldwide (Gevorgyan et al., 2026).

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Mobilisation of silicic melt in the shallow crust: a case study of the Streitishvarf composite dyke, eastern Iceland

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Silicic bodies make up ~10% of the Icelandic lava pile, with many found at shallow depths in the upper 1–3 km of crust. However, under certain circumstances, these silicic melts can ascend higher in the crust and/or erupt. Here we use the Streitishvarf composite dyke in the east of Iceland as a study to investigate how multiple magmas move and interact within a dyke, and how composite dykes can enable silicic melts to mobilise and ascend in the shallow crust. The 10.7 (± 0.2 Ma) basaltic-rhyolitic dyke is ~26–30 m wide, with basaltic margins, hybrid transition zones, and a rhyolitic centre hosting visually distinct, elongate mafic enclaves (<1 cm – 1 m). The dyke extends over 15 km of horizontal distance and 700 m of vertical distance. We studied the dyke at three main sites, collecting field observations, oriented hand samples for mineralogy and petrography analyses, and photographs for enclave shape analysis and distribution analyses. We observe that to the south, deeper in the crust, the enclaves are generally aligned sub-parallel to strike and more randomly oriented in the dyke centre. This indicates that the flow was more turbulent towards the end, and/or that the enclaves were elongated and oriented by shear flow closer to the margins. To the north, at a shallower crustal depth, the enclaves are aligned sub-perpendicular to the dyke strike, which could be due to reduced shear or settling out of the enclaves. Above this, the rhyolitic core extends higher into the crust, beyond the mafic margins. The mineralogy reveals that some of the mafic products contain quartz xenocrysts, and interstitial quartz and alkali feldspar, indicating hybridisation is occurring early in the dyke formation. We discuss our results in terms of previous magnetic fabric analysis and geochemical analysis work at this dyke, the production of enclaves, and magma flow dynamics within a dyke. The basaltic margins likely facilitated the higher ascent of the rhyolitic magma core by superheating the melt and decreasing the viscosity. It is likely then that rhyolitic melt can mobilise with little warning and could pose an eruption risk, by composite dykes under some circumstances, which should be considered in hazard and risk assessments where silicic magma bodies are present in the shallow crust (e.g., Krafla, Iceland).

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The role of the Elbe Fault Zone in the late- to post-Variscan evolution of Central Europe

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The Elbe Fault Zone (EFZ) is one of the most important long-lived structures in Central Europe. Extending from the southeastern North Sea across northern Germany into southwestern Poland, it forms a broad NW–SE to WNW–ESE-trending zone of crustal weakness that has been repeatedly reactivated since the final stages of the Variscan Orogeny (Scheck et al., 2002).

During the late stages of the Variscan Orogeny the EFZ evolved as a continental-scale strike-slip fault system separating major Variscan crustal domains (Ziegler, 1990; Scheck et al., 2002). Continued post-collisional deformation was accompanied by widespread extensional collapse throughout the European Variscides, before post-orogenic extension and rifting became dominant across Central and Northern Europe at ca. 300-290 Ma (Wilson et al., 2004). Each of these tectonic stages was accompanied by syn-tectonic magmatism, making precise timing and geochemical characterization on EFZ magmatism essential for understanding its geodynamic evolution.

We present new zircon U-Pb CA-ID-TIMS ages from magmatic rocks of the EFZ, including the syn-kinematic granitoids of the Meissen Massif, the Markersbach Granite, and volcanic rocks of the Meissen Volcanic Complex. The data document pulsed magmatism with three main phases at 333-330 Ma, 313-312 Ma, and 300-299 Ma. Comparison with published U-Pb CA-ID-TIMS ages from the eastern Erzgebirge and the Lusatian Block reveals closely linked temporal and spatial relationships between EFZ magmatism and magmatic activity in adjacent regions throughout all three episodes. Consistent whole-rock trace-element signatures within each episode indicate broadly similar magma sources and petrogenetic processes across the region.

By integrating high-precision geochronological and geochemical datasets, we establish a three-stage evolutionary model for the EFZ that links episodic magmatism to changing tectonic regimes during the late- to post-Variscan evolution of Central Europe.

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In search of zircon: petrographic record of crystallization and temperature estimates for Permo-Carboniferous rhyolites of the Polish Lowland drill cores Błotno, Międzyzdroje, Samlino

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The Permo-Carboniferous rhyolites of the northern part of the Polish Lowland, associated with highly volatile and explosive volcanism, exhibit consistently elevated zircon saturation temperature that deviate from the regional trend of increasing temperatures from southeast to northwest (Słodczyk et. al., 2024). This study investigates rhyolites from drill cores of Błotno, Międzyzdroje and Samlino by comparing their whole-rock geochemistry and petrography, and by examining zircon occurrence and mineral associations using SEM-EDS imaging. Zircon grains were characterized through typological classification following Pupin (1980), complimenting temperature estimates and geochemical constraints on zircon crystallization. In addition to the SEM investigations of the separated zircon grains, SEM analysis of the thin sections was conducted to assess zircon distribution, inclusion patterns, and morphological features, thereby illuminating the crystallization environment. The samples are dominated by differently textured feldspar and quartz matrices, as well as mostly albitizised feldspar phenocrysts and multiple types of highly altered mafic phenocrysts, resulting in alteration products of biotite-like phases, fibrous aggregates, and clay minerals (illite-like) with varying Fe- and Ti-oxide contents. Międzyzdroje and Samlino show more pronounced hydrothermal alteration compared to Błotno. Thin-section analysis shows multiple occurrences and morphologies of zircons associated with different phenocryst types and alteration stages: Błotno contains predominantly euhedral grains with mostly resorption-induced shapes, Międzyzdroje features resorbed and broken grains, and Samlino is characterized by zircons with abundant fractures. Morphological classification of prism and pyramid faces indicates zircon saturation temperatures of ca. 900 °C (Pupin, 1980), with zircon type D (most abundant), J5, J4 and J3 identified across all samples. These temperature estimates confirm differences observed for volcanism of this region.

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Does every rhyolite alter in the same way? Application of Alteration Indices for the comparison of Permian–Carboniferous high-silica rocks

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Despite broadly similar felsic compositions, rhyolites may exhibit substantial differences in the extent of post-magmatic alteration. Such variability may result from differences in primary mineralogy and geochemistry, but can also reflect regional variations in hydrothermal activity. Therefore, alteration indices can be used to evaluate alteration intensity and explore spatial and temporal patterns in well-constrained rhyolitic occurrences such as the Permo-Carboniferous rhyolites of Central Europe (Słodczyk et al., 2024). While alteration indices may also be affected by surface weathering, geochemical investigations generally avoid strongly weathered samples, allowing elevated values to be interpreted primarily as evidence of hydrothermal alteration.

The aim of this study was to compare Permian–Carboniferous rhyolites occurring within the Polish and German Basins) and to evaluate the usefulness of selected alteration indices in revealing variability among rocks of similar age, composition, and geographic setting (Słodczyk et al., 2024). The analysis was based on published whole-rock geochemical data used to calculate nine alteration indices: Alteration Index (AI), Chlorite–Carbonate–Pyrite Index (CCPI), Silica-Alumina Ratio (R), Vogt Residual Index (V), Chemical Index of Weathering (CIW), Plagioclase Index of Alteration (PIA), Silica–Titanium Index (STI), Chemical Index of Alteration (CIA), and Weathering Index of Parker (WIP). A total of 14 rhyolite samples derived from eight different volcanic systems were evaluated.

The obtained results indicate a high degree of similarity in the values of the AI, CIW, and PIA indices, reflecting a comparable extent of feldspar alteration. At the same time, the remaining indices exhibited variability related to regional differences in the intensity of hydrothermal alteration that may be associated with the tectonic and magmatic evolution. A decreasing trend in several index values was observed with decreasing rock age and with a northwestward shift in sample location. The results suggest that the applied alteration indices may serve as effective tools for comparing high-silica rocks and for revealing spatial and temporal trends that may record variations in hydrothermal alteration history.

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The Athesian Volcanic District: Timescales and Evolution of an Ancient Caldera System

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The study of geologically young and active caldera systems has advanced our understanding of the petrogenetic processes that govern their generation and evolution. A major challenge in these systems is the inaccessibility of time-integrated records of the entire caldera cycle, as the earliest and smaller eruptive units are often not exposed. In the Southern Alps of Italy, exceptional exposures of volcanic and plutonic expressions of a large Permian silicic magmatic system provide access to an extended suite of pre- and post-caldera magmatic products. This offers an opportunity to test models of caldera cyclicity, magmatic system longevity, and magma storage conditions in an ancient caldera system.

The Athesian Volcanic District (AVD) covers an area of more than 4500 km² and includes deposits of at least two caldera-forming super-eruptions with volumes of over 1000 km^3. We applied high-precision zircon geochronology, zircon geochemistry, and geochemical analysis of apatite inclusions in zircons to eruptive units across the entire volcanic sequence. We aim to address questions about the duration of individual caldera cycles, the chemical evolution of the melt (including volatiles), and the architecture of the plumbing system.

High-precision geochronology results constrain the volcanic activity in the AVD to approximately 5 Myr (from ~281.4 to ~276.1 Ma). The results also show similar build-up periods of about 2 Myr prior to each super-eruption, with each build-up period extending from preceding smaller eruptions to the respective major event. Additionally, there is an apparent volcanic quiescence of about 1 Myr between the two periods. These results are consistent with models of crustal thermal evolution, which show that super-eruption reservoirs develop within long-lived magmatic systems (Karakas et al., 2017).

The smaller eruptions preceding each major event show geochemical similarity. Conversely, each super-eruption is characterized by its own distinct geochemical fingerprint. The older super-eruption deposit (Gargazzone Ignimbrite) is compositionally heterogeneous, displaying relatively broad ranges of zircon trace elements (such as Ti, Ce anomaly, Zr/Hf) and changes in the volatile cargo reflected in marked variations of apatite Cl contents. The younger one (Ora Ignimbrite) displays a more homogeneous and evolved geochemical trend, with overall lower Ti, Zr/Hf, and Cl values. These differences inspire questions about the divergent processes involved in building both super-eruptions and could provide evidence for different models of super-eruption generation within a single magmatic system.

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Magmatic differentiation on Mars: Can we identify evolved rocks?

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Recent advances in the Martian exploration by rovers, together with analyses of Martian meteorites, indicate that Martian magmatism is more compositionally differentiated than previously recognized. This interpretation is further supported by remote-sensing spectral observations that have identified rare felsic lithologies, providing evidence for prolonged magmatic evolution. However, due to the limited availability of high-resolution imagery and corresponding spectral datasets, our understanding remains largely biased toward the largest volcanic systems. Therefore, constraining Martian magmatic evolution requires reconstructing the eruptive history and spatiotemporal evolution of individual volcanic systems using remotely sensed morphological observations, which may reflect variations in lava rheology associated with magmatic evolution.

Through a detailed geological reconstruction of a dyke-fed plumbing system, we demonstrated a progressive spatiotemporal transition in eruptive activity, from highly mobile lava flows emplaced along the entire fissure to more viscous eruptions localized at a single vent, ultimately leading to the construction of a small volcanic cone. This evolution suggests that the volcanic system remained active for at least ≥9 Ma (Pieterek & Jones, 2023) and underwent progressive magmatic differentiation. These geological observations have been supported by remotely sensed mineralogical analyses derived from the orbital hyperspectral datasets of the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM). Spectral analyses revealed distinct mineralogical signatures among morphologically and temporally distinct volcanic units fed from the same plumbing system (Pieterek et al., 2026). The earliest fissure-fed lava flows exhibit olivine-dominated signatures, consistent with magma derived from a deep mantle or lower-crustal reservoir, whereas the younger finger-like lava flows on the summit cone are characterized by high-calcium pyroxene, indicating eruption of a more compositionally differentiated magma.

Overall, these results indicate progressive evolution of the volcanic system through crustal magma storage and differentiation, likely involving fractional crystallization and crustal assimilation. They demonstrate that orbital observations alone can help constrain magma evolution, improving our understanding of Late Amazonian volcanism in Tharsis.

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Emplacement mechanisms of trachyandesite magma intrusions in the Intra-Sudetic Synclinorium at the Polish-Czech border

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Silicic magma emplacement events have been documented less frequently than mafic sheet intrusion in Earth´s active volcanic regions recently. Thus, geological investigations of ancient, well-exposed subvolcanic intrusions and their host rocks, combined with numerical modelling, are essential to understand near-surface silicic magma emplacement dynamics. We document contact features between Early-Permian trachyandesite intrusions and their host rocks outcropping along a ca. 15 km-long NW-SE belt in the Intra-Sudetic Synclinorium along the Polish-Czech border, by using Uncrewed Aerial Systems (UAS) photogrammetry and virtual outcrop products. The former quarries of Głuszyca and Świerki-Dworki, and the active quarries of Tłumaczów and Gardzień expose several 40- 80 m-thick and hundreds of meters long intrusions of microcrystalline trachyandesite. The magmas were intruded into a 10- 30 m-thick sequence of Early-Permian Walchia Shale, underlain by the Building Sandstone, and overlain by a 10- 30 m-thick Góry Suche rhyolitic ignimbrite. The ignimbrite is dated at ca. 300 Ma and suggested to originate from the putative Góry Suche caldera centred in the Czech Broumov area. Each quarry shows a varying degree of magma-induced host-rock deformation and hydrothermal alteration. At Głuszyca, two stacked intrusive sheets are exposed; the horizontal roof contact of the lower one is brecciated, and host shale is locally folded and imbricated. At Świerki-Dworki, the vertical edges of the two adjacent intrusions are brecciated, and the sedimentary roof is highly altered, with replacement by quartz, chalcedony, and accessory minerals. At Gardzień, magma near contacts is brecciated, and shales near contacts are intensively folded or sheared, and sandstone layers are folded. Altogether, the observations testify to laterally variable thermal and mechanical interactions between shales, pore fluids and trachyandesite magma, and shear strain localization along pre-existing structural weaknesses in likely mildly consolidated sedimentary host rocks. The spatial relationship to the Góry Suche rhyolite tuffs further suggests emplacement of the trachyandesite intrusions in the upper kilometer of the Upper Carboniferous – Lower Permian succession as post-ignimbrite intrusive sheets near the margin of the Góry Suche caldera. Anisotropy of magnetic susceptibility, paleomagnetism, and aerial magnetic data will further aid in reconstructing an emplacement model of this complex volcanic system.

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Reconstructing Supereruption Magma Systems: Geochemical Constraints from Fiamme in Late Paleozoic Near-Solidus Rhyolites of Central Europe

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One of the largest clusters of Late Paleozoic caldera systems produced by catastrophic silicic VEI-7 to VEI-8 eruptions is preserved along the Elbe Lineament, where these events generated voluminous silicic pyroclastic successions. Collectively, these caldera complexes record a major tectonic transition from the late collisional stage (Teplice and Tharandt calderas; Casas-García et al., 2019; Breitkreuz et al., 2021) into the early development of continental rifting (e.g., Wurzen and Flechtingen calderas; Repstock et al., 2022, 2025). In this study, we use μ-XRF analyses of fiamme to constrain the conditions of the upper-crustal magma chambers that fed these extensive caldera systems.

Fiamme are widely interpreted as representative relics of magma originating from upper-crustal, eruptible reservoirs. The analyzed rhyolitic fiamme record temperatures between approximately 700 °C and 900 °C. Because similar temperature ranges are documented across multiple Late Paleozoic caldera systems in Central Europe, these results demonstrate recurrent magma-mingling between contemporaneously cooler and superheated rhyolitic magmas within these reservoirs. Barometric estimates from the fiamme consistently yield pressures of ~2–3 kbar, indicating upper-crustal magma storage at roughly 10 km depth, whereas other compositions point to magma generation within the middle crust (5–7 kbar, ~20–25 km depth).

The occurrence of near-solidus rhyolites along the Elbe Lineament further suggests that the continental crust remained sufficiently thick to trap mantle-derived magmas in different crustal levels, sustain prolonged fractional crystallization, and support the development of large silicic magma chambers, ultimately enabling these systems to evolve to near-solidus conditions.

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Insights into crystallization processes and magmatic temperatures of Permo-Carboniferous rhyolites from the Polish Lowland drill cores (Kamień Pomorski, Jarkowo, Gosław)

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Rhyolites, extrusive igneous rocks with high silica content, are widely distributed across Europe and frequently associated with continental rift systems. The Permo-Carboniferous rhyolites of the Polish Lowland are scientifically interesting as they offer windows into the tectonic evolution of the region. Previous studies noted a deviation from the trend observed in Central European rhyolites, where magma temperatures gradually decrease from southeast to northwest: zircon saturation temperatures calculated for zircons from the Northern Polish Lowland appear consistently higher than those of Central European rhyolites (Słodczyk et al., 2024).

This study aimed to investigate additional samples from the region to understand this deviation and the crystallization processes of the Permo-Carboniferous rhyolites of the Polish Lowland. For this purpose, we investigated and compared the whole-rock geochemistry of three localities (Kamień Pomorski, Jarkowo, and Gosław), and examined the occurrence of zircon grains in thin sections using SEM-EDS. The crystallographic development of separated zircon grains from the same localities was studied to characterize these grains using the Zircon classification introduced by Pupin (1980). The samples are dominated by anhydrous minerals such as quartz, K-feldspar, plagioclase, Fe-oxides, and Ti-oxides, characterizing them as hot-dry and reduced rhyolites. They include phenocrysts and glomerocrysts of illite-like weathering products, usually in combination with Fe-oxides, which signal later hydrothermal alterations of primary volcanic glass and feldspars. Zircon grains within these thin sections were found either in the rock matix or in association with the aforementioned mineral phases, with the illite-like phases incorporating the highist number of zircons. The typological classification provided estimated zircon saturation temperatures for the investigated zircons, all exceeding 850 °C, with Kamień Pomorski exhibiting the highest temperatures. These estimates confirm higher temperatures for volcanic activity in the region.

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Chlorine and HCl solubility in hydrous silicate melts: from melt composition to volcanic gas

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Chlorine is a key volatile in magmatic and volcanic systems, both as a ligand for metal transport and as a source of reactive chlorine in volcanic plumes. Yet the effects of melt composition and H_2O on Cl solubility remain poorly constrained, particularly at magmatic pressures. In this study we used high-pressure high-temperature experiments to determine Cl solubility in hydrous silicate melts and relate Cl dissolved in the melt to HCl in the coexisting volcanic gas.

We performed experiments at 1200 °C and 0.5–1.63 GPa on hydrous andesite, dacite and rhyolite containing up to ~8–9 wt. % H_2O. We used Ag–AgI–AgCl buffers to control fCl_2, while graphite-saturated C–O–H fluids maintained fO_2 near the CCO buffer. Together with fCl_2 and fO_2, chlorine concentrations in the quenched glasses define chloride capacity (C_{Cl}), which we combined with previous anhydrous data and hydrous experiments conducted on basaltic composition (Rusiecka & Wood, 2025). LASSO regression of the combined dataset gives a revised C_{Cl} model that better describes evolved, silica- and alkali-rich melts.

Water has surprisingly little direct effect on chloride capacity. An explicit H_2O term remains statistically insignificant up to ~8–9 wt. % H_2O. Instead, H_2O affects C_{Cl} mainly by diluting the network-forming and network-modifying cations in the melt. Thus, even at high melt H_2O contents.

We then coupled the revised C_{Cl} model to H_2–H_2O–HCl equilibria and C–H–O–S–Cl fluid speciation. The resulting expression predicts $fHCl$ from melt composition, pressure, temperature and fH_2O, without requiring independent estimates of fCl_2 and fO_2. Applied to natural melt inclusions, the model gives very low fCl_2 (~10^{-10}–10^{-6} bar) but much higher $fHCl$ (~10^{-1}–10^{2} bar), consistent with HCl-dominated volcanic emissions. It also reproduces SO_2/HCl ratios measured during the 2002–2003 Mt. Etna eruption and predicts large changes in SO_2/HCl and S/Cl during decompression as sulphur and chlorine capacities respond differently to pressure.

These results link Cl preserved in melt inclusions and glasses to HCl in magmatic gases and provide a way to investigate magma degassing, plumbing-system behaviour and volcanic halogen fluxes. (Rusiecka & Wood, 2026).

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Missing pieces of the puzzle: Decoding the magmatic evolution of a highly evolved rhyolitic system from zircon records?

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Large silicic magmatic systems are capable of producing some of the most voluminous and explosive eruptions on Earth, generating thousands of cubic kilometres of pyroclastic material and triggering caldera-forming events following the evacuation of magma reservoirs. Despite their significance, the timing and processes governing the formation and evolution of these highly differentiated crustal melts are not always straightforward. Zircon geochronology, combined with trace-element geochemistry, provides a powerful tool for reconstructing the evolution of such magmatic systems.

This study focuses on the Miocene Szerencs high-silica rhyolitic pyroclastic succession in the Tokaj Mountains (NE Hungary), emplaced at ca. 12 Ma during a period of continental extension associated with the final stages of subduction-related volcanism. With an estimated volume exceeding 100 km³, the Szerencs Unit represents one of the largest silicic volcanic units in the Pannonian Basin.

The Szerencs Unit comprises five volcanic levels, four of which are exposed at the surface and were investigated in this study. We examined zircons previously dated and chemically characterised by Lukács et al., (2024) using LA-ICP-MS. We focused particularly on crystal textures revealed by CL and BSE imaging, combined with Hf concentration maps and Th/U ratios obtained by EMPA, as well as Eu anomalies. Based on textural characteristics and Hf concentrations, four zircon populations were distinguished, each recording a different stage in the evolution of the larger magmatic reservoir. Notably, specific zircon zones display a decoupling between Hf enrichment and Th/U ratios, suggesting that these parameters responded differently to the changing magmatic conditions. Particular attention is given to the origin of dark zircon cores characterized by highly fractionated geochemical signatures. We propose alternative models for the formation of these complex zircon crystals, providing a basis for further discussion of magma differentiation, storage, and remobilization within the Szerencs rhyolitic system.

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Compositionally boring rhyolites with surprisingly complicated glomerocrysts

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The designation of rhyolite as the "Rock of the Year 2026" has provided an opportunity to reflect on decades of research devoted to these remarkable volcanic rocks. Rhyolites represent the ultimate products of prolonged magmatic differentiation within the continental crust. These high-silica magmas are generated through a combination of fractional crystallization of less evolved melts and partial melting of crustal material, ultimately producing some of the most voluminous and explosive eruptions on Earth. Despite their importance, the timescales and mechanisms governing the generation and evolution of rhyolitic magma reservoirs remain incompletely understood.

Zircon has become one of the most powerful tools for reconstructing magma assembly, storage, and differentiation histories. However, geochronological studies commonly focus on isolated zircon crystals, often overlooking their petrographic context. As a result, the connection between zircon crystallization and specific stages of magma evolution may be obscured, leading to interpretation not connected to zircon occurrence.

Here, we summarize observations from several Permo–Carboniferous rhyolitic systems of the Southern Permian Basin (particularly Polish and German Basins) linked to zircon associations. Special attention is given to the Halle Volcanic Complex (Germany), that consists of multiple laccoliths composed of both fine-grained and coarse-grained rhyolites. Drill cores penetrating up to 500 m provide exceptional access to the internal architecture of the magma system and preserve textural relationships rarely observed in erupted rhyolites.

Our petrographic and mineral-chemical investigations reveal that zircon occurs almost exclusively within glomerocrysts, interpreted as crystal aggregates assembled from components formed during different stages of magma evolution. These aggregates are dominated by mineral phases characteristic of less evolved magmas, indicating that zircon crystallization began prior to the generation of the final high-silica rhyolitic melt. Consequently, zircon ages obtained from these crystals may record earlier, pre-rhyolitic stages of magma evolution rather than solely the timing of rhyolite emplacement or eruption.

The results demonstrate that zircon cannot be fully interpreted independently of its textural environment. Integrating geochronological data with detailed petrographic and mineral-chemical observations provides a more comprehensive reconstruction of silicic magma evolution and highlights the role of crystal recycling and magma mixing during the assembly of rhyolitic reservoirs. Our study emphasizes that the petrographic context of zircon is essential for decoding the temporal and genetic evolution of silicic magmatic systems.

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Large-volume Middle Permian rhyolitic–dacitic volcanism of the Tisza Mega-unit (Hungary and Romania): Insights from petrology, geochemistry, and geochronology

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Permian rhyolitic–dacitic volcanic rocks are widespread within the Upper Paleozoic intramontane molasse sequences of the Tisza Mega-unit (Carpathian–Pannonian region), extending from the western Mecsek Mts (southern Transdanubia, Hungary) through the basement of the Pannonian Basin (SE Hungary) to the western–central Apuseni Mts (Romania). Their present structural position reflects a complex tectonic evolution involving Alpine nappe stacking and Neogene extension, while their textures and compositions were variably modified by hydrothermal and deformation-related processes. Traditionally interpreted as continental rift-related rhyolitic lavas of Early Permian age, these rocks have been substantially reinterpreted based on petrological, whole-rock geochemical, and zircon U–Pb geochronological studies, particularly regarding the timing, character, and regional relationships of Permian felsic volcanism in the Tisza Mega-unit.

Petrographic observations indicate that the felsic rocks are mainly pyroclastic, with subordinate lavas and subvolcanic rocks. Crystal-rich rhyodacitic–dacitic lapilli tuffs predominate, whereas crystal-poor rhyolitic varieties occur locally. Despite textural and minor mineralogical differences, relatively immobile trace elements (REEs and other HFSEs) indicate a broadly similar crustal source and are consistent with an extensional, continental rift-related setting. Zircon U–Pb geochronology yielded Middle Permian ages (~271–259 Ma) for the felsic volcanic rocks, supporting a regionally extensive Guadalupian rhyolitic–dacitic volcanic episode that may serve as a chronostratigraphic marker horizon within the Tisza Mega-unit. The studied rocks also show similarities to Permian felsic volcanic rocks of the Western Carpathians, suggesting a broadly comparable tectonomagmatic evolution.

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Proximal deposits of a caldera-forming event: the ca. 13.1 Ma Sátoraljaújhely eruption, Carpathian-Pannonian Region

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Background and aims

The ca. 13.1 Ma Sátoraljaújhely (SAU) eruption is the oldest and largest of four mid-Miocene silicic units in the Tokaj Mountains, northeastern Pannonian Basin. Across 150 km², ~300-m-thick volcaniclastic strata and later dacitic–rhyolitic lava domes are complemented by boreholes >1000 m deep. These combined data help identify the potential source area.

Materials and methods

We integrate mapping, facies logging, petrography and accidental lithic-clast provenance with Sau-8 (0–890 m), Rbcs-1 (500–1018 m) and Szh-2 (535–731; 1178–1302 m) cores. Zircon U–Pb dating and volcanic-glass geochemistry constrain age and composition.

Results

Eleven lithofacies define the surface and borehole succession: massive lithic breccia (mlBr), lithic-rich lapilli tuff (lrLT), pumice-rich lapilli tuff (pmLT), massive lapilli tuff (mLT), welded lapilli tuff (wLT), massive tuff (mT), stratified lapilli tuff (sLT), tuffite (Tf), claystone–marl (CM), massive dacite (mD) and massive rhyolite (mR). The pmLT–mLT ignimbrite cooling units are several to tens of metres thick; mlBr–lrLT contain basement lithics >1 m across, matching local substratum. Basal or palaeovalley-confined welding indicates high-temperature proximal deposition; mT–sLT record dilute phases and Tf–CM shallow-marine sedimentation. Dacitic–rhyolitic lava bodies are tens of metres thick, locally >100 m. Overlapping zircon ages of 12.92–13.18 Ma (± 0.21 Ma) link the explosive and effusive phases; volcanic glass preserves a coherent rhyolitic fingerprint. Zeolitic–argillic alteration in tuffs and silicification–clay replacement in lava domes define a focused hydrothermal system.

Proximal setting and palaeogeography

Large basement-derived lithics, valley-confined welding, a >1-km-thick volcanic succession, post-collapse dacitic–rhyolitic lava domes and focused hydrothermal alteration jointly demonstrate a proximal caldera setting and identify Sátoraljaújhely as the SAU source caldera. Marine fossils and Tf–CM interbeds place the caldera on the Central Paratethys shoreline, with pyroclastic density currents entering adjacent shallow-marine basins.

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Temporal and compositional evolution of the Permian Valganna volcano-plutonic complex (Southern Alps)

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The Southern Alps preserve an extensive record of Early Permian magmatism, related to post-Variscan extensional and strike-slip tectonic setting (Schaltegger & Brack, 2007). This magmatic province stretches across a 250 km E-W belt and includes major volcanic centers that produced caldera-forming eruptions alongside basins that are dominated by sedimentary units. One of the key feature of the Early Permian magmatic province is the exposure in multiple locations of magmatic rocks solidified at different crustal levels.

One location where associated plutonic and volcanic units are present is the Valganna district, SSW of Lake Lugano. This area hosts a granitic stock (Ganna granite), that underlies and crosscuts portions of a thick (ca. 1800) volcanic sequence (Bakos et al., 1990). The timing of emplacement of the Ganna granite in relationship to the volcanic sequence is poorly defined as are the geochemical characteristics of the eruptive units. In order to provide a robust geochronological framework for the district and to better understand the compositional evolution of the eruptive products, we present the results of bulk-rock geochemistry and LA-ICP-MS zircon U-Pb and trace element analyses from intrusive and volcanic rocks of the Valganna district.

Zircon geochronology results indicate a multi-phase magmatic history that features at least two major eruptive episodes intercalated by the intrusion of the Ganna granite. The earliest volcanic episode is initially characterized by a magmatically-starved phase, dominated by clastic inputs and partial sedimentary reworking of rare rhyolitic ignimbrites layers. The system then transitions into a volcanically active, compositionally diverse (andesite, dacite, rhyolite) phase, which terminates with the intrusion of the Ganna granite. Coeval to post-dating the emplacement of the Ganna granite intrusion is the last volcanic episode, characterized by a set of rhyolitic tuff and ignimbrites including a peculiar, fayalite-bearing vitrophyre. The bulk-rock results indicate that the system is dominated by silicic eruptive (rhyodacites to high-silica rhyolites; 69-77 wt. % SiO_2) and intrusive (high-silica granites; ca. 77 wt. % SiO_2) lithologies. Zircon trace element budget shows consistent evidence for relatively cool (low Ti), highly differentiated (low Eu anomaly, Zr/Hf) magmas. Exception to this trend is presented by volumetrically minor andesite lavas and fayalite-bearing vitrophyre, whose anomalous bulk-rock and zircon composition indicate transient changes in magma generation processes.

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Rhyolites of the Altenberg–Teplice and Tharandter Wald calderas: from magnetic fabrics to geomagnetic excursions

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The Late Carboniferous Altenberg–Teplice (ATC) and Tharandter Wald (TWC) calderas in the NW Bohemian Massif preserve a record of ~315–313 Ma rhyolitic magmatism, from pre-caldera volcanism, through caldera-forming eruptions, to syn- and post-collapse intrusions. This contribution synthesizes geological, magnetic fabric, paleomagnetic, and rock-magnetic results from proximal and outflow ignimbrites, their source dyke swarm, associated ash-fall deposits, and ring dykes.

Magnetic fabrics of pre-caldera, small-volume, moderately welded ignimbrites of the ATC indicate westward transport from vents along the E margin of the future caldera. The voluminous caldera-forming ignimbrites were intensely welded and rheomorphically deformed, locally obscuring their primary depositional fabrics. Nevertheless, their fabric pattern, combined with field relations, petrography, geochemistry, and geochronology, links them to a rhyolite dyke swarm along the NW caldera margin and documents transport towards the S and SE. Fabrics within the feeder dykes record magma flow through a segmented plumbing system controlled by regional strike-slip tectonics. The distribution, isopachs, and grain-size trends of the outflow ignimbrites document SE-directed transport and associated co-ignimbrite ash fall within the Bohemian Carboniferous basins. Terminal collapse involved emplacement of microgranitic to rhyolitic ring dykes, whose fabrics indicate localized ascent and lateral flow of crystal-rich magma along the ring fault.

The TWC rhyolitic ignimbrites contain several magnetic subfabrics, whose separation distinguishes depositional transport and compaction from later rheomorphic and hydrothermal modification. Zircon thermometry indicates derivation from 770–930 °C felsic magmas, whereas thermal demagnetization of lithic clasts and the host ignimbrite constrain deposition at 550–600 °C. Paleomagnetic components unblocked at 350–450 °C reflect deuteric oxidation and syn- to post-caldera hydrothermal alteration.

In the ATC, alternating-field and thermal demagnetization isolate stable characteristic remanent magnetizations carried by single-domain and vortex-state low-Ti titanomagnetite. Most samples retain a primary thermoremanent magnetization acquired during cooling in the reversed-polarity Chron PE5r. Certain intra-caldera ignimbrites and younger ring dykes, however, preserve distinct intermediate directions deviating by more than 45° from the expected dipole states. Combined with cross-cutting relations and U–Pb ages, these directions record two short-lived geomagnetic excursions between 314.7 and 312.6 Ma within the ~318–265 Ma Kiaman Reverse Superchron.

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Late Paleozoic Gréixer Rhyolite Complex (Southern Pyrenees): Rock-magnetic and paleomagnetic evidence for tectonic history and graben-caldera origin

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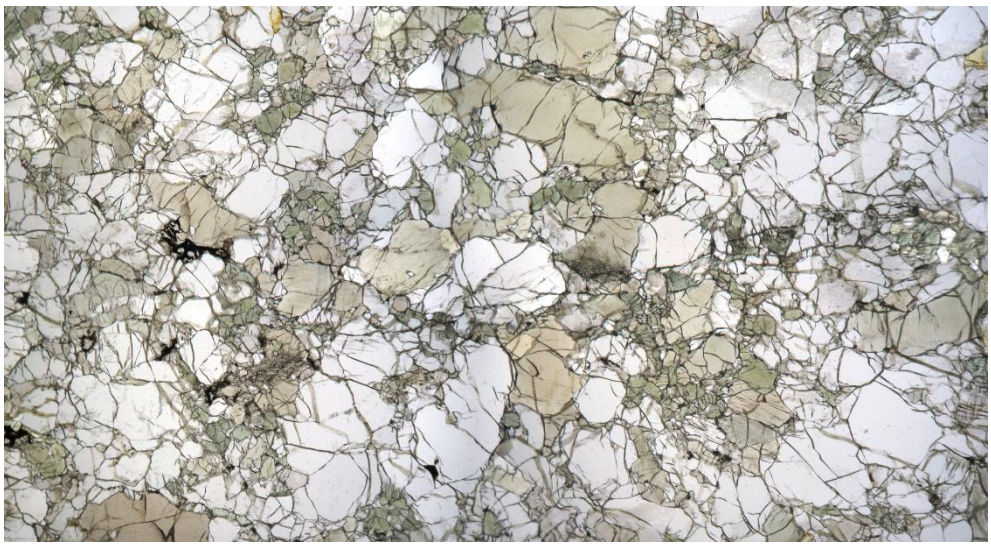
The Late Variscan Gréixer Rhyolite Complex (GRC) in the Catalan Pyrenees comprises a ~12 km long, 350–700 m thick deposit of predominantly welded to rheomorphic felsic ignimbrites interpreted as intra-caldera fill. This study integrates geological mapping, petrography, rock-magnetic analyses, anisotropy of magnetic susceptibility (AMS), and paleomagnetism to constrain the GRC's depositional kinematics, source vents, and tectonic history. The magnetic mineralogy is dominated by primary magnetite (ranging from superparamagnetic to a multi-domain state) and minor hematite. Pre-caldera dacitic volcanism depleted the magma chamber, which triggered a graben-style caldera subsidence within a transtensional tectonic regime. AMS data reveal subhorizontal magnetic foliations and W–E-trending shallow magnetic lineations, demonstrating that ignimbrites erupted from rim vents and traveled within the confined graben. Parataxitic textures and steep magnetic foliations record localized rheomorphic secondary flow or return flow towards the caldera's topographic center, while lineations remained E–W as magnetite grains rolled perpendicular to the graben axis. Anomalous fabrics mark zones where primary and secondary flows intersect. Paleomagnetic stepwise thermal demagnetization isolated three remanence components: a modern field overprint (Component A); a Cretaceous thermoviscous remagnetization (Component B, 300–580 °C) linked to low-temperature Alpine metamorphism; and a high-temperature hematite component (>580 °C) capturing the primary Late Carboniferous geomagnetic field. These data delineate a three-step tectonic evolution: primary Variscan deposition followed by a 35° counterclockwise vertical axis rotation of Iberia; north-directed tilt around a horizontal axis during early Alpine deformation (persisting long enough to remagnetize magnetite); and final rotation into its present south-dipping orientation. Overall, these findings reconstruct the complex eruptive, rheomorphic, and structural timeline of the GRC.

31st Meeting of the Petrology Group of the Mineralogical Society of Poland

Mantle Fascination



Peridotite xenoliths in basalt, Dreihausen quarry, Vogelsberg, Germany
(photo: J. Puziewicz)



Peridotite from Montboissier quarry, Massif Central, France. Optical image, plane polarized light. Width of the photo ~4 cm. (photo: J. Puziewicz & M. Matusiak-Małek)

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Volatiles in the Variscan orogenic cycle as told by orogenic peridotites and mantle xenoliths

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The transport of volatile elements from the exosphere to the mantle via subduction, and their long-term storage in Earth's interior - versus re-entry into the atmosphere via magmatism and tectonic degassing - remain poorly constrained. The lithospheric mantle (LM), at the interface between these two major reservoirs, represents a potentially important sink and source of volatiles, and its role is only starting to be systematically addressed (Gibson & McKenzie, 2023). Here, we consider the effects of the orogenic cycle on the volatile element inventory of LM that evolved in a palaeo-convergent plate boundary affected by subduction, tectonic accretion, collapse and rifting. We take the European Variscan Orogen (EVO) and subsequent development of the European Cenozoic Rift System (ECRIS) through parts of the EVO as an example, keeping in mind the evolutionary diversity of this vast terrain.

LM is initially stabilised by decompression melting, where H_2O behaves like a highly incompatible element, while redox-melting extracts CO_2 initially stored in refractory graphite/diamond. Sulfur extraction efficiency depends on S solubility in the melt, S content and melt fraction, and refractory residues are predicted to be S-poor. The effect of continental (and preceding oceanic) subduction on the volatile element inventory of the mantle wedge is gauged by tectonically exhumed peridotite, which suggests a net addition of COHS via introduction of carbonate, hydrous and sulphide minerals accompanied by moderate oxidation (Förster et al., 2024). The emplacement of syn-/late-/post-orogenic Mg-K-rich magmas (lamprophyres and lamproites) with subduction-related affinity testifies to the protracted (10s Ma) subsequent remobilization of earlier-formed hydrous mantle metasomes (Krmíček et al., 2020), the low solidi of which facilitate melting during heating and/or decompression. The effects on C and S are unclear, but fO_2 remained mostly below sulphate stability, and sulphides may have persisted in the residue.

Tectonic reconstructions (Vanderhaeghe et al., 2020) and basalt-borne xenoliths with garnet break-down microstructures (Puziewicz et al., 2025) concordantly point to a Variscan orogenic evolution marked by crustal thickening and gravitational collapse in a context of lithospheric convergence accommodated by slab retreat, which induced thinning of the upper plate lithospheric mantle. This brought huge volumes of carbon-enriched (~1,000 μg/g C; Förster et al., 2024) garnet-facies LM to depths where decarbonation and associated mantle-CO_2 degassing could occur if subsequently heated ± decompressed (~1.8 Mt yr^{-1} for the French Variscides, for an area of 400x600 km and 50 Ma duration). Pressure-temperature paths for various Variscan peridotite occurrences (Sizova et al., 2024) compared to the

peridotite + H_2O + CO_2 solidus and to the decarbonation reaction boundary indicate that peridotites in most parts of the European Variscides would have crossed both boundaries. Peridotites from the Ulten Zone tectonic mélange are a notable exception, however, and these are known to contain abundant carbonates (e.g., Sapienza et al., 2007).

The recent find of a garnet-bearing xenolith in a core drilled into a Cretaceous ultramafic lamprophyre from the Delitzsch Carbonatite Complex, which intruded Saxothuringian basement near the southern edge of the Mid-German Crystalline Zone, provides a surprising twist on post-Variscan LM thickness evolution: Geothermobarometry retrieves a depth of ~190 km, which far exceeds the modern lithosphere-asthenosphere boundary (for which various estimates exist), while its mosaic to mosaic-fluidal microstructure and composition, which resemble sheared cratonic peridotites, attests to intense deformation and metasomatism (Röper et al., 2025). Whether the lamprophyre sampled tectonically partially exhumed orogenic peridotite, or whether passive lithosphere thickening by thermal relaxation occurred after orogenic gravitational collapse, remains to be established. In the French Variscides, the latter hypothesis is supported by the formation of lithospheric-scale sag basins, such as the Paris and Aquitaine basins, which suggest that orogenic collapse was followed by thermal subsidence and LM thickening (Vanderhaeghe et al., 2020). Regardless, the emplacement of a spectrum of carbonatites and ultramafic lamprophyres indicates that the LM contained, or had retained, volatile-bearing metasomes that could be mobilised during Eo-Alpine reactivation of inherited Variscan sutures.

The effect of ECRIS development and minor (~5 km) associated thinning on the collage of Variscan LM is gauged by mantle xenolith studies (Puziewicz et al., 2020). During this stage, magma affinity shifted to anorogenic, reflecting earlier (partial) consumption of volatile-rich metasomes, which left the LM largely below its solidus. Interaction with carbonated silica-undersaturated basalts and associated wehrlitisation of shallow LM suggests a CO_2 flux of 1.7 ± 1.1 Mt yr^{-1} in the ECRIS (Aulbach et al., 2020), similar to the estimate for the French Variscides. There is evidence in some EVO xenolith suites for introduction of hydrous and sulphide minerals during rift-related carbonated melt metasomatism; stable isotope data are required to understand the inherited subduction- vs. rift-related mantle metasomatic origin of volatile elements in the LM.

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Hydrous phases, fluids and melts as controls on upper mantle deformation: insights from peridotite microstructures

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It is well known that the H_2O component can influence upper-mantle deformation through its presence in hydrous minerals, aqueous fluids, hydrous melts, and structurally bonded H_2O in nominally anhydrous minerals (NAMs). However, natural peridotites provide direct evidence that these forms of H_2O do not have equivalent effects on mantle microstructures or rheology. While synkinematic interstitial melts may significantly weaken the mantle and induce a transition to stress-controlled dissolution-precipitation creep, the mere presence and abundance of stable hydrous minerals do not exhibit a systematic relationship with olivine fabric strength or crystallographic preferred orientation (CPO) symmetry. Although hydrous mineral phases control the water storage capacity of the mantle, their presence alone seems to have a limited impact on rheology under dislocation creep conditions. Furthermore, the formation of hydrous minerals depends on the whole-rock composition (e.g., the availability of Na and K) and physicochemical conditions (P-T). Their low modal abundance (<2 vol. %) in refractory peridotites does not preclude significant percolation of interstitial aqueous fluids, as an excess of fluid may not lead to additional hydrous-mineral crystallization under unfavorable conditions. Thus, the low abundance of hydrous phases and low H_2O content in coexisting NAMs cannot be considered evidence of a dry system under shallow upper-mantle conditions. In subsolidus conditions, particularly in the shallow mantle domains beneath the hyperextended subcontinental lithosphere, at oceanic transform faults, and in mantle wedges, microstructural records suggest that the feedback of synkinematic aqueous fluids on deformation may alter the olivine CPO symmetry and promote oriented crystallization rather than conventional dislocation creep, thereby facilitating fluid-assisted dissolution-precipitation creep. In contrast, despite experimental evidence indicating a relationship between the concentration of structurally bonded H_2O in olivine and CPO symmetry, the global natural record does not show a clear systematic correlation between these parameters. Altogether, these observations suggest that the transient availability, distribution, and transport of aqueous fluids and hydrous melts may exert a stronger influence on upper-mantle deformation and microstructural evolution than the mere presence of hydrous minerals or the absolute H_2O content of NAMs. Deformation may occur only while fluids or melts are available and may cease once they are exhausted or redistributed. The availability and transport of fluids and melts are governed by transient processes that may exert greater control over deformation than prolonged near-equilibrium conditions. Consequently, permanent microstructural signatures preserved in the mantle may reflect short-lived, intermittent fluid- and melt-assisted deformation events. A comprehensive understanding of upper-mantle deformation therefore requires constraints on when and how fluids and melts are generated, become available, and are mobilized in the lithosphere.

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From ocean-continent transition to transform faults: The relationships between deformation and melt percolation

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Continental margins and transform faults play a fundamental role in shaping the structure and evolution of the lithosphere. Over the past two decades, studies of ocean–continent transitions (OCTs), based on both oceanic drilling and dredging and on their exhumed analogues in orogenic belts such as the Alps, have revealed that the architecture of passive margins is considerably more complex than suggested by early models. Rather than being characterized by thick oceanic crust and symmetric structure, magma-rich accretion, OCTs may involve highly thinned continental crust, exhumed mantle, isolated continental blocks, and mantle domains with distinct compositional and structural histories.

Here, I focus on the mantle and investigate how deformation, melt percolation and chemical modification interact during lithospheric extension. I first present results from the Platta, Totalp and Tasna peridotite massifs in the Swiss Alps. Pyroxene compositions provide constraints on the evolution and geodynamic setting of mantle domains throughout the ocean continent transition (with a decrease in Na_2O toward the ocean). These peridotites also record strong localization of deformation associated with high temperature amphibole enriched in K, trace-element enrichment, highlighting a close coupling between hydrated melt infiltration and mechanical weakening of the mantle. Secondly, I discuss mantle deformation beneath oceanic transform faults, based on results from the St. Paul and St. Peter and the Romanche transform systems in the equatorial Atlantic. These systems provide evidence for deformation assisted by hydrous melts and fluids, accompanied by major mineralogical reactions, which is probably a major mechanism for mantle weakening.

Together, these examples demonstrate that mantle deformation beneath ocean-continent transition and transform faults cannot be considered independently from hydrous melt migration. Melt–fluid interaction may profoundly modify mantle mineralogy and chemistry, while simultaneously facilitating and localizing deformation, establishing a strong feedback between chemical and mechanical processes in the lithosphere.

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Tectonic Architecture and Lithospheric Inheritance of the European Variscan Belt

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The European Variscan belt formed through diachronous Laurussia–Gondwana convergence and accretion of peri-Gondwanan continental ribbons during Pangaea assembly. Its architecture reflects inherited contrasts between rigid cratonic blocks and extended continental margins. Geological and geophysical results, zircon provenance, metamorphic petrology and mantle xenoliths distinguish preserved cratonic domains from reworked orogenic lithosphere (Schulmann et al., 2022; Mazur et al., 2025, 2026).

Relatively coherent pre-Variscan terranes contrast with the intensely reworked Variscan Internal Zone (Galicia–Moldanubian zone). Avalonia, Baltica and Brunia formed the northern foreland, whereas Saxo-Thuringia–Ossa-Morena and Armorica–Teplá–Barrandia represent intervening continental ribbons. Gondwana-derived domains occupy a much greater area than the internal orogenic crust. Early Palaeozoic rifting produced attenuated margins and ribbons whose contrasting mechanical properties influenced subduction and deformation. The Internal Zone is not simply a Laurussia–Gondwana boundary, because Gondwanan terranes also occur to its north.

Detrital zircon spectra support widespread Gondwanan provenance but reveal along-strike differences: Saxo-Thuringia and Armorica show northwestern African affinities, whereas Central Iberia records a northeastern African–Arabian signature. These contrasts imply significant lateral displacement before and during Variscan assembly. Gondwanan provenance does not establish continued attachment to Gondwana during collision; sedimentary recycling and drainage reorganisation must also be considered (Collett, 2025; Mazur et al., 2025).

Seismic data distinguish cratonic, transitional and Variscan orogenic crust (Schulmann et al., 2022). Gravity-constrained crustal models and lithosphere–asthenosphere boundary (LAB) depths additionally reveal contrasting lithospheric preservation. Baltica retains thick, three-layered crust and a LAB reaching approximately 250 km. Its deep lithosphere extends approximately 100–150 km southwest of the Teisseyre–Tornquist Zone beneath the external Variscan belt. This rigid buttress helped control the approximately 90° change in orogenic trend towards Poland. Avalonia and Armorica retain deep mantle roots despite crustal modification, whereas Saxo-Thuringia, Teplá–Barrandia and much of the Internal Zone have thin lithospheric mantle. Brunia's architecture resembles a magmatic arc. The lithospheric mantle-to-crust thickness ratio highlights these contrasts.

High- and ultrahigh-pressure assemblages in the Internal Zone, including eclogites associated with felsic granulites and migmatitic gneisses, record deep burial followed by exhumation, thermal relaxation and partial melting. These associations are interpreted as evidence for crust–mantle decoupling and accretion of buoyant material detached from downgoing slabs. Representative sections combine approximately 30–40 km of crust with

only about 40 km of lithospheric mantle. Negative gravity anomalies are consistent with a substantial felsic component, rather than uniquely indicating crustal thickening. Some eclogites may record crustal thickening rather than subduction, requiring distinct burial histories to be considered.

The integrated evidence supports a bivergent model, with south- to southeast-directed subduction along the northern branch and north-dipping subduction along the southern branch (Mazur et al., 2026). Southward retreat of the latter slab promoted mantle thinning, asthenospheric upwelling and heating of the orogenic root. Partial melting weakened the crust, facilitating exhumation and gravitational redistribution (Vanderhaeghe et al., 2020). The Bohemian Massif retains crust locally exceeding 40 km, with prominent vertical extrusion and limited lateral flow. Conversely, the French Massif Central and Iberia record extensive flow of partially molten lower crust and extensional collapse, producing a broadly flattened Moho at approximately 30–32 km. Mantle delamination is a proposed further consequence.

Mantle xenoliths define three mantle types recording inheritance and modification (Puziewicz et al., 2020). Depleted harzburgitic suites are interpreted as heterogeneous remnants of an orogenic mantle wedge containing accreted continental and oceanic components. Refertilised lherzolites record interaction of harzburgitic protoliths with melts resembling mid-ocean ridge basalts, plausibly associated with asthenospheric upwelling during orogenic collapse (Mazur et al., 2026). A third mantle type was strongly modified by Cenozoic rifting and reactive basaltic melt percolation. Light rare-earth-element depletion in clinopyroxene of refertilised lherzolites contrasts with enrichment in strongly rift-modified suites. Mineral chemistry and deformation fabrics indicate that lithospheric memory can survive younger metasomatism, while cautioning against attributing all mantle characteristics to Variscan processes.

The European Variscides preserve a dual inheritance: older rift architecture and rigid lithospheric promontories controlled collision, while Variscan subduction, crustal flow and mantle reworking established persistent heterogeneities. Permian–Mesozoic extension, Alpine deformation and Cenozoic rifting subsequently modified this framework. Present-day lithospheric structure is therefore not an unaltered image of the Palaeozoic orogen; its interpretation requires geological, petrological and geophysical evidence to distinguish inherited architecture from younger tectonothermal overprints.

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The evolution of the Patagonian Lithospheric Mantle, Argentina: an Overview

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Patagonia is the southernmost part of the South American Plate could be considered as a microcontinent and thought there is a debate about their alochthone or autochthone origin, the prevalent theory based on recent studies support the alochthony arguing that it is comprised of multiple lithospheric fragments with different origin and stabilization ages. Two massifs dominate Patagonia namely the Northern Patagonia Massif (NPM) and the Deseado Massif (DF) to the south. Patagonia has been shaped by the ongoing subduction of the Nasca and the Antarctic oceanic plates, which are responsible for the formation of the Andean continental arc and the back-arc region. The back-arc region is characterized by voluminous, late Miocene "main plateau" tholeiitic basalts and less-voluminous Pliocene "post plateau" alkali basalts. The latter frequently carry mantle xenoliths up to 30 cm in diameter.

Mantle xenoliths are divided into two categories; those which are located along and in various distance from the subduction zone in the back-arc region are mainly related to the development of a slab window and those that are not related to the subduction processes.

The main features of the mantle xenoliths along the subduction zone in the back-arc region is the presence of hydrous phases such as amphibole and/or phlogopite. In the NPM the Comallo xenolites experienced hydrous modal metasomatism while those not related to subduction processes are lacking of modal metasomatism. However, in the DF to the south, mantle xenoliths from Tres Lagos and Cerro Fraile despite their proximity to the subduction zone record only cryptic metasomatism. The opposite is true for the mantle xenoliths from Gobernador Gregores, a region far away from the subduction zone, that experienced intensive modal metasomatism. Garnet-bearing xenoliths from Pali Aike also contain abundant metasomatic hydrous phases.

Os isotope data on selected mantle xenoliths from the NPM, reveal domains of subcontinental Lithospheric Mantle (SCLM) with stabilization ages of 1.1-1.3 Ga and 1.7 Ga, whereas domains in the DM record ages ranging from 0.9-1.3 Ga, 1.3-1.7 Ga and 2.7 Ga for Pali Aike, highlighting the complex evolution of the Patagonian lithosphere.

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Mantle root of the European Variscides – the xenolith story

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Mantle xenoliths hosted by volcanic rocks provide a major source of information on the lithology, composition and physicochemical state of the subcontinental lithospheric mantle. Mantle peridotites are metamorphic to ultrametamorphic rocks, the foliation and lineation of which are commonly not or poorly developed or difficult to recognize in xenoliths. Consequently, conventional xenolith studies often lack the textural constraints required to establish mineral crystallization sequences, which ideally requires rock sections cut perpendicular to foliation and parallel to lineation. This limitation can be overcome through analysis of crystal-preferred orientations (CPO) by electron-backscatter diffraction, which allows deformed and undeformed fabric elements and their relative orientations to be identified, and, in turn, helps constrain mineral crystallization sequences. Combining CPO analysis with *in situ* chemical analytical techniques (electron-probe microanalysis and inductively-coupled plasma mass spectrometry) enables a comprehensive chemical and textural characterization of mantle xenoliths, and provides insight into the evolution of their parental peridotite series. This contribution discusses the significance of recently accumulated data on xenoliths coming from the mantle root of the Variscan orogen of Europe.

The European Variscides comprises several distinct subduction-collision systems formed during the Late Paleozoic collision between Gondwana and Laurussia. Slices of garnet peridotite occurring in the exposed Variscan metamorphic basement indicate that the mantle root of the thickened orogen reached the garnet peridotite facies during the orogenic stage (Ackerman et al., 2025). Today, Moho beneath much of the Variscan belt lies at depths of approximately 30-32 km, whereas the lithosphere-asthenosphere boundary (LAB) is probably situated at about 70-80 km (Mazur et al., 2026).

Xenoliths from the southern French Massif Central represent “asthenosphere-derived mantle” in the terminology of Puziewicz et al. (2020). They record large-scale rejuvenation of the mantle during late-orogenic collapse in the latest Carboniferous and Early Permian, followed by localized, probably Cenozoic, hydrous metasomatism. These xenoliths are considered representative of the lithospheric mantle beneath the southern part of the Variscan orogen, which was modified during Mesozoic and Cenozoic evolution of the adjacent Alpine Tethys.

The xenoliths from the northern French Massif Central, and from the Saxo-Thuringian and Rheno-Hercynian zones of the Variscan orogen come from the “Variscan orogenic mantle” *sensu* Puziewicz et al. (2020). This type of lithospheric mantle consists of fossil Variscan mantle wedge(s) together with mantle slices accreted to them. Regions underlain by this mantle record Mesozoic cooling and subsidence, followed by Cenozoic uplift and rifting related to Alpine orogenic processes (Meier et al., 2016). Clinopyroxene occurring in peridotites forming this mantle was replaced and/or added during Cenozoic volcanic activity.

Combined xenolith, geological, and seismic evidence therefore indicates contrasting late- and post-orogenic evolution of the lithospheric mantle beneath the northern and southern European Variscides. Despite these regional differences, the Variscan domain as a whole records shallowing and flattening of the Moho to approximately 30 km and shallowing of the LAB, probably as a consequence of late-orogenic Variscan collapse (Mouthereau et al., 2021). Later Cenozoic rifting and associated alkaline volcanism affected large parts of the Variscan basement and brought mantle xenoliths to the surface, providing a direct record of the long-term evolution of the mantle root of the European Variscides.

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Reaction experiments granitic melt-mantle rocks: insights into crust-mantle interaction products

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Crust-mantle interaction is responsible for mantle refertilization. Slab crustal material transported by melts and/or fluids interacts with the overlying mantle during subduction and enriches it in incompatible elements. An example of this process is the primary melt inclusions trapped in eclogite lenses within peridotite bodies in the Granulitgebirge, Bohemian Massif (Germany). These eclogites are produced by the interaction between a granitic melt now trapped in them and a (ultra)mafic layer already present in the peridotite at 2.2 GPa and 1000 °C. However, the nature of the pre-existing layer is still unknown.

To identify this layer and better constrain the role of crust-mantle interaction in the genesis of garnet-bearing rocks, we performed melt-rock reaction experiments at the conditions at which the interaction took place in the Granulitgebirge. The experiments were performed with a piston cylinder at 1.5, 2.2, and 2.9 GPa and 1100 °C with two melt:rock weight proportions (1:9 and 3:7). The starting materials are two mantle protoliths (a pre-synthetized fertile lherzolite and a natural spinel clinopyroxenite) and a granitic glass with the same composition as the melt measured *in situ* in the Granulitgebirge eclogites.

The reaction lherzolite-granitic melt generated orthopyroxene-rich websteritic assemblages with garnet and rare phlogopite at 2.2 GPa and amphibole rather than garnet at 1.5 GPa.

The reaction spinel clinopyroxenite-granitic melt constantly produces garnet and clinopyroxene along dacitic-basaltic andesitic residual melt. The new clinopyroxenes have higher X_{Mg} and Na and Al content increasing with melt:rock ratio. Granet modal concentration increases with pressure, and at 1.5 GPa garnet grows as a giant poikilitic grain (~ 1 mm), suggesting a very fast crystallization rate. From core to rim, garnets display an increase in X_{Mg} and Ca and a decrease in Ti. These last reaction experiments successfully reproduce the mineral assemblage and garnet composition of the Granulitgebirge eclogites, and thus the pre-existing layer was most likely a spinel clinopyroxenite.

Our results show that: (i) pyroxenites are very reactive and they may play an important role in the genesis of mantle heterogeneities; (ii) the products and assemblages of the experiments are similar to metasomatized mantle rocks worldwide indicating the contribution of continental crust subduction in generating garnet-bearing mantle rock and re-fertilizing the mantle; (iii) garnet growth is very fast and likely enhanced by the presence of melt.

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Samples of terrestrial planetary mantles: what do the rocks say?

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The silicate mantle of terrestrial planetary bodies is the source of basaltic or ultramafic magmas. Any combination of olivine with orthopyroxene + clinopyroxene + an Al-bearing phase can undergo partial melting to yield such magmas, so there are few constraints on the composition of planetary mantles other than that they are likely ultramafic. The Earth's slightly hydrous mantle with its homogeneous Mg# of 89-92 is a poor analogue for other planetary mantles, since Mg#s of planetary mantles are thought to range from 99 (Mercury) to 74 (Vesta). We therefore need to investigate examples of ultramafic rocks derived from planets, moons and asteroids for more information about the mantles of extraterrestrial planetary bodies.

Much is known about the mantle of the Earth, as a consequence of studying the abundant mantle xenoliths brought to the surface by volcanism. Although equivalent fragments of the mantle of any other solar system body are very rare, some have been recently identified. A dunite clast with an Mg# of 83 in a brecciated lunar meteorite may be a fragment of the lunar mantle. A recent study (Bhanot et al., 2024) has proposed that the Apollo 17 olivine-rich sample 72415-7 (Mg# = 87.4) is a piece of the lunar mantle, excavated to the surface during an impact. Intergrowths of Cr-spinel and pyroxene in these samples are considered to be relics of garnet, implying crystallization at depths >400 km.

Ultramafic achondrite meteorites dominated by olivine and pyroxene may provide insights into the mantle of terrestrial planetary bodies. Some dunite or harzburgite clasts with Mg#s of 82-92 are considered to be derived from the Vestan mantle, as may be the case for olivine-rich meteorites of Vestan affinity showing a wider range of Mg#s (71-91). Some rare ungrouped ultramafic achondrite meteorites with extremely high Mg#s (99) may represent the mantle of an unknown FeO-poor parent body.

Ureilites are the most common ultramafic achondrite meteorites. They are pieces of the residual mantle of a differentiated asteroid, dominated by olivine but also containing varieties of pyroxene. Ureilites show a wide range of Mg#s from 75 to 99, covering the range of mantle compositions predicted for Mars, Vesta and Mercury, and so might offer useful analogues for a variety of planetary mantles. However, a major difference between the parent body of ureilites and other terrestrial planetary bodies may be compositions of magmas produced, as their observed extracted melts are intermediate rather than basaltic (Downes et al., 2024).

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Probing a Heterogeneous Mantle beneath the Carpathian–Pannonian Region: Olivine–Spinel Records from Late Miocene–Quaternary Alkali Basalts

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The emplacement of basaltic magmas is one of the most prominent geological processes on Earth. Plate tectonic theory explains most volcanic activity by processes at plate boundaries, whereas intraplate volcanism appears to be controlled primarily by mantle processes. Most basaltic magmas are generated by partial melting in the upwelling asthenosphere, yet the mechanisms initiating melting remain poorly understood. Petrogenetic modelling suggests that mantle melting may occur at depths of up to ~100 km beneath the lithosphere. Such deep melting is facilitated by the presence of water or recycled crustal components, such as eclogite or pyroxenite, to lower the solidus and enhance melt productivity. Growing evidence also indicates that melting occurs over a broad depth interval and that erupted basalts represent aggregated melts derived from compositionally heterogeneous mantle sources.

Early-crystallized minerals such as olivine and spinel provide valuable information about mantle melting processes. Trace elements in olivine, including Ni, Mn, Ca, and Zn, are sensitive to source lithology, whereas Al can constrain crystallization and mantle potential temperatures. Spinel inclusions in olivine macrocrysts also reflect the nature of the mantle source. Here, we investigate olivine–spinel pairs in alkaline basalts from several volcanic fields in the Pannonian Basin.

Olivine compositions from the central and northern Pannonian Basin, including Putikov, the youngest basaltic volcano in the region, indicate that the mantle source likely contained eclogite and/or pyroxenite, consistent with trace-element modelling. Ca diffusion modelling in olivine suggests that basaltic magmas ascend from the upper mantle to the surface within a few days, although in some cases magma accumulated at the crust–mantle boundary. Calculated mantle potential temperatures (1350–1400 °C) do not support the presence of a thermal anomaly but provide constraints on the lithospheric geotherm. In contrast, basaltic magmas from the Perșani volcanic field in the southeastern Carpathians were generated by partial melting of peridotite, presumably metasomatized by fluids released from the descending slab beneath the Vrancea zone. The wide compositional range of spinel, even within individual basalts, further confirms the heterogeneous nature of the asthenospheric mantle and supports an aggregated-melt model for basaltic magma generation.

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Amphibole-bearing xenoliths from Mt. Bar: a hydrous story from the lithospheric mantle beneath the Massif Central, France

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Amphibole-bearing mantle xenoliths occur in several suites across the French Massif Central (Puziewicz et al., 2026). We investigated the Mt. Bar xenoliths from the Devès volcanic field in the southern mantle domain to characterize their petrological and geochemical variability and compare their amphibole with that recently described from Marais de Limagne.

The Mt. Bar xenolith suite comprises peridotites and pyroxenites varying from Cpx-poor harzburgites to pyroxene-rich lherzolites, containing dispersed amphibole (0-4 vol. %). Olivine has Fo 88.3-90.6, and orthopyroxene has Mg# 0.89-0.91. Across the suite, clinopyroxene (Mg# 0.89-0.92) becomes progressively enriched in Al and Ti and depleted in Cr with increasing modal pyroxene content. Its REE patterns range from LREE-depleted to enriched. Enrichment occurs in a few xenoliths without systematic relation to modal pyroxene abundance or Cpx composition. Pargasitic amphibole REE patterns mimic those of coexisting Cpx. Ol and Opx commonly define a coherent CPO framework, whereas Cpx CPO varies from broadly aligned with the Ol-Opx fabric to more dispersed or locally misaligned. Amp exhibits a weak to locally well-developed CPO, broadly aligned with pyroxene CPOs.

Xenoliths with LREE-depleted Cpx experienced variable degrees of refertilization by reactive percolation of DMM-derived MORB-like melts (Ziobro-Mikrut et al., 2024). The refertilization was not restricted to a single post-kinematic event but occurred at different stages relative to deformation. The LREE enrichment reflects a subsequent limited cryptic metasomatic overprint. Amp records a spatially heterogeneous, limited hydrous metasomatic overprint related to diffuse and/or low-flux percolation of an H_2O-rich, Rb-Ba-Sr-bearing melt or fluid, similar to that at Marais de Limagne (Puziewicz et al., 2026), and decoupled from the earlier refertilization and cryptic enrichment. Together, these relationships indicate that Mt. Bar preserves a first-order refractory-to-refertilized compositional trend that was subsequently overprinted by spatially heterogeneous cryptic and late hydrous metasomatism, producing a mantle mosaic with variable deformation and metasomatic histories.

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Secondary microstructures in mantle peridotite xenoliths as tracers of mantle processes beneath the Głubczyce area

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Basaltic rocks from the Głubczyce area (Opole Silesia) contain scarce peridotite xenoliths. These xenoliths provide valuable information on the composition and evolution of the lithospheric mantle beneath the easternmost part of the Cenozoic Central European Volcanic Province. Their limited size (typically <2 cm) hampers reconstruction of primary lithological relationships, making secondary reaction microstructures particularly important records of late-stage mantle modification.

The xenoliths are spinel harzburgites with predominantly protogranular textures. They consist of olivine (Fo = 85.98–92.23), orthopyroxene (Mg# = 0.88–0.93), scarce clinopyroxene (Mg# = 0.89–0.93) and spinel (Mg# = 0.44–0.73; Cr# = 0.15–0.65).

The peridotites contain abundant fine-grained intergranular reaction aggregates representing three textural and compositional types. Type 1 consists of elongated clinopyroxene (Mg# = 0.91–0.94), olivine (Fo = 90.25–90.70) and glass/feldspar. Where primary spinel is present, it is strongly corroded and disintegrated along grain boundaries while preserving the overall shape of the original crystal. Type 2 forms oval, fine-grained domains dominated by vermicular clinopyroxene (Mg# = 0.80–0.91) and olivine (Fo = 88.13–88.78), surrounded by coarser-grained, compositionally zoned clinopyroxene (Mg# = 0.90–0.93) and feldspar; some of the zoned clinopyroxene grains contain pargasitic or kaersutitic amphibole cores. Type 3 consists of subhedral zoned clinopyroxene showing a pronounced decrease in Mg# from ~0.90 in the cores to ~0.75 at the rims, homogeneous Fe-rich olivine (Fo = 79.18–82.80), spinel and scarce phlogopite enclosed in a feldspathic matrix. In addition, some xenoliths contain clinopyroxene that is spongy throughout the grain (Mg# = 0.91–0.93) and is commonly associated with primary spinel undergoing rim corrosion and surrounded by numerous small euhedral spinel crystals.

The microstructures record several distinct processes of xenolith evolution. Type 1 aggregates are interpreted as products of melt-mediated dissolution and replacement of primary spinel. Type 2 aggregates probably record a decompression-related net-transfer reaction of amphibole. Type 3 aggregates reflect infiltration of a mafic melt, as indicated by strongly Fe-enriched clinopyroxene rims. Spongy clinopyroxene and associated spinel textures are interpreted as products of dissolution–reprecipitation promoted by melt infiltration. Together, these secondary microstructures record a complex history involving mantle metasomatism, decompression and melt–rock interaction shortly before or during xenolith entrainment.

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Temporal constraints on the growth of the lowermost crust in the Ivrea–Verbano Zone

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The Ivrea–Verbano Zone (IVZ) records Permian transcrustal magmatism and provides insights into the development of the crust–upper mantle transition. These processes can be investigated along the eastern contact of the Balmuccia Massif, where igneous relationships are preserved among the massif, the Contact Series, and the structurally overlying lower-crustal rocks of the Layered Series, which forms the base of the Paragneiss-bearing Belt and the upper Mafic Complex. The Contact Series forms a mafic–ultramafic carapace composed of interlayered pyroxenites and gabbronorites, constructed through repeated injections and storage of mantle-derived melts at the crust–mantle transition (Pieterek et al., 2024). Previously unavailable U–Pb zircon geochronology of the Contact Series therefore constrains the temporal evolution of the IVZ and the timescales of lower lithospheric construction.

The combined interpretation of CL textures, crystal morphology, and EPMA-based elemental distribution and chemical composition identify three genetically distinct zircon populations: magmatic, metamorphic, and inherited. The timing of zircon growth within each population was subsequently constrained using U–Pb SHRIMP-derived geochronology.

Prismatic to stubby zircon grains displaying oscillatory CL zoning and Hf zoning are interpreted as magmatic and document three crystallization events at ~304, 294, and 282 Ma, with the 294 Ma event representing the main stage of the Contact Series growth. Importantly, this event predates the principal underplating event recorded by the Mafic Complex, dated at 284 ± 2 Ma. Metamorphic zircon population consist of generally large, euhedral zircon grains characterized by bright CL, chemically homogeneous interiors in EPMA elemental maps, and the absence of primary oscillatory zoning, yielding an age of 276 Ma. Inherited zircons preserve much older ages (461–2900 Ma), reflecting incorporation of crustal material.

Together, these data indicate that the crust–mantle transition developed through multiple pulses of magmatism that predated emplacement of the Mafic Complex by at least ~10 Myr and was subsequently overprinted by peak metamorphism. These findings support a dynamic magma processing zone model for the lithospheric roots of IVZ.

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Multiphase inclusions in the Svartberget peridotite body, Western Gneiss Region (Norway): tracing the evolution of a metasomatic agent

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Metasomatized ultramafic bodies incorporated within subducted continental crust can represent natural laboratories for tracking crust-mantle interaction. During subduction, fluids and melts released from the crust can infiltrate the surrounding mantle, transfer elements, and be trapped as primary inclusions in minerals growing during the process. When such inclusions remain isolated within their host, they retain their original composition; therefore, they provide direct constraints on crust-mantle interaction. Svartberget (Western Gneiss Region, Norway) is an ideal locality for investigating this phenomenon, as it preserves an ultramafic body exhibiting a complex network of crosscutting veins attributed to pervasive metasomatism resulting from the interaction with crustal-derived material presumably originating from the host migmatitic gneiss (Vrijmoed et al., 2013). To better constrain the fluid-rock interaction from the perspective of the metasomatic agent, i.e., the fluid *s.l.*, we present new data on primary multiphase inclusions hosted by garnet and clinopyroxene in phlogopite-garnet-websterite and garnetite veins within the Svartberget ultramafic body.

The phlogopite-garnet-websterite veins consist of clinopyroxene, garnet, phlogopite, and amphibole. Micro-Raman spectroscopy analysis reveals two types of multiphase inclusions, ~15 mm in diameter, that occur either isolated or in clusters within poikilitic clinopyroxene and garnet. Type I inclusions contain quartz, feldspar polymorphs, micas, amphibole, osumilite, carbonates, sulfides, and CO_2. Type II inclusions mainly comprise amphibole, anhydrite, carbonates, and CO_2, with minor chlorite, micas, pyrophyllite, talc, margarite, corundum, spinel, hematite, and sulfides. The garnetite veins contain garnet and phlogopite, with minor clinopyroxene and amphibole. Garnets host Type I and II multiphase inclusions (10-50 μm in diameter) with mineral assemblages similar to those in the websterites.

Type I inclusions have an assemblage suggesting a granitoid composition; hence, they can be regarded as nanogranitoids, i.e., crystallized melt inclusions. They potentially represent the crustal-derived granitic melt metasomatizing the peridotite body. Type II inclusions might represent a C-O-H fluid. The coexistence of fluid inclusions with nanogranitoids in the same metasomatic rocks suggests primary fluid-melt immiscibility; however, further petrological and geochemical analysis will better constrain the nature of crust-mantle interaction in Svartberget.

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Olivine and clinopyroxene chemistry as tracers of magma evolution and storage conditions in the Strzelin Volcanic Field, Poland – preliminary results

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The Strzelin Volcanic Field (SVF) is a part of the Central European Volcanic Province and is an example of intraplate alkaline basaltic volcanism associated with lithospheric extension, asthenospheric upwelling and interactions between mantle-derived melts (Awdankiewicz et al., 2016). In this study we report preliminary results on the chemistry and crystallization conditions of olivine and pyroxene phenocrysts from nephelinites, basalts and trachybasalts from SVF.

Olivine and pyroxene phenocrysts are up to 2 mm size. Both phases vary in habit from euhedral to subhedral and anhedral. Clinopyroxenes often form glomerocrysts, display sector zonation and hourglass texture. Chemically clinopyroxenes are dominated by high-Ca phases, with most analyses plotting within the diopside field or close to the diopside-augite boundary. Olivines show normal zonation and frequently display embayments. Forsterite contents vary from ~Fo_{90} to ~Fo_{70}. The Mg-rich olivines (~Fo_{90}) are also characterized by elevated Ni concentrations and can be interpreted as fragments of disaggregated mantle-derived ultramafic enclaves. The differences in composition of olivines reveal distinct crystal populations which suggests the coexistence of several generations of olivine formed at different stages of magmatic evolution. The three rock types studied show broadly similar composition of olivine and clinopyroxene, although the nephelinites are characterized by a wider compositional range compared to basalts and trachybasalts.

The electron-microprobe data was used to calculate crystallization pressures and temperatures of olivine and clinopyroxene using selected thermometers and thermobarometers given in Putirka (2008). Olivine crystallization temperatures range from 1380 ± 58 to 1224 ± 72 °C, whereas clinopyroxene crystallization temperatures range from 1267 ± 45 to 1107 ± 45 °C. and clinopyroxene barometry gives pressures from 14.2 ± 1.6 to 0.5 ± 1.6 to kbar.

These preliminary results indicate crystallization over a broad range of depths within the lithospheric mantle and the crust and suggest that magmas experienced polybaric crystallization at multiple levels within the magmatic plumbing systems prior to eruption. Further research, integrating mineral chemistry, thermobarometry, and CO_2 fluid inclusion data, is needed to better constrain the architecture and evolution of the magmatic plumbing systems beneath the Strzelin Volcanic Field.

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Lithospheric mantle evolution during the opening of the Upper Rhine Rift: the record in xenoliths from the Vogelsberg (Germany)

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Spinel peridotite xenoliths from the 18–14.7 Ma Vogelsberg volcanic field (Upper Rhine Graben, Central Germany) offer an opportunity to study the evolution of the Variscan lithospheric mantle in a Cenozoic continental rift setting. We investigated xenolith suites from the Breitenborn and Nidda quarries.

The peridotites are mainly harzburgites and clinopyroxene-poor lherzolites, typically containing >70 vol. % olivine. Granular textures are common in the Breitenborn suite, whereas porphyroclastic to tabular textures are typical of the Nidda xenoliths. Crystal-preferred orientation (CPO) data show that most peridotites consist of an olivine framework to which clinopyroxene exhibiting a dispersed CPO was added later. Orthopyroxene CPO typically follows that of olivine but is dispersed in some samples. Olivine has Fo 89.5–91.7%, orthopyroxene has Mg# 0.90–0.92 and 0.10–0.23 Al atoms per formula unit (pfu), clinopyroxene has Mg# 0.89–0.93 and 0.11–0.28 Al atoms pfu, and spinel has Cr# 0.14–0.58. Clinopyroxene REE patterns define two major peridotite groups: (1) LREE-depleted and (2) variably LREE-enriched.

The olivine-rich composition of the peridotites, high mineral Mg# values, and partial preservation of LREE depletion in clinopyroxene indicate that the lithospheric mantle beneath the Vogelsberg underwent one or more major melt-depletion events. Most of this mantle was subsequently modified by Cenozoic rift-related melts, which added variably LREE-enriched clinopyroxene or modified the preexisting one.

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General Session

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Selective capture and separation of rare earth elements from aqueous solutions using functionalized mesoporous silica and carbon nanomaterials

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Rare earth elements (REEs) are essential to energy, electronic and defence technologies, yet their recovery from water is difficult because trivalent REE ions have similar ionic radii and coordination behaviour (Artiushenko et al., 2023; Kaaya et al., 2025). This study investigates two complementary functionalized sorbents for selective REE capture: ordered mesoporous silica matrices and carbon nanomaterials. Mesoporous silica offers a high surface area, a uniform pore system, and reactive silanol groups that can be modified with chelating ligands, thereby enabling rapid mass transfer and adjustable affinity for metal ions (Costa et al., 2021; Artiushenko et al., 2023). The first part evaluates the separation of Ce(III) and Sc(III) on mesosilicate matrices with different functionalisations. Ion concentrations before and after contact with the sorbents are determined by stripping voltammetry, enabling sensitive assessment of uptake efficiency and separation performance. The effects of pH, contact time, sorbent dosage, initial concentration, and competing ions are examined to distinguish adsorption from hydrolysis or precipitation and to identify conditions favouring selective binding. The second part examines graphene-based and related carbon nanomaterials, whose large surface area, chemical stability, and tunable surface chemistry make them promising REE sorbents. Oxygen-, nitrogen-, and phosphorus-containing groups can bind REE(III) ions through electrostatic attraction, Lewis acid-base interactions, and surface complexation. As high uptake alone does not ensure selectivity, adsorption capacity is evaluated alongside separation factors, desorption efficiency, and regeneration potential. By integrating electroanalytical measurements with structure-property relationships, the study aims to establish how pore architecture and surface functionality control affinity and selectivity towards Ce(III), Sc(III), and other REEs. The findings will support the design of reusable mineral-carbon sorbents for recovering critical elements from complex aqueous streams.

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Geochemical mapping in the Carpathians using G-Base stream sediments

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Geochemical mapping was conducted in the tectonically and lithostratigraphically complex Bystre Slice in the Polish Carpathians. An innovative research method was used, employing sampling G-Base stream sediments (Johnson et al., 2005) in first- and second-order watercourses (Stahler, 1957).

The Bystre Slice belongs to the Western Carpathians and is located in the Bieszczady Mountains in the southeastern part of the Silesian Unit of the Outer Carpathians. Presence of Cretaceous rocks in the profile and intense silicification, are found as diagnostic features of the mineralization environment in the Bystre Slice. The occurrence of arsenic sulfides was found within strongly silicified sandstone-shale formations belonging to the Upper Lgota and Istebna Beds. The presence of arsenic mineralization (realgar and orpiment) was the subject of earlier studies and research (e.g., Kita-Badak, 1971; Jaworski, 1979; Rybak, 2000; Jarmołowicz-Szulc et al., 2024).

Variable contents of arsenic, calcium, strontium, copper, and zinc were detected. The geochemical results indicate a significant correlation between the anomalies of individual elements and the geological structure of the area, especially with the presence of faults and overthrusts. Moreover, further studies of G-base stream sediments may be a valuable tool for geochemical prospecting as well as searching for possible pathways for solutions migration in the Carpathian orogen.

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Iron mineralogy of carbonaceous chondrites (rocks older than Earth) studied by Mössbauer spectroscopy

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Carbonaceous chondrites (CC) provide key information on the early evolution of the Solar System and presence of water in the early Universe. Iron in CC occurs in various chemical (mineralogical) forms and valence states. The iron speciation can be used as tracer of aqueous alteration and indicator of redox conditions by $Fe^{3+}/Fe^{2+}/Fe^{0}$ ratio.

Twelve CC mainly from falls observed in the 21st century were studied by ^{57}Fe-MS. Iron speciation appears to be specific to particular groups of CC and indicates that: 1) CM chondrites suffered extensive aqueous alteration on their parent asteroids and their original minerals reacted with liquid water forming hydrous phyllosilicates (clays), 2) C2-ung chondrites probably suffered moderate alteration by liquid water, 3) CO chondrites demonstrate very little water alteration, if any at all, 4) CK chondrites confirm a high degree of oxidation, and heavy thermal metamorphism. Probably, a heating events on the asteroid dehydrate the clay minerals and heat cause Fe^{3+} to reduce back into Fe^{2+}.

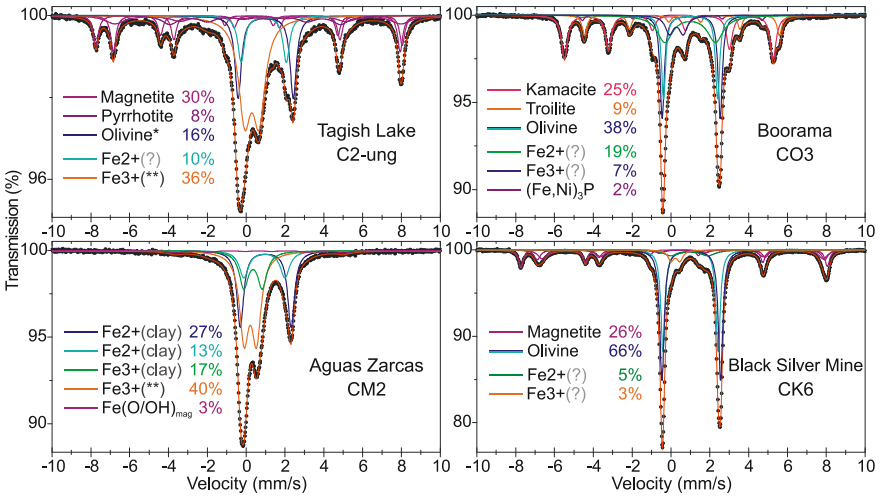


Figure 1. Mössbauer spectra of studied carbonaceous chondrites. Iron speciation, i.e. relative percentage distribution of Fe atoms into individual mineral phases and valence states is presented.

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Blueschist-facies garnet-chloritoid schists from the Karkonosze-Izera Massif: a rare record of early Variscan subduction

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Saxothuringian medium-grade metamorphic rocks in the Bohemian Massif often bear a cryptic record of high-pressure–low-temperature (HP–LT) metamorphism, commonly related to early Variscan continental subduction. In the lower allochthon of the Karkonosze-Izera Massif, remnants of this episode have been documented in mica schists in the form of chloritoid-in-garnet inclusions and phengite (Žáčková et al., 2010; Konopásek et al., 2019). In this study, petrological investigation of a unique garnet-chloritoid schist from Sowia Pass in Karkonosze Mts. reveals a clear record of HP–LT metamorphism with only limited signs of subsequent re-equilibration.

The studied schists are composed of garnet, chloritoid, chlorite and white mica, with accessory ilmenite, rutile and graphite. Their bulk composition is consistent with a Fe-rich, probably chamositic shale protolith (17.24 wt. % FeO).

Garnet porphyroblasts reach up to 3 mm in diameter and account for ca. 20-25% of the rock's volume. Garnet shows chemical zonation: in the core grossular and spessartine together account for approx. 40% of the composition (X_{Grs} = 0.24, X_{Sps} = 0.15), whereas at the rim garnet composition approaches pure almandine (X_{Alm} = 0.91). White mica is mostly muscovite, but phengite is also present, with Si content reaching 3.45 a.p.f.u..

Phase-equilibria modelling shows that the mineral assemblage comprising Grt + Cld + Chl + Ph + Ilm + Rt crystallized under blueschist facies conditions, at ca. 17 kbar and 485-525 °C. Muscovite most likely reflects the partial re-equilibration of the studied rocks at lower pressures, below 8 kbar. Results of graphite thermometry suggest that temperature most likely did not exceed 585 ± 58 °C, which is consistent with the regional geological context.

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Geologic events in the central Andes recorded by automorphic feldspars and associated minerals in limestones of the Ashua Formation, Peru

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Numerous automorphic (euhedral) feldspar crystals have been found in the Late Cretaceous siliciclastic-carbonate-evaporitic Ashua Formation in southern Peru. There are three possible hypotheses regarding the origins of this type of rare occurrence: (1) authigenic; (2) metasomatic regeneration of detritus, and (3) delivery from a nearby igneous center into the carbonate sediment, followed by diagenesis and epigenetic transformations.

Geological field observations, combined with laboratory analyses, have been used to solve the complex problem of the origin of automorphic feldspars and associated silicates and aluminosilicates identified in the Ashua Formation limestones and their metamorphosed crystalline varieties. The elongation of the crystals, the type of twinning, and the SI index exclude the authigenic origin of the feldspars. It has been proven that the automorphic feldspars in the limestones of the Ashua Formation are mainly epiclasts derived from the erosion of earlier volcanic-sedimentary formations, most likely the Early Cretaceous Matalaque Formation (Paulo et al., 2019). As volcanic detritus, albite was abundantly supplied to the siliciclastic sediments and to the partly hypersaline marine basin, where limestones, including celestine, barite, and opal, precipitated.

The two oldest generations of feldspars (albites A and B), together with sericite and adular, were formed mainly in a post-igneous environment, and the regenerative rim C was formed in the Paleogene under the influence of the hypabysal intrusion of the Chejol dacite, giving the feldspars an automorphic shape. In the metamorphic halo of this intrusion, under the influence of low-temperature solutions, whose temperatures rarely exceeded 250 °C, metasomatic exchange and crystallization of zeolites, authigenic quartz, Al-titanite, magnesium chlorite, and talc occurred, as well as pseudomorphic replacement of albite or stilbite with quartz (Ciesielczuk et al., 2026).

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Effect of progressive mineral carbonation of serpentinized peridotite on subsequent Ni, Co, and Cr leachability during acidic extraction

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Ultramafic rocks are promising feedstocks for permanent CO_2 storage through both ex situ and in situ mineral carbonation because they are rich in reactive Mg-bearing minerals, particularly forsterite. Carbonation process involves extensive dissolution-precipitation reactions that may modify the distribution and subsequent leachability of potentially hazardous metals such as Ni, Co, and Cr. Understanding these changes is important for evaluating whether carbonated ultramafic residues can be safely stored or reused.

A series of single-stage carbonation experiments was conducted on partially serpentinized peridotite from the Braszowice-Brzeźnica Massif (SW Poland) at 185 °C and 100 bar CO_2 for 6-96 h. Mineralogical and chemical changes were characterized by XRD, SEM, whole-rock analysis and ICP-OES, followed by TCLP-based leaching tests using extraction fluids with initial pH values of 2.88 and 4.93 and ultrapure H_2O controls. Carbonation was most rapid during the first 24 h and continued more slowly thereafter. Forsterite decreased from 54.2 wt. % to 10.6 wt. % after 24 h and 5.9 wt. % after 96 h, while magnesite increased to 48.2 and 57.4 wt. %, respectively. Most Ni, Co and Cr remained associated with the solid products, with only small fractions present in the final post-carbonation fluids. However, acidic leaching revealed a non-linear response of Ni and Co. At an initial pH of 2.88, Ni leachability increased from 6.57% in the starting material to 10.09% after 12 h, while Co increased from 4.83% to 10.91%. Both subsequently became less extractable with increasing carbonation time. We hypothesize that early carbonation leads to the formation or accumulation of a transient Ni- and Co-bearing reservoir that is relatively susceptible to acidic leaching, followed by its progressive transformation into less leachable forms at more advanced stages of carbonation. Chromium remained essentially non-leachable, with extracted fractions $\leq 0.06\%$, while Ni and Co release in ultrapure H_2O was also very low.

The results demonstrate that carbonation does not necessarily cause substantial net loss of Ni, Co, or Cr from ultramafic feedstock, but it can strongly modify the accessibility of retained Ni and Co to subsequent acidic extraction. Partially carbonated residues may therefore contain larger acid-accessible Ni and Co fractions than both unreacted and more extensively carbonated materials. We therefore suggest that the degree of carbonation should be considered when assessing the potential release of Ni and Co from carbonated ultramafic residues.

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High pressure granulite overprint on eclogite in the Caledonides of southern Norway: Significance of partial melting

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In the Western Gneiss Region (WGR), Norwegian Caledonides, an amphibolite facies overprint has largely obliterated the eclogite facies mineral assemblages that formed during transient subduction of continental crust. However, where peak pressure (P) and temperature (T) were highest, an initial high-pressure granulite retrogression is well preserved, especially in large mafic massifs (Engvik et al., 2018). In these, garnet granulite has a distinctive poikiloblastic clinopyroxene texture differing from the familiar symplectite that signifies decompressive breakdown of omphacite. Also, abundant mm-size patches of oligoclase, quartz and biotite, merging into films of oligoclase between the major mineral phases, have been interpreted as *in-situ* partial melt. These have been equated with macroscopic leucotonalite leucosomes. However, the textural and mineralogical relationships of the leucosomes and host mafic granulite have yet to be described in detail from well preserved examples. At Lyngstad near Molde, leucosomes (Pl + Qz + Bt ± Ap) cut across the eclogite modal lamination. Omphacite, phengite and zoisite are preserved as inclusions in garnet. In the matrix, Cpx (Na-Al diopside) is poikiloblastic-skeletal hosting optically continuous patches of oligoclase. Approaching the leucosomes, films of oligoclase around Grt and between Omp grains become more common and wider. At leucosome margins and isolated within the leucosome the skeletal Cpx develops an idioblastic habit, indicating equilibrium with the leucotonalite melt. The Cpx has evolved from omphacite, so incongruent melting contributed its jadeite component to the melt. These features together are consistent with experimental results (Skjerlie & Patino-Douce, 2002) for fluid-absent melting of a Ph-Zo-Qz eclogite at P<1.5 GPa. Melting experiments on intact natural eclogite by Larikova et al., (2011) show films and collars of tonalitic melt and skeletal Cpx identical to the features observed in the Lyngstad eclogite, reinforcing the above interpretation. Conventional thermobarometry yields ca. 850 °C at 1.2 GPa (presumably for crystallisation of the melt) but phase equilibrium modelling by Engvik et al. (2011) in similar rocks nearby yielded suprasolidus T > 900 °C, raising the possibility of a thermal pulse during decompression (see Faryad & Cuthbert, 2020). Leucosome composition strongly resembles Archaean TTG's, so these rocks hold promise for studying the genesis of such important crust-building melts.

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Comparing detrital rutile signatures: Vahic, Magura, and Silesian Superunits in the Western Carpathians

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The Vahic Supernit, a critical tectonic element of the Western Carpathians, is inferred as the oceanic suture zone separating the Central Western Carpathians (CWC) from the North European Platform. Interpreted as the eastern continuation of the South Penninic (Alpine Tethys) oceanic domain, the Vahicum is primarily represented by the Belice Unit, which preserves a sedimentary record of the Vahic Ocean's evolution. This sequence includes Upper Jurassic radiolarites and Lower Cretaceous pelagic limestones, conformably overlain by Upper Cretaceous flysch.

To constrain the timing and dynamics of the Vahic domain closure, U-Pb geochronology was performed on detrital rutile grains from six sandstone samples collected across the Vahic Superunit. Approximately 200 rutile grains per sample were analyzed, with roughly half selected for detailed age and trace element analysis.

The Vahic rutiles show predominant ages typical of the Variscan orogeny . Only in two samples a few grains with much younger ages (80-130 Ma) were found, most likely derived from Alpine HP rocks. Despite their low number, the presence of these young rutiles points to a similar source of material as in the Magura and Rhenodanubian Superunits. These findings are compared with previously acquired data from the Magura, Rhenodanubian and Silesian Superunits to better constrain regional provenance. In the Magura transect, prominent age peaks align with Variscan (ca. 400–280 Ma) and Alpine (ca. 160–90 Ma) events, including dominant Alpine maxima at 137–126 Ma and 115–105 Ma. In contrast, the Silesian samples consistently exhibit a prominent Variscan peak, with Alpine tectonic signatures (e.g., a dominant peak at 95 Ma) appearing only in the youngest, Oligocene deposits.

Integrating the rutile age data from the Vahic Superunit into this regional framework allows for a more comprehensive reconstruction of the evolving paleodrainage and tectonic maturation of the Carpathian orogenic wedge.

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Ductile-brittle behavior at UHP conditions: the geological record from eclogite breccia stored in the Monviso Massif (Western Alps)

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Fluids are a key component of deformation along subduction plate interfaces, where variations in pore-fluid pressure can strongly modify rock strength and deformation style. At depths corresponding to ultra-high-pressure conditions, however, direct constraints on the interaction between fluid flow, transient porosity, and mechanical behavior remain scarce. Fossil subduction plate interfaces exposed at the surface offer the opportunity to investigate these processes directly from their preserved geological record.

Here, we investigate eclogite breccia from the Lower Shear Zone of the Monviso Massif (Western Alps), an Ultra-High-Pressure fossil plate-interface mélange exhumed from depths of ~90 km. The breccia are matrix-supported and consist of angular eclogite clasts enclosed in a coarse-grained omphacite–garnet matrix. Clasts preserve a pre-existing high-pressure foliation, whereas the breccia matrix records extensive mineral growth associated with fracture development and subsequent sealing. Brecciation is restricted to specific domains within the mélange, suggesting that deformation and fluid migration were strongly localized by contrasts in lithology and permeability.

Mineralogical, petrological, and microstructural observations document repeated switches between ductile deformation and brittle failure. Fracture formation required transient reductions in effective stress under high pore-fluid pressure, whereas subsequent mineral precipitation progressively sealed the newly formed pore space and reduced fluid connectivity. Repetition of these processes produced cycles of porosity generation and destruction and promoted episodic reorganization of fluid pathways within the plate interface.

The Monviso breccias therefore record transient fluid-pressure fluctuations and repeated changes in permeability at depths of ~90 km. These observations show that even deeply subducted, initially low-porosity rocks can undergo short-lived episodes of brittle failure and fluid channelization under UHP metamorphic conditions. Such behavior provides a geological framework for interpreting transient fluid-rich domains and low-velocity zones detected within active deep subduction interfaces.

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Amphibolites from the Piława Górna quarry (Góry Sowie Massif, SW Poland): geochemical affinities and geotectonic constraints

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The Góry Sowie Massif (GSM) situated in NE part of the Bohemian Massif is a high- to medium grade metamorphic unit consisting of paragneisses (migmatites) with minor orthogneisses, metabasites and felsic granulites derived from early Palaeozoic protholits. Due to its current extensive exploitation, the Piława Górna quarry (NE part of GSM) offers unique access to the GSM paragneisses and amphibolites. This geochemical study aimed to constrain the origin and palaeotectonic setting of the protolith of the amphibolite bodies exposed in the quarry.

Amphibolite samples were collected from a suite of thick mafic bodies and dark boudins embedded in migmatites. They mostly exhibit chemical characteristics typical of subalkaline basalts and basaltic andesites (SiO_2: 45.9–54.8 wt. %), with a high concentration of Al_2O_3 (14.1–19.4 wt. %), variable amounts of TiO_2 (0.7–2.6 wt. %) and MgO (3.9–11.4 wt. %). The Mg# (44–74) and varying concentrations of major and trace elements (e.g. Ni: 17–114 ppm, Cr: 103–301 ppm, La: 2–21 ppm, Y: 11–51 ppm and Zr: 56–345 ppm) suggest the chemical composition of the protoliths to the studied amphibolites was at least partially shaped by fractional crystallisation of a mafic cumulate. The rocks have high ratios of Zr/Nb (12–51), La/Nb (1.1–2.8), moderate of Zr/Y (3.3–6.7), Th/Yb (0.17–0.75), Ti/V (28–58) and low of Nb/Y (0.09–0.27). The profiles on chondrite–normalized REE plots show predominantly negative slope due to fractionation of LREE and MREE over HREE ($[La/Yb]_{CN}$: 1.1–3.1, $[Gd/Yb]_{CN}$ 1.2–1.7). A non-systematic Eu anomaly (Eu/Eu*: 0.7–1.2), is also observed. In both primitive mantle- and N-MORB-normalised diagrams, the patterns largely show a negative inclination, with variable negative anomalies for Nb, Ta, Ti and P. Compared to N-MORBs, these profiles also reveal variable enrichment in incompatible elements, which is overall intermediate between that of E-MORBs and OIBs.

Geochemical signatures (e.g., Ti/V, Nb/Y vs. Zr/Y, Th/Yb vs. Nb/Yb, Zr/Nb, TiO_2/Yb) suggest shallow depths of magma generation (spinel facies) from intrinsically depleted mantle sources akin to DMM. The observed enrichment in Th and LREE and negative anomalies for HFSE suggest metasomatic changes in the source induced by components mobilized by subduction-related processes. Therefore, a volcanic arc geotectonic setting seems to be the plausible explanation for the genesis and emplacement of the protolith of the studied amphibolites. However, the variable degree of subduction input and metasomatic enrichment of the magma source also suggest affinities with a back-arc basin environment situated close to a continental margin.

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Natural devitrite $Na_2Ca_3Si_6O_{16}$ from the Bellerberg volcano xenoliths

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Devitrite is a Na-Ca silicate with the ideal composition $Na_2Ca_3Si_6O_{16}$, originally described as a crystalline phase formed during the devitrification of soda-lime-silica glasses (Holland & Preston, 1937). Although it has been well studied in synthetic and glass-related systems, it is a relatively uncommon phase that typically crystallizes from Na-rich silicate melts or glasses (Knowles & Thompson, 2014). A potentially new mineral, the natural analogue of devitrite, has been identified in xenoliths from the Bellerberg volcano, Germany. This partially altered xenolith is dominated by diopside, K-feldspar, calcite, and subordinate Ca-hydrosilicates. Devitrite, together with titanite, perovskite, leucite, wollastonite, and fluorellestadite, forms the accessory assemblage. Natural devitrite rarely exhibits the elongate, fibrous habit commonly observed in synthetic materials, it more often occurs as subhedral crystals up to 70 μm in size. The empirical formula of devitrite, calculated on the basis of 16 O atoms, is $(Na_{2.00}K_{0.02})_{2.02}(Ca_{2.31}Sr_{0.56}Pb_{0.05}Mg_{0.04}Ba_{0.03}Mn_{0.01}Fe_{0.01})_{3.01}Si_{5.98}O_{16}$, indicating substantial Sr substitution at the Ca sites.

The crystal structure of natural devitrite was refined from single-crystal X-ray data, using the structural model of synthetic analogue reported by Kahlenberg et al. (2010). The refinement confirmed triclinic symmetry (*P*-1) with unit-cell parameters: a = 7.2630(8) Å, b = 10.1634(12) Å, c = 10.7534(12) Å, V = 726.04(15) Å^3, Z = 2. The crystal structure belongs to the multiple-chain silicate family and is characterized by dreier quadruple silicate chains propagating along [100]. These silicate chains are interconnected by double chains of edge-sharing CaO_6 octahedra, while the remaining Na and Ca cations occupy irregularly coordinated sites within tunnel-like channels of the tetrahedral-octahedral framework. The structure refinement indicates partial substitution of Sr for Ca at two of the three Ca sites.

The textural relationships suggest that devitrite formed during a relatively late stage of crystallization. It mainly occurs in the interstitial spaces between well-developed diopside and K-feldspar crystals. The presence of devitrite with associated silicate phases indicates crystallization in a silica-rich, alkali- and Ca-bearing environment. Its interstitial occurrence within the xenolithic assemblage may indicate crystallization from a residual silicate melt during high-temperature processes. The natural occurrence of devitrite therefore extends the known geological significance of this phase beyond synthetic and glass-related systems.

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Unraveling evidence for Paleozoic high-pressure metamorphism in the Richarddalen Complex, Svalbard

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The Richarddalen Complex in NW Svalbard is a key locality for reconstructing Arctic paleogeography. It comprises felsic and mafic rocks metamorphosed under eclogite-facies conditions of 2.4–2.5 GPa and 720–740 °C (Elvevold et al., 2014). Despite decades of study, the timing of high-pressure (HP) metamorphism remains debated, with proposed ages ranging from Proterozoic (Koglin et al., 2022; Peucat et al., 1989) to Paleozoic (Gromet & Gee, 1998; Mazur et al., 2022). Here, we used Lu–Hf garnet, U–Pb zircon, and Rb–Sr mica geochronology to constrain the age of HP event. We studied eight samples: orthogneisses, eclogites, paragneiss, and a leucosome cutting eclogite. Lu–Hf dating of garnet I in orthogneisses yields ages of 967 ± 44, 961 ± 53, and 959 ± 33 Ma, consistent with U–Pb zircon ages of 965 ± 10, 973 ± 33, and 959 ± 17 Ma in the felsic rocks. U–Pb zircon dating constrains metamafic protolith ages to 726 ± 21, 643 ± 9, and 652 ± 19 Ma. Results from the leucosome and analyses of low-U zircon rims from the eclogite-hosting paragneiss provide the best constraints on HP metamorphism at 492 ± 7 and 484 ± 21 Ma. Precise dating of the younger garnet generation was precluded by its very low Lu content. Similarly, limited zircon growth and low U contents hamper precise dating of HP metamorphism. Rb–Sr ages of white mica and biotite from orthogneisses constrain post-HP decompression to 477 ± 17 and 475 ± 5 Ma.

Our results confirm a Paleozoic HP event in the Richarddalen Complex, as envisaged by Mazur et al. (2022), but place it in the late Cambrian–Early Ordovician, substantially earlier than the Late Ordovician timing inferred in that study. Overall, the Richarddalen Complex preserves a polyphase record of protolith formation, HP metamorphism, and subsequent decompression, providing constraints on the tectonometamorphic evolution of Svalbard.

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Late Oligocene interglacial environments on King George Island, South Shetland Islands, Antarctica

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New geochemical, geochronological and palynological results from the Destruction Bay Formation (DBF) on King George Island (KGI), South Shetland Islands, provide insight into the late Oligocene warming period in the Antarctic Peninsula region. Outcrops revealed from beneath the currently retreating ice exposed a complete sequence of the DBF with well-defined erosional boundaries at the base and top of the central part of the unit. New age data of 26-24 Ma, obtained from U-Pb zircon and strontium isotope stratigraphy (SIS), confirm paleontological and micropaleontological age estimations and fit well with the warming period of Late Oligocene age that has been recorded in the marine oxygen isotope global temperature curve. Facies and sedimentological analysis, together with petrographic, geochemical and palynological investigations, allow reconstruction of the interglacial sedimentary and diagenetic estuarine environment as one of a high-energy meandering tidal channel and much lower-energy sand-silty tidal flat of an inner shelf, backed by a coastline of basalts of the Sherratt Bay Formation (SBF). Sediment was derived mainly from local basaltic and andesite lavas and their pyroclastic equivalents that were weathered and affected by early diagenesis. The generally monotonous composition of the sediments was disrupted by local tributaries containing more felsic erratics transported by glaciers from the Transantarctic and Ellsworth mountains of the central part of the Antarctic continent. The geological and ecological evidence indicates the dominant mild climatic conditions that prevailed for both the marine and terrestrial paleo-ecosystems at around 25 Ma in this region.

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Hydrothermal replacement of metamict thorite by zircon and redistribution of Th-U-Y-REE-Pb in the White Tundra pegmatite

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The White Tundra pegmatite is a Zr-REE-Nb-rich NYF body associated with Neoarchaean A-type granites of the Keivy alkaline province, Kola Peninsula. This study reconstructs the hydrothermal alteration of Th- and U-bearing minerals and the redistribution of Th, U, Y, REE and Pb. Three samples were analysed by SEM-BSE/EDS, EPMA, EBSD and Raman spectroscopy; monazite-(Ce) was chemically dated using EPMA.

The porous, fractured crystals are Th-dominant, U-bearing thorite (~16 at. % U in Th+U). Embayed and branching zircon domains follow the fractures, isolating the thorite relics and forming irregular reaction fronts (Fig. 1), documenting replacement through coupled dissolution-reprecipitation. Micrometre-scale thorite inclusions in porous zircon are Th-depleted and U-Y-REE-enriched (27-40 at. % U in Th+U). This suggests local reprecipitation rather than mechanical fragmentation. U-Y ± Pb rich microveinlets indicate short-distance transport. The late fracture-hosted Pb-U-Si domains described as kasolite-like, as the crystal structure, U oxidation state and H_2O content remain not well determined.

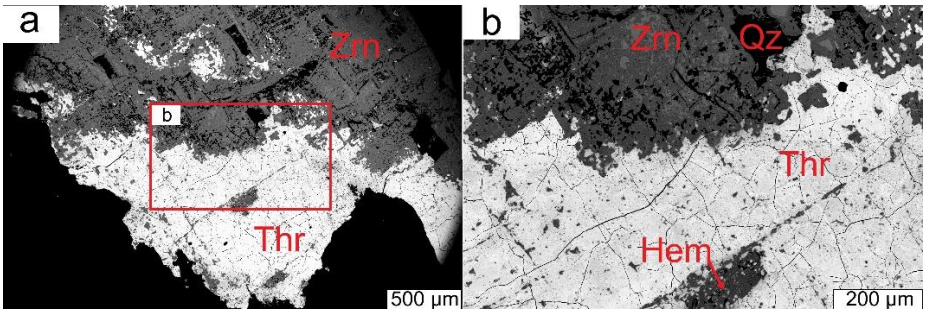


Figure 1. BSE images of sample 2-8-6: a) thorite (Thr) in contact with porous zircon (Zrn); b) enlarged view of irregular zircon domains penetrating thorite along the fractures. Qz - quartz, Hem - hematite.

The results of EBSD and Raman spectroscopy indicate the presence of extensively metamict thorite with local tetragonal relics; huttonite was not confirmed. Radiation damage enhanced porosity and fracture-controlled reactivity. Monazite-(Ce) from the altered zircon zone yielded a weighted mean chemical age of 1663 ± 184 Ma (1σ; n = 9), indicating the reactivation during the Palaeoproterozoic rather than the age of all secondary textures. The sequence involves the crystallization of Th-rich, U-bearing orthosilicates, metamictization and fracturing, replacement by zircon, local reprecipitation of U-Y-REE-enriched thorite, and late mobilisation of U and Pb. The mobility was selective: Th remained near reaction fronts; U, Y, REE and Pb entered secondary inclusions, veinlets and fracture-hosted phases.

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Optimization of rare earth elements extraction and recovery via phosphate acid leaching and selective precipitation of lead phosphates and REE oxalates

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China's market monopoly drives the search for new REE recovery routes from alternative, secondary sources. One promising approach combines phosphoric acid leaching of apatite with Pb-assisted phosphate coprecipitation (Sordyl et al., 2023). This study focuses on a combined two-stage approach for REE extraction from apatite-rich materials, precipitation of crystalline Pb-phosphate with REE substitutions, and subsequent selective element separation.

In the first stage of this study, apatite-bearing natural rock was subjected to acid leaching process using a mixed 1M H_3PO_4 and 1M HNO_3 solution. Based on new discovery of REE compatibility with lead phosphates (Staszel & Manecki, 2023), a sequence of controlled additions of NaCl and $Pb(NO_3)_2$ to the leachate at pH=3 promoted the selective precipitation of pyromorphite $Pb_5(PO_4)_3Cl$ which acts as a host structure for REE incorporation.

In the second set of experiments a dissolution-precipitation procedure was optimized for separation of Pb and REE. An equimolar mixture of synthetic Pb- and La-oxalates (0.1 g each) was treated with ethanol and sulfuric acid, driving the control conversion of lead oxalates into sulphates ($PbSO_4$). Following addition of water and dilute H_2SO_4 enabled selective dissolution of La-oxalates into the aqueous phase, achieving clean separation of REEs from lead.

The demonstrated method improve a viable pathway for scavenging REEs into crystalline phosphate hosts followed by clean separation of the target elements from lead, which underpins the application of this method in circular economy processes. The ongoing research will focus on applying the separation method optimized in the second stage to the procedure applied to real samples and REE-rich pyromorphites precipitated in the first part of the study.

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Effect of particle size on the efficiency of mineral carbonation of ultramafic rocks

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Mineral carbonation enables permanent CO_2 storage through the formation of stable carbonate minerals. Mg-rich ultramafic rocks are considered promising materials for this purpose because their silicate minerals can provide Mg for carbonate formation (Sanna et al., 2014). The aim of this study was to evaluate the effect of serpentinite particle size on mineral carbonation efficiency.

The investigated serpentinite from Przemiłów (SW Poland) consisted mainly of lizardite and antigorite, with minor magnetite and Cr-bearing spinel. The material was divided into four particle-size fractions: <50, 50–125, 125–250, and 250–500 μm, with specific surface areas ranging from 1.89 m^2/g for the coarsest fraction to 12.77 m^2/g for the finest. Each fraction was carbonated separately in a stirred batch autoclave using 15 g of serpentinite and 150 mL of ultrapure water at 185 °C and 100 bar CO_2 for 48 h. Solids and post-reaction solutions were analyzed to assess mineralogical changes, carbon uptake, and solution chemistry.

After carbonation, magnesite was detected only in the two finest fractions. The <50 μm fraction showed the highest carbonation efficiency of 3.49%, compared with 0.88%, 0.65%, and approximately 0% for progressively coarser fractions. Higher Mg and Si concentrations in solutions from the finest fraction were also consistent with more extensive dissolution. These results indicate that particle size affected carbonation under the applied conditions, although the overall CO_2 uptake remained low and fine grinding alone did not result in substantial carbonation.

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Inclusion thermobarometry: reconstructing the pressure-temperature evolution of eclogites from the Tsäkkok Nappe, Sweden

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Reconstructing the pressure-temperature (P-T) evolution of high-pressure (HP) metamorphic rocks is essential for understanding processes occurring in subduction zones. This study focuses on eclogites from the Tsäkkok Lens of the Scandinavian Caledonides. They belong to the Seve Nappe Complex, which forms the upper part of the Middle Allochthon of the Caledonian Orogen. The Tsäkkok Lens represents the outermost Baltican margin that was subducted in the Late Cambrian/Early Ordovician during closure of the Iapetus Ocean (Bukała et al., 2020). The focus of this study is zircon and quartz inclusions entrapped in garnets from the eclogite sample previously studied by Bukała et al. (2020) to reconstruct the P-T history.

Eclogite consists of garnet, omphacite, phengite, amphibole, clinozoisite, carbonates, quartz and rutile. Microscopic observations reveal two distinct garnet textures: fine-grained garnet aggregates and larger subhedral to euhedral porphyroblasts. X-ray maps and compositional profiles of garnets show chemical zoning. The chemical composition of garnet varies from $Alm_{62}Grs_{22}Prp_{11}Sps_5$ in the core to $Alm_{59}Grs_{20}Prp_{20}Sps_1$ in the rim. Spessartine shows oscillatory zonation in the outer rim. Garnet hosts voluminous inclusions including quartz and zircon, thus allowing the application of quartz-in-garnet (QuiG) and zircon-in-garnet (ZiG) thermobarometry. Raman spectroscopy was applied to 11 quartz and 51 zircon inclusions, which were further processed following the protocol by Gilio et al. (2025).

The ongoing work combines the compositional record preserved in garnets with residual stress measurements of quartz inclusions. Preliminary results are providing HP-LT conditions for the prograde path typical for the cold-subduction regime. Final results are expected to further constrain the metamorphic P-T conditions of the Tsäkkok eclogites and to evaluate the potential of Raman elastobarometry in HP-LT metamorphic rocks.

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Microbial mechanisms of metal mobilization from copper slags by *Pseudomonas fluorescens*

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Copper slags contain residual metals whose mobility depends not only on their occurrence within individual solid phases, but also on the chemical and biological conditions developing at the slag-solution interface. Microbes may alter these conditions through (1) the production of extracellular metabolites, including siderophores and organic acids, which can promote metal complexation and solid-phase dissolution (i.e., indirect interactions) and (2) direct interactions with the slag surface, including bacterial attachment and biofilm formation. Determining the relative importance of these processes is essential for understanding metal behavior in metallurgical wastes.

The present study investigates the mechanisms of metal mobilization from amorphous and crystalline copper slags mediated by *Pseudomonas fluorescens*. A dialysis-based experimental approach was applied to separate the influence of metal-complexing metabolites from processes requiring physical adhesion of bacterial cells to the slag surface. In one experimental configuration, bacterial cells and slag were separated by a dialysis membrane permeable to dissolved metabolites. In parallel systems, bacteria were allowed to interact directly with slag particles, providing conditions for surface colonization and biofilm development. Abiotic variants were included as reference systems.

The experiments combine short-term (1–7 days) and long-term (up to several months) observations to assess how microbially mediated metal mobilization evolves over time. Temporal changes in pH and redox potential are monitored, while major and trace elements are determined in both leachates and acid-digested bacterial biomass using ICP-OES and ICP-MS.

This experimental design enables the role of extracellular metabolites in metal mobilization to be evaluated against the combined effects of metabolites, bacterial attachment and biofilm development. Comparison of two structurally different slags additionally provides a basis for assessing how material characteristics influence their response to microbial activity. The study aims to identify the processes governing metal release and retention at the microbe-slag interface and to evaluate their relevance for biologically assisted recovery of metals from metallurgical residues.

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REE-bearing scheelite from the porphyry Mo-Cu-W Myszków deposit (Poland): preliminary insights from LA-ICP-MS and cathodoluminescence spectroscopy

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Scheelite from the Variscan porphyry Mo-Cu-W Myszków deposit (Poland) was investigated by cathodoluminescence (CL) imaging and spectroscopy combined with *in situ* LA-ICP-MS to constrain crystal growth, trace-element incorporation and hydrothermal evolution. Scheelite occurs mainly in quartz-feldspar stockwork veins associated with potassic alteration and molybdenite. Although commonly homogeneous in BSE, CL reveals complex internal architecture, including oscillatory and sector zoning, dissolution surfaces, fractures and late overgrowths, highlighting its sensitivity to chemical and structural variations.

Scheelite shows strong compositional variability, with Mo ranging from 116 to 176688 ppm and ΣREE from 6.7 to 3999 ppm. ΣREE correlates strongly with Na (R = 0.83), indicating dominant incorporation through $REE^{3+} + Na^{+} \rightleftharpoons 2Ca^{2+}$ (e.g., Brugger et al., 2000). Nevertheless, the incorporation of pentavalent cations also contributed to charge balancing, as indicated by the moderate positive correlation between (Nb + Ta) and ΣREE (R = 0.47).

CL spectra record distinct effects of Mo and REE activity. Increasing Mo shifts emission from blue WO_4^{2-} (~400–435 nm) toward green MoO_4^{2-}-related emission (~515–529 nm), reflecting increasing powellite component (Poulin et al., 2016). REE-related Sm^{3+}, Dy^{3+} and Tb^{3+} emission is observed in REE-enriched regions, whereas domains with ΣREE >2500 ppm show reduced CL intensity, consistent with CL quenching.

The combined data record hydrothermal evolution from early REE- and Mo-rich scheelite formed from high-temperature, oxidized magmatic-hydrothermal fluids, through extreme Mo enrichment (~18 wt. %), to late Mo- and REE-depleted rims formed during cooling and fluid dilution. The correlation between Mo and Eu/Eu* (R = 0.73) further supports saline, oxidized magmatic-hydrothermal fluids. CL-guided microanalysis of scheelite therefore provides a high-resolution record of fluid evolution and mineralization in the Myszków porphyry system.

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Quartz-in-garnet elastic barometry at the Hohl eclogite type-locality (Koralpe, Eastern Alps, Austria) – preliminary results

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Quartz-in-garnet elastic barometry provides an independent means of constraining the P–T conditions of garnet crystallization, relying solely on the mechanical properties of minerals rather than on thermodynamic calculations. In this study, we apply this method to four distinct rock types from the Hohl outcrop, located in the Saualpe-Koralpe Complex (Eastern Alps, Austria), which forms part of the eclogite type-locality. The SKC comprises mica schist, gneiss, marble, and amphibolite, hosting meter- to kilometer-scale lenses of eclogite and metagabbro. The complex was metamorphosed during Permian rifting, associated with emplacement of the eclogite protolith – gabbro – and high-temperature metamorphism with peak conditions of 0.38–0.65 GPa and 600–650 °C, and subsequently during Late Jurassic to Cretaceous convergence, recording widespread high-pressure metamorphism at 1.5–2.2 GPa and 620–740 °C.

The Hohl outcrop comprises four main rock types. The main eclogite body, surrounded by paragneiss, shows variable degrees of equilibration under eclogite-facies conditions and variable intensity of deformation. Two types of enclaves occur within this eclogite: Grt-Amph-Zo-dominated enclaves and host-paragneiss enclaves. In this study, two samples represent the eclogitic mineral assemblage (Grt + Omph + Amph + Zo + Qz + Ky + Rt) at differing intensities of equilibration and deformation: HE07, an eclogitic metagabbro showing almost no deformation and still preserving relict texture and mineralogy of the protolith, and HE03, a fully equilibrated, mylonitized eclogite from the vicinity of the Grt-Amph-Zo-dominated enclave (sample HE02). Sample HE11 is a paragneiss enclave with the main mineral assemblage Qz + Pl + Wm + Grt + Zo + Bt.

Quartz-in-garnet elastic barometry indicates maximum entrapment conditions of ~2.0 GPa at adopted temperature of 700 °C across all investigated samples, consistent with previously published thermodynamically derived P–T estimates. These results point to negligible viscous relaxation of the recorded entrapment pressures, despite temperatures well within the range at which such relaxation would be expected to occur.

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The Carpathian zircons deposited in the loess from W Ukraine and SE Poland, and in the modern alluvial sediments of the Vistula River

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A comparative provenance study of Carpathian Flysh and the MIS12, MIS10, MIS8, MIS6, MIS4 and MIS2 loess from W Ukraine and SE Poland was carried out. The modern alluvial sediments from the Vistula riverbed were also sampled in eight localities situated in the upper and middle river sections for estimation of content of Carpathian zircons. The U-Pb ages of detrital zircons were determined using a SHRIMP IIe ion microprobe. Zircons from both sedimentary environments yield predominantly the Carpathian i.e. Ediacaran to Cenozoic zircons. Proterozoic zircons originally derived from the Fennoscandian Shield and Sveconorwegian orogen became dominant only in the northernmost fluvial site (ca. 30 km north –west of Warsaw). All studied aeolian sediments represent mountain provenance-river transport mode of loess origin. Similar age spectra characteristics for the fine- and coarse-grained zircons can indicate predominance of short distant transport of detrital material in the loess. Almost the same age spectra observed in some horizons of the loess of different age can indicate a certain redeposition of sediment or similar alimentation areas with primary source of zircons in the Carpathians. Slight differences may be associated with some variability of glaciers extend and ancient river systems, and consequently migration of alimentation areas.

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Mobilization of metal(loid)s from mining waste rocks after the historical Cu-mining operation in Miedzianka (SW Poland)

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Mining operations generate waste rock that can serve as a source of potentially harmful metal(loid)s. These metal(loid)s may be mobilized from waste rock when exposed to weathering processes within waste heaps. Therefore, the aim of this study was to investigate the mobilization of metal(loid)s from mining waste rock collected from a heap in Miedzianka (SW Poland), formed as a result of historical Cu mining activities. Due to the long-term disposal of mining waste rock within the heap, the material was classified as a Hyperspollic Technosol with the horizon sequence Ol-Ofh-AC-1C-2C-3C-4C-5C-6C-7C-8C. Selected properties of the fine earth fraction (< 2 mm) from the mineral horizons were analyzed, including mineral composition by XRD, elemental composition following acid digestion and determination by ICP-OES and ICP-MS, pH, and carbonate content determined using the Scheibler volumetric method. Metal(loid) mobilization was assessed through leaching experiments using *Acidithiobacillus thiooxidans* in a growth medium (BAC) and a sterile growth medium (MED).

The mineral composition of the fine earth was dominated by quartz, feldspar, chlorite, mica, and calcite. The pH of the surface horizon (Ofh) was close to 5, whereas in the middle part of the profile it ranged from 7 (AC) to 8 (4C). In contrast, the pH of the deepest horizon was below 5. Carbonate content was generally below 3% in most horizons, whereas carbonates were absent in AC, 7C, and 8C. The chemical composition of the fine earth was dominated by SiO_2, Fe_2O_3, and Al_2O_3, reaching up to 53%, 26%, and 26%, respectively (4C and 7C horizons). Metal(loid) concentrations were relatively high, reaching up to 24,200 mg kg^{-1} Cu and 3,535 mg kg^{-1} Zn in horizon 8C. Among the analyzed elements, Zn, Cd, Co, and Cu exhibited the highest mobilization rates, with Zn reaching up to 77% of its total content in both BAC and MED treatments. The greatest mobilization of metal(loid)s was observed in the deepest horizon (8C), highlighting the strong influence of pH on metal(loid) mobility.

The study demonstrates that: (a) the first signs of soil-forming processes within the mining waste heap include the accumulation of organic matter in the upper part of the profile and intensive weathering and oxidation of waste materials in the lower part; (b) bacteria play an important role in the biotic mobilization of metal(loid)s, with the highest bacterial mobilization observed in horizons characterized by low pH; and (c) the relatively high potential for metal(loid) mobilization from the mining waste indicates a significant environmental risk.

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Compositional and Secondary-Phase Controls on Iodine Release from $Me_5(AO_4)_3I$ Apatites

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The apatite supergroup combines exceptional crystal-chemical flexibility with the ability to host monovalent anions in structural channels. Iodide-bearing apatites therefore provide a systematic model for testing how framework chemistry controls mineral stability and aqueous behaviour, while also offering candidate hosts for long-lived ^{129}I ($t_{1/2} = 1.57\times10^7$ yr). We investigate 15 $Me_5(AO_4)_3I$ end-member compositions defined by Me = Ca, Sr, Ba, Cd, Pb and A = P, As, V, forming a 5 × 3 matrix that separates cationic and tetrahedral substitution effects.

Density functional theory (DFT) calculations were performed with CASTEP code following the thermodynamic approach validated by Benisek & Dachs (2018). Structural relaxation and lattice-dynamics calculations provided total energies and phonon-derived heat capacities. These were used to obtain standard entropies and 298.15 K enthalpy corrections. Formation enthalpies were derived from internally consistent oxide-iodide reaction cycles combining DFT energy differences with referenced thermodynamic data. Together, these quantities yielded temperature-dependent Gibbs energies and dissolution constants for all 15 compositions.

At 298.15 K, calculated logK values for the defined dissolution reactions span nearly 100 units across the compositional matrix, demonstrating exceptionally strong chemical control on intrinsic apatite stability. Temperature-dependent shifts are composition specific, showing that room-temperature rankings alone are insufficient to describe higher-temperature behaviour. The log K(T) functions were implemented in PHREEQC to calculate aqueous iodine concentrations and saturation indices of secondary phases.

Importantly, intrinsic solubility does not necessarily predict iodine release. For $Pb_5(VO_4)_3I$, precipitation of $Pb_2V_2O_7$ (chervetite) sequesters framework components and promotes continued incongruent dissolution, whereas $Ba_5(PO_4)_3I$ shows limited congruent dissolution without comparable secondary-phase feedback. Thus, secondary mineral equilibria, apatite composition and temperature jointly control iodine retention. This composition-thermodynamics-alteration framework provides new data for thermodynamically uncharacterized iodine apatites and a quantitative basis for evaluating candidate hosts for ^{129}I immobilization.

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Petrogenesis and metamorphic records of the eastern Alashan block (NW China): insights into the making of a Cordillera-type paleo-margin

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The Alashan block preserves key tectonic records of construction of the southern Central Asian Orogenic Belt and the transition from Rodinia to Pangea. Our study presents new geochemical, isotopic and geochronological data that constrain, for the first time, the petrogenesis of early Paleozoic metamorphic amphibolites, micaschists and migmatites in the eastern Alashan block. The results suggest that the protoliths of amphibolites were derived from a moderately enriched mantle source during late Mesoproterozoic–early Neoproterozoic time, in an intra-plate setting. The host metasediments were deposited during continental rifting of the same age and show a detrital affinity with the Ordos block. Combined petro-structural, metamorphic and geochronological studies reveal that the northernmost rocks record a Silurian prograde (M1) metamorphic event, overprinted by a regional Devonian Barrovian-type (M2) metamorphic event. Together with the cessation of continental arc magmatism (ca. 458–436 Ma), this suggests that the D1-M1 event (ca. 430 Ma) reflected northward underthrusing of the eastern Alashan block. The subsequent Barrovian metamorphism (ca. 411–394 Ma) and concomitant magmatic resurgence (ca. 423–397 Ma) reflect increasing heat flow associated to supra-subduction thickening D2-M2 and crustal melting. This sequence depicts the development of an early Paleozoic Cordillera paleo-margin in the eastern Alashan block, affected by a late phase of Andean-type shortening and thickening, and contrasting with the evolution of the neighboring North-China craton. Assuming late Devonian tectonic coupling of the eastern Alashan block and the Ordos block, this work offers a new contribution to the regional geodynamic model for the assembly of the Tarim–North China collage in the southern Central Asian Orogenic Belt.

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Limitations and challenges in the application of Pb-modified zeolite for arsenic immobilisation in complex aqueous systems: insights from Icelandic geothermal waters

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Geothermal waters are valuable natural resources used for geothermal energy production and balneotherapy, but their complex geochemistry may result in elevated concentrations of potentially toxic elements, including As, Pb, Hg or Sb, alongside economically important elements such as Li, Ge and REEs. Arsenic is of particular concern due to the contrasting toxicity, mobility and reactivity of As(III) and As(V), making its removal dependent on speciation and water chemistry. Pb-modified clinoptilolite has shown high potential for arsenic immobilisation through the formation of sparingly soluble lead apatite - mimetite ($Pb_5(AsO_4)_3Cl$). Here, we assess the applicability and limitations of Pb-clinoptilolite for As immobilisation in Icelandic geothermal waters where [As] ranged from 0.089 to 0.154 mg/L.

Arsenic removal effectiveness was much higher in alkaline, sulphate-rich Blesi and Konungshver waters from the Geysir area (pH ~9.3) than in marine-derived, Cl-rich Grey Lagoon water from Reykjanes (pH ~6.5). Powdered Pb-modified clinoptilolite reduced [As] within 1h from 89 to 7 µg/L in both Blesi and Konungshver and from 154 only to 38 µg/L in Grey Lagoon. After 24 h, [As] remained stable in Blesi and Konungshver, but increased to 93 µg/L in Grey Lagoon. The contrasting As removal was accompanied by substantial differences in Pb mobilisation after 24 h. In Blesi and Konungshver dissolved Pb was below 7 mg/L while in Grey Lagoon it reached 1174 mg/L. SEM observations revealed secondary Pb-bearing phases, including cotunnite ($PbCl_2$) and anglesite ($PbSO_4$), while mimetite occurred only in minor amounts. This resulted in pronounced Pb mobilisation in saline, chloride-rich waters and represents a major limitation for stable As immobilisation.

A pronounced difference in As removal was also observed between the two forms of Pb-clinoptilolite used in the experiments: granulated and powdered. Granules were less effective both in waters form Blesi ([As] reduced only to 68 µg/L compared to 7 µg/L with powder) and in waters from Grey Lagoon ([As] reduced only to 128 µg/L compared to 38 µg/L with powder). In waters from Konungshver granules reduced [As] to below 5 µg/L. The lower performance of granules may reflect reduced accessibility of reactive sites.

Under natural geothermal conditions, the performance of Pb-modified clinoptilolite differs from that in simplified laboratory systems due to complex water chemistry and variable physicochemical conditions affecting As immobilisation and Pb release. These findings highlight the need for testing materials under realistic, application-relevant conditions.

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Metamorphic evolution of metapelites from the Velké Vrbno unit, Eastern Sudetes

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The Velké Vrbno unit, located in the Eastern Sudetes, forms part of the Moravo-Silesian domain at the eastern margin of the Bohemian Massif. Its internal structure comprises an upper structural unit dominated by an eclogite-bearing orthogneiss sheet with metapelite intercalations, thrust over a volcano-sedimentary sequence forming a lower unit locally exposed in a tectonic window.

In this study, two garnet-bearing mica schists, VVD01 representing the upper structural unit and VVD05c collected in the lower structural unit, were investigated using petrographic observations, mineral chemistry, phase-equilibria modelling and quartz-in-garnet Raman elastic barometry. Sample VVD01 contains garnet porphyroblasts in a matrix dominated by staurolite, white mica and quartz, with chloritoid, chlorite, staurolite, rutile and quartz preserved as inclusions in garnet. Sample VVD05c contains garnet porphyroblasts in a matrix composed of white mica, quartz and plagioclase, with subordinate epidote. The garnet hosts inclusions of epidote, plagioclase, white mica, biotite and rutile.

Phase-equilibria modelling and garnet compositional isopleths indicate garnet growth at ca. 9–10.5 kbar and 530–580 °C. Quartz-in-garnet Raman elastic barometry yields broadly consistent pressures of ca. 9–11.5 kbar assuming temperatures of 550–600 °C, with some individual inclusions yielding pressures of up to ca. 12 kbar.

The new results indicate that metapelites from both structural units record broadly comparable pressure conditions, but distinctly lower temperatures than those previously reported for the Velké Vrbno unit. Previous work documented metamorphic peaks of ca. 10–11 kbar at 620–640 °C in metapelites from both the upper and lower structural units (Štípská et. al., 2006), whereas our data indicate garnet growth at similar pressures but temperatures mostly below 600 °C. This difference suggests that the metamorphic evolution of the Velké Vrbno unit may have been more complex than represented by a single P–T trajectory, although the significance of the contrasting thermal records remains unresolved.

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Hematite is a mineralogical marker of ancient climate change on Mars

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The crystallographic characteristics of hematite in sedimentary rocks of Gale crater were investigated using X-ray diffraction (XRD) data acquired by the Curiosity rover. Whole-powder-pattern modelling of the hematite reflections (mainly (104) and (110) ones) was used to determine crystallite sizes in two crystallographic directions and to assess crystallite morphology. Hematite is approximately equant, with crystallite sizes ranging from ~5 to 65 nm in the stratigraphically lower Murray formation, whereas crystallites are <10 nm in the overlying Carolyn Shoemaker and Mirador formations. In contrast, hematite crystallites formed during weathering on Earth typically have a platy morphology. Comparison with laboratory experiments indicates that the small, equant crystallites are consistent with hematite formation from ferrihydrite under low-temperature, neutral to slightly alkaline conditions.

The systematic variation in crystallite size and trends in crystallite size distributions within the Murray formation are consistent with Ostwald ripening, involving dissolution of smaller crystallites and growth of larger ones during prolonged groundwater interaction. In contrast, the preservation of small hematite crystallites together with goethite in the stratigraphically higher Carolyn Shoemaker and Mirador formations indicates more limited aqueous alteration and lower temperatures. These differences record a transition from prolonged aqueous alteration under relatively warm conditions to colder, more water-limited conditions during postdepositional evolution.

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Raman Spectroscopic Study of Hydration Mechanisms in Chlormayenite and Chlorkyuygenite

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Chlormayenite ($Ca_{12}Al_{14}O_{32}[\square_4Cl_2]$) and chlorkyuygenite ($Ca_{12}Al_{14}O_{32}[(H_2O)_4Cl_2]$) are minerals belonging to the mayenite group. They are characterized by a unique microporous framework with an "anti-zeolitic" structure. The aluminous framework of these minerals forms structural cages in which the *W* site enables ion migration and molecular adsorption (Galuskin et al., 2015). While synthetic analogues predominantly have "free oxygen" (O^{2-}) at this site, natural minerals exhibit a wide range of configurations resulting from varying degrees of hydration (Środek et al., 2018).

This study presents the results of Raman spectroscopic analyses of chlormayenite and chlorkyuygenite from new occurrences: a metacarbonate xenolith in Balaton area (Hungary), and pyrometamorphic rocks of the Hatrurim Complex (Israel). Raman spectroscopy enabled the precise description of the mechanisms by which hydrogen is incorporated into the crystal structure of the chlorine-bearing members of the mayenite group. These minerals had previously been mainly investigated in the fluorine-bearing members of this group (Środek et al., 2018). The results show that primary chlormayenite undergoes a process of "kyuygenitization" at temperatures below 400–600 °C. This involves filling of structural vacancies with neutral water molecules ($^{W}\square \rightarrow {}^{W}(H_2O)$), producing characteristic broad Raman bands in the 3200–3400 cm^{-1} region. At higher temperatures (>900 °C), the dominant mechanism is the incorporation of hydroxyl groups (OH^-) into the structural cages ($^{W}\square \rightarrow {}^{W}OH$), resulting in a Raman band at around 3570 cm^{-1}.

Further hydration modifies the aluminous framework: the substitution of the O*2* oxygen site by three OH^- groups changes the aluminum coordination from tetrahedral to octahedral, which is linked to a Raman band at approximately 3670 cm^{-1}. During the final stages of low-temperature alteration, hydrogarnet-type defects (~3605 cm^{-1}) form, resulting in the transformation of mayenite into katoite ($Ca_3Al_2(OH)_{12}$). These results demonstrate that Raman spectroscopy of the mayenite supergroup minerals can be a usefull tool for reconstructing the thermal and fluid evolution of natural pyrometamorphic systems.

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Petrography of products of pyrometamorphism from Silesian coal waste dumps

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Pyrometamorphism is also known as combustion metamorphism. It occurs in burning coal waste dumps (BCMD). This is a typical process in many mining regions around the world where spoil has been burned during spontaneous combustion. Examples include northern France, the Chelyabinsk coal basin in Russia and 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). The aim of this study was to establish a comprehensive petrographic classification of pyrometamorphic rocks occurring on coal mine waste dumps in Lower and Upper Silesia. These rocks, including paralavas, clinker rocks, and buchites, constitute the products of high-temperature transformations induced by the spontaneous combustion of coal mine waste and have hitherto remained insufficiently characterized from a petrographic standpoint. Previous investigations have predominantly focused on the identification of mineral phases and geochemical characterization, whereas a systematic petrographic classification integrating the textural and structural attributes of these rocks has not yet been developed (Thiery & Guy, 2015). The waste material resulting from the extraction of coal is inherently heterogeneous. It consists of a mixture of sedimentary rocks, including sandstones, arkoses, clay shales, argillites and limestones, as well as fragments of coal. In some cases, the mixture also contains anthropogenic waste, such as metal scrap, fly ash and demolition materials. This variability in composition exerts a significant influence on the petrographic diversity of the products formed during the spontaneous combustion of waste heaps. The outcomes are based on thin-section analyses of samples from Upper and Lower Silesia. The investigation was primarily conducted utilizing optical microscopy and scanning electron microscopy (SEM). The results obtained by this method allow for the creation of a preliminary database, which can then be used for the subsequent classification of pyrometamorphic formations. The objective of this preparatory collection is twofold: firstly, to disseminate knowledge regarding these formations, and secondly, to systematise the nomenclature, thereby facilitating comprehension, particularly within the context of popular science publications.

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Long-term environmental stability of waste sulfide clays after Fe-Pb-Zn ore exploitation

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Historical exploitation of Fe-Pb-Zn deposits in Poland's Silesian-Cracow region has left a legacy of untreated waste sulfide clays. At the abandoned Bibiela mine, these wastes have weathered for over a century. This study investigates the mineralogical transformations and geochemical mobility of potentially toxic elements (PTEs) within these wastes and adjacent Technosols to assess the risk of contaminant propagation.

A multi-analytical approach (XRF, ICP-MS, XRD, SEM-EDS) and comprehensive leaching protocols (deionized water, pH-static, and 0.01 M $CaCl_2$) were used to describe water-soluble, pH-dependent, and bioavailable PTE fractions.

Geochemical analyses reveal extreme PTE enrichment in the surface layers of the waste heap and Technosols, reaching maxima of 25.0 wt. % Zn, 24.1 wt. % Pb, 1170 mg kg^{-1} As, and 155 mg kg^{-1} Cd. Primary sulfides (marcasite and pyrite [FeS_2], sphalerite [ZnS]) show extensive, yet incomplete oxidation. The resulting secondary phase assemblage includes sulfates (jarosite [$KFe_3(SO_4)_2(OH)_6$], copiapite [$Fe^{2+}Fe^{3+}_4(SO_4)_6(OH)_2 \cdot 20H_2O$], gunningite [$ZnSO_4 \cdot H_2O$]), carbonates (cerussite [$PbCO_3$], smithsonite [$ZnCO_3$]), phosphates (kintoreite [$PbFe_3(PO_4)(PO_3OH)(OH)_6$]), and goethite (FeO(OH)). While PTEs are partially adsorbed onto clay minerals or goethite, leaching data demonstrate ongoing mobilization. Continuous oxidation of residual sulfides generates hyperacidic conditions (leachate pH 2.37–2.67), undermining the stability of the secondary mineral assemblage. Under these regimes, soluble sulfates and carbonates act merely as transient sinks. This phenomenon is corroborated by deionized water leaching tests (EN 12457-2), confirming the phase breakdown and significant releases of Cd (up to 3.56 mg L^{-1}) and Zn (up to 527 mg L^{-1}). According to the pH-static extractions, such emissions are characteristic of environments with pH $\leq$ 5. Although Pb and As are less prone to leaching, the wastes' buffering capacity is overwhelmed by persistent acid generation leading to their mobilization and subsequent accumulation in Technosols adjacent to the heap as well. $CaCl_2$ leaching confirms substantial PTE bioavailability (especially As, Cd, and Zn), explaining the complete barrenness of the surrounding Technosols.

Even after a century of weathering, the Bibiela waste sulfide clays lack environmental stability. The secondary mineral assemblage provides only temporary PTE retention. Sustained extreme acidity from sulfide oxidation continuously drives the migration of Zn, Pb, Cd, and As into the adjacent environment. Ultimately, these results highlight the need to develop effective remediation methods for similar mining wastes, especially considering their severe environmental instability over timescales exceeding 100 years.

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Preliminary Raman geothermometry of carbonaceous material in metasedimentary rocks from the Niemcza Shear Zone and Kamieniec Metamorphic Belt (NE Bohemian Massif)

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Raman spectroscopy of carbonaceous material (RSCM) provides estimates of maximum temperatures attained during metamorphism and is widely used as an independent or complementary metamorphic geothermometer (Beyssac et al., 2002; Rahl et al., 2005).

We present preliminary RSCM geothermometry from graphitic quartzites, mylonites, and mica shists collected at three localities in the Niemcza Shear Zone (NSZ) and two in the Kamieniec Metamorphic Belt (KMB). Previous thermometric estimates from the NSZ were obtained mainly from narrow structural domains proximal to syntectonic granitoids and may therefore represent localized thermal maxima rather than regional metamorphic conditions.

Raman spectra were evaluated using the characteristic D and G bands of carbonaceous material, and temperatures were calculated using the calibrations of Rahl et al., (2005) and Beyssac et al., (2002). In the NSZ, calculated temperatures range from ~550 °C to values reaching or exceeding the upper limits of the applied calibrations (700 °C for Rahl et al., 2005 and 650 °C for Beyssac et al., 2002). In the KMB, temperatures range from ~475 to ~680 °C using the Rahl et al. (2005) calibration and from ~495 to ~600 °C using the Beyssac et al. (2002) calibration.

The NSZ results partly overlap with independent estimates of ~650–710 °C, including Zr-in-rutile temperatures of 630–710°C (Wicher-Jarząb et al., in press), but also indicate spatial variability in maximum temperatures recorded across the shear zone. In the KMB, temperatures obtained using the Beyssac et al., (2002) show closer agreement with previous petrological estimates of ~530–570 °C (Szczepański et al., 2022) than those calculated using the Rahl et al. (2005) calibration. These preliminary results suggest that RSCM may help distinguish regional metamorphic temperatures from localized thermal effects and provide additional constraints on the metamorphic evolution of the eastern part of the Bohemian Massif.

Acknowledgements: This work was supported by the "Excellence Initiative – Research University" program at the University of Wrocław through grant BPIDUB.4610.57.2026 to the first author.

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Nanostructure of metamorphic monazites from the Napier Complex

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Monazite ($REEPO_4$) is an accessory mineral, which is of great importance for the study of metamorphic radioactive decay of uranium and thorium that allows for U-Th-Pb geochronology. Two competing processes have influence on the degree of radiation damage in monazite:

1) self-irradiation creates damages in crystal structure,
2) annealing process at elevated temperature causes recovery of the crystal lattice.

However, unlike zircon, natural monazite never becomes fully metamict due to fast recovery processes, but for both minerals the redistribution of Pb* was documented (Seydoux-Guillaume et al., 2003; Kusiak et al., 2015; Turuani et al., 2023).

For this study metamorphic monazite grains from orthogneisses from the Napier Complex in East Antarctica were selected, to analyze the chemical composition and nanostructure utilizing electron microprobe and transmission electron microscopy. Monazite domains differing in Th concentration showed different nanostructures. Areas of high content of Th have developed porosity together with Si- and Pb-enriched nanoparticles. Additionally, hedyphane ($Ca_2Pb_3(PO_4)_3Cl$) was documented. Low Th domains contain nanoinclusions of apatite. The analyzed monazites were younger than 2.5 Ga (UHT metamorphic event in the Napier Complex) that indicates post-UHT loss of Pb or another metamorphic process.

The fact that Pb is redistributed in monazite has implications for geochronology. Therefore, the knowledge about this process is crucial to understand and interpret geochronological data.

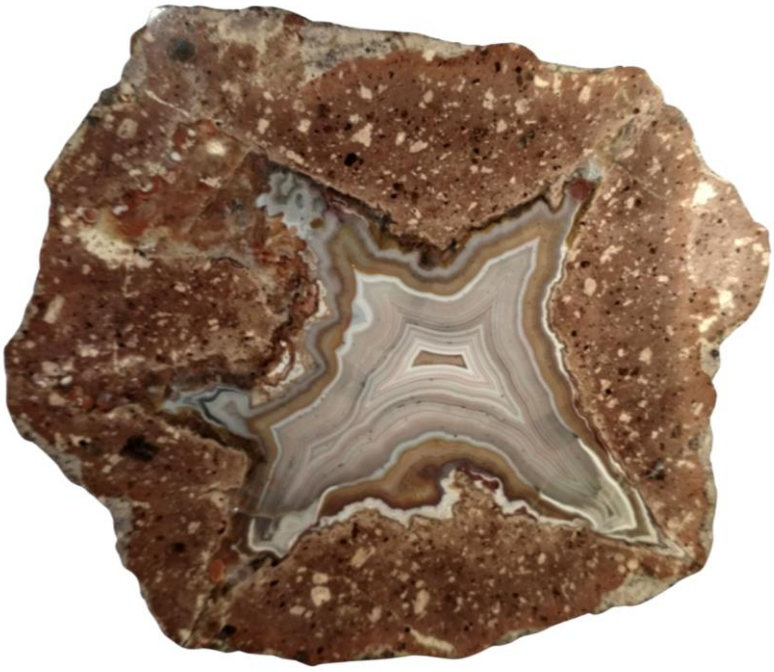
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31st Meeting of the Petrology Group of the Mineralogical Society of Poland

Field trip guide



Lithophysal agate with a star-shaped pattern from Nowy Kościół (photo: Stanisław Madej)



Drusy quartz on agate from Nowy Kościół (photo: Stanisław Madej)

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Permian rhyolitic volcanism and associated agate mineralization in the North-Sudetic Synclinorium (SW Poland) – field trip

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Introduction

In the late Carboniferous and Permian times large areas of Europe were shaped by intense volcanism linked with the activity of a "felsic-dominated large igneous province" (e.g. Paulick & Breitkreuz, 2005). In the Sudetes, in the south-eastern part of this province, volcanic rocks crop out in volcano-sedimentary successions of the Intra-Sudetic and the North-Sudetic synclinoria. Here, volcanism resulted in the formation of several eruptive centres (e.g. small shield volcanoes, maars and tuff rings, ignimbrite caldera) with the emplacement of lava flows, various pyroclastic deposits as well as sills and laccoliths. The volcanic and subvolcanic rocks show calc-alkaline to mildly alkaline geochemical characteristics reflecting their late/post-orogenic to extensional intracontinental geotectonic setting (more details in Awdankiewicz, this volume).

This field trip presents selected outcrops of Permian volcanic rocks of the North-Sudetic Synclinorium (NSS; Fig. 1A). Here, the Permian volcanic rocks are interbedded in the Lower Permian Wielisławka Formation. The latter is up to 900 m thick and comprises conglomerates, sandstones and shales with minor limestones that originated in alluvial fan, alluvial plain and lacustrine environments (Wojewoda & Mastalerz, 1989). In the central part of the NSS the volcanic rocks comprise rhyolites, rhyolitic tuffs and basaltic andesites (Fig. 1B). The field trip is focused on the rhyolites as the "Rocks of the Year 2026". Stop 1 at the Organy Wielisławskie quarry provides an excellent opportunity to examine a spectacular exposure of columnar-jointed rhyolite. The site illustrates several challenges in interpreting ancient volcanic successions, including distinguishing intrusions from extrusions, evaluating the various applications of geophysical methods, and assessing the potential and limitations of petrological interpretations in strongly altered volcanic rocks. Such alterations, although rather troublesome from a petrological perspective, bring some aesthetically stunning and scientifically intriguing results such as agates, which will be the subject of the field trip stops 2 and 3. These various aspects of rhyolites highlight their distinctive position within the volcanic rock spectrum.

Finally, it shall be noted that the field trip stops are located in the "Land of Extinct Volcanoes", an area featuring numerous well-preserved, impressive occurrences of not only Permian, but also Cambrian, Ordovician as well as Cenozoic volcanic rocks and volcanoes

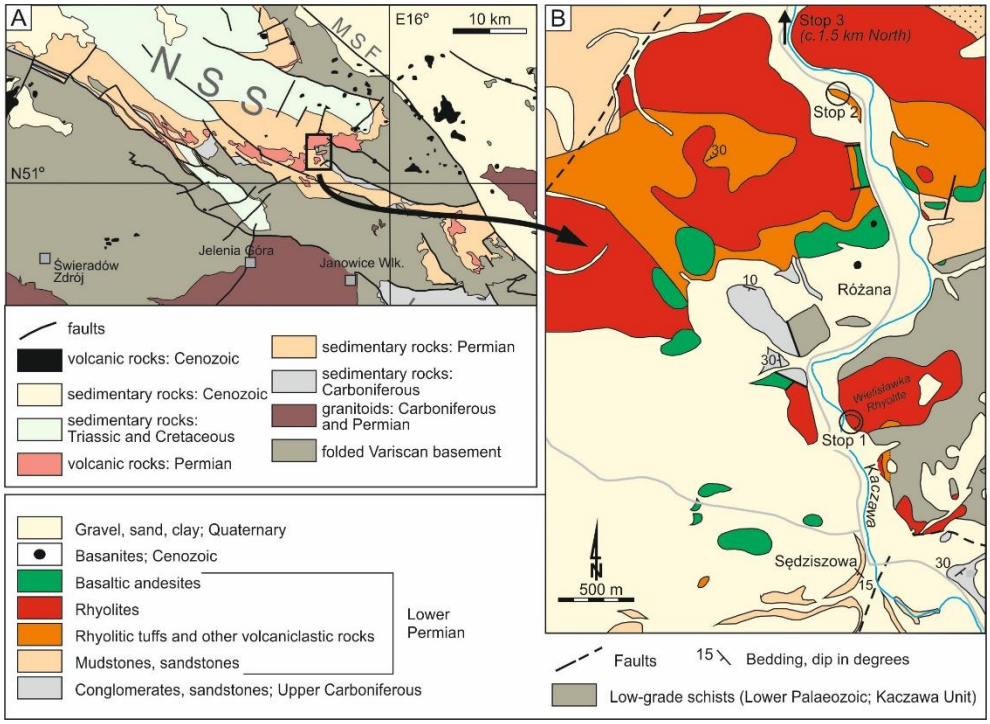


Figure 1. A. Geological sketch map of the North-Sudetic Synclinorium (NSS; modified from Bossowski et al., 1981; Milewicz et al., 1989) showing the field trip area (rectangle near the centre). MSF - Marginal Sudetic Fault. B. Geological map of the field trip area (modified from Frąckiewicz, 1958; Milewicz & Kozdrój, 1995) with location of the field stops 1-3.

– extinct, already cold - but cool! The great natural, geological and historical values of this region were long recognized and culminated recently (2024) in the designation of the area as an UNESCO Geopark (https://www.gorykaczawskie.pl/en/).

Stop 1. Rhyolites at Organy Wielisławskie

leaders: M. Awdankiewicz, M. Petronis, S. Poppe

(51.0344581N, 15.8695319E)

Geologic setting, previous work and ongoing research

The Organy rhyolite is part of the larger rock unit within the Permian succession of the North-Sudetic Synclinorium, distinguished as the Wielisławka Rhyolites (Fig. 1B; Szczepara, 2018). The Wielisławka Rhyolites form a NEE-elongated outcrop 1.2 x 0.4 km in size, situated near the western end of an uplifted basement block, the Świerzawa Horst, which consists of the low-grade metasedimentary basement rocks of the Cambrian to the early Carboniferous Kaczawa unit (Baranowski et al., 1990). The rhyolites were emplaced mostly within these metasediments and partly within the younger cover, consisting of the latest Carboniferous-Permian siliciclastic sedimentary rocks with interbedded mafic volcanics. The origin of the Wielisławka Rhyolites has been the subject of differing interpretations for over a century. These include emplacement as an elongated stock, laccolith, or as a lava flow

filling a basement trench (Kühn & Zimmermann, 1918; Jerzmański, 1956; Kozłowski & Parachoniak, 1967 and references therein). More recently, the rocks were described as an eroded lava dome or cryptodome (Awdankiewicz et al., 2010; Szczepara, 2018; Petronis et al., this volume). A thermal aureole up to 150 m wide in the adjacent basement has been recognized using Raman spectroscopy-based geothermometry on organic matter in the slates (Lis et al., 2025). The rhyolite yielded a zircon SHRIMP U–Pb ages of 292.8 ± 2.1 Ma (Awdankiewicz et al., 2014) and 297.5 ± 2.8 Ma (Mikulski & Williams, 2014). These dates marginally overlap within uncertainties, and it is likely that the older one may be closer to the emplacement age of the rhyolites, whereas the younger one was affected by Pb loss (cf. Przybyło et al. 2020).

In recent years, we have carried out geologic mapping, additional petrological and mineralogical study (Fig. 2), as well as paleo- and rock magnetic study (see Petronis et al, this volume). In the following section, we provide an updated interpretation that re-evaluates the existing information and uses the new data to constrain the emplacement geometry and cooling history of the Wielisławka magma and the formation of the Wielisławka rhyolite.

Lithologies and magmatic structures

The preserved rhyolite represents roughly the lower half of the original volcanic body with the upper portion removed by erosion. The volume of extruded magma is estimated to have been at least 0.4 km³ and possibly as much as 1 km³ or more, based on the preserved outcrop and accounting for post-emplacement erosion. This represents a substantial volume for a silicic magma body. A coherent, porphyritic rhyolite dominates the exposed bedrock outcrops and float along the slopes of Wielisławka Hill. Locally, rhyolitic breccias and vesicular rhyolites occur as loose blocks in the upper, eastern part of the exposed rhyolite (Fig. 2D). The localized brecciation could be interpreted as intrusive breccias, autoclastic breccias, and/or cataclasitic deformation along the rhyolite margin. Distinguishing these processes can provide important clues to whether the rhyolite was emplaced as an intrusion or extrusion. The presence of small mineral-filled vesicles (drusy cavities) supports degassing during emplacement and subsequent fluid circulation at a shallow emplacement depth. Although the contact zones of the Wielisławka rhyolite are not exposed, lithologies typical of carapace facies such as e.g. spherulitic rhyolites or thick autoclastic breccias seem scarce, in contrast to typical rhyolitic lava domes or flows (McPhie et al. 1993).

The emplacement of the Wielisławka rhyolite magma produced distinctive spatial patterns of magmatic fabrics (Fig. 2A, B): flow foliation, flow banding, and phenocryst alignment, as well as locally folded flow banding, boudinage-like structures, and brittle fractures. The brittle fractures cross-cut the flow fabric, indicating that fracturing occurred after the rhyolite had cooled sufficiently to transition from ductile to brittle behavior, likely after emplacement had ceased. Cooling structures include columnar jointing and joint networks. In the well-exposed central part of the rhyolite along and adjacent to the ridgeline of the Wielisławka hill, concentric macroscopic magma flow foliation and radially arranged columnar joint sets define a relatively simple, symmetric flowage and cooling architecture. We see no evidence for nested domes or cross cutting cooling surfaces indicative of multiple coalesced magma pulses. Flow foliation generally outlines the margins of the rhyolite body. At the Organy quarry, the inverted radial fan of the columnar joints reflects cooling away from the center and against the country rock, approximately normal to a curved intrusive contact, which is steep near the top of the hill and becomes subhorizontal towards the base. The columnar joints as viewed from the parking lot converge towards a common area about 20-30 meters above the quarry wall. The pervasive formation of columnar joints was likely favored by relatively rapid, single-stage, near-surface emplacement, significant undercooling, the

formation of volcanic glass (see below), and cooling under relatively stable conditions (cf. Li, 2025). However, the poorly exposed eastern and western margins of the Wielisławka rhyolite show more irregular structures reflecting magma interaction with the country rocks.

Petrological aspects

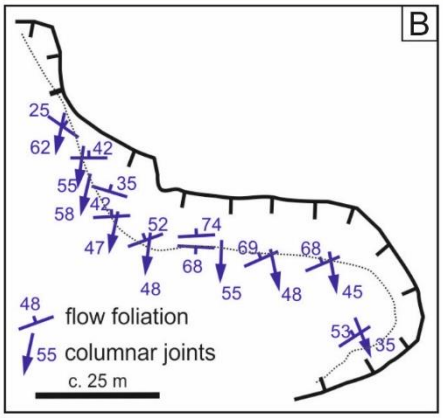
The Wielisławka magma underwent significant crystallization within a crustal magma reservoir prior to emplacement, as indicated by phenocrysts of K-feldspar, quartz, plagioclase, and biotite (Fig. 2C). The rhyolite magma was relatively uniform in terms of phenocryst content (mean of 10 rhyolite samples is 14% by vol.; Szczepara, 2018) although there are also alternating bands of strongly and poorly porphyritic rhyolite. Degassing upon the magma ascent and emplacement resulted in partial decomposition of biotite (e.g. opacite rims). Small vugs in the rhyolite (later filled with clay minerals) reflect continuing degassing during the emplacement. Groundmass textures of the rhyolite constrain cooling and solidification conditions (Fig. 2E, F). At the time of emplacement, the Wielisławka rhyolite magma was sufficiently undercooled to quench as volcanic glass. Subsequent devitrification and recrystallization produced the micropoikilitic groundmass texture that characterizes most of Wielisławka rhyolites. Some rocks underwent devitrification later, at lower temperatures, resulting in the microgranular/felsitic groundmass texture (cf. McPhie et al. 1993; Gifkins et al. 2005, and references therein). The primary minerals and textures of the Wielisławka rhyolites, as well as the bulk-rock chemistry, were modified by post-magmatic processes. On alteration diagrams, the Wielisławka rhyolites plot outside of the unaltered rhyolite fields and follow a hydrothermal trend of strong to intense, K-type alteration (cf. Gifkins et al. 2005). The chemical changes most strongly affected silica, alkalis (Na, K), and more mobile trace elements like the Large-Ion Lithophile Elements (Ba, Sr). Related mineralogical changes included partial replacement of the igneous K-rich alkali feldspar by almost pure orthoclase, replacement of plagioclase by albite, illite and kaolinite, and crystallization of quartz, K-feldspar and clay minerals in vugs.

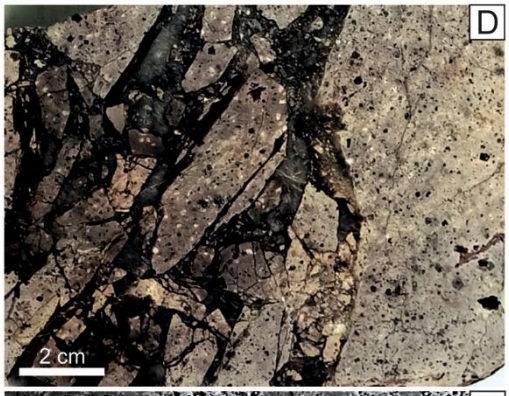
Magnetic fabrics and paleomagnetic results

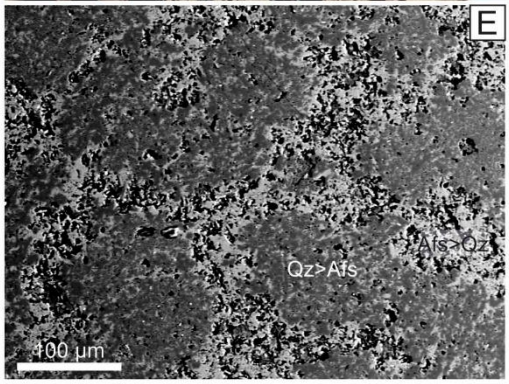
Magnetic fabrics can provide structural information where conventional field observations are limited and have been shown to reflect a record of magma flow during construction of the intrusion. Anisotropy of magnetic susceptibility (AMS) provides an important means of extracting this information by characterizing magnetic fabrics related to

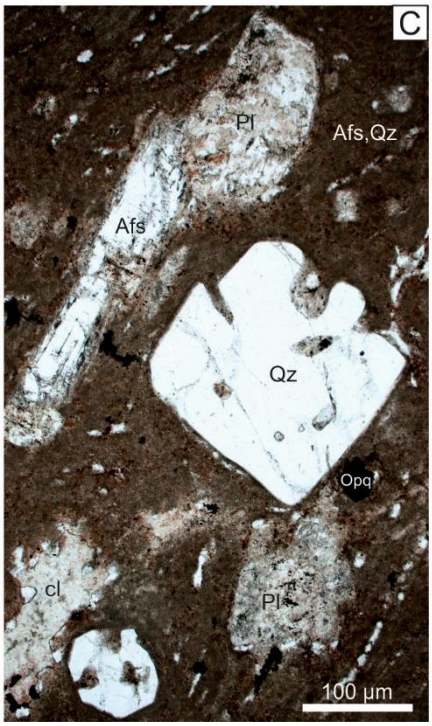
Figure 2 (next page). Structural and petrographic features of the Wielisławka rhyolites. A. The Organy Wielisławskie quarry with radial, downward-fanning columnar joints and concentric flow foliation. B. Orientation of columnar joints and flow foliation in the quarry. C. Coherent rhyolite showing porphyritic texture with phenocrysts of quartz, alkali feldspar, altered plagioclase and opaque minerals. Microcrystalline groundmass consists mostly of alkali feldspar and quartz, locally with clay minerals in vugs. Photomicrograph, plane-polarized light. D. Polished specimen of rhyolitic breccia with porphyritic rhyolite clasts in a groudmass of similar, small fragments with abundant haematite and quartz. E. Micropoikilitic texture of the Wielisławka rhyolite groundmass: oval domains of quartz contain fine intergrowths of alkali feldspar and are enveloped by alkali feldspar. Back-scattered electron image. E. Felsitic groundmass texture of the Wielisławka rhyolite with intergowths of, predominantly, anhedral alkali feldspar and quartz. Back-scattered electron image. Afs - alkali feldspar, cl - clay minerals, Opq - opaque minerals, Pl - altered plagioclase, Qz - quartz.

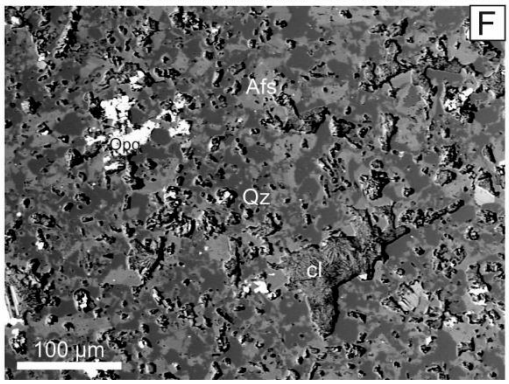

A
NW
SE
columnar joints
flow foliation
10 m


B
25
62
42
55
35
58
42
47
52
74
68
69
68
48
55
48
45
53
35
48 flow foliation
55 columnar joints
c. 25 m


D
2 cm


E
Afs>Qz
Qz>Afs
100 µm


C
Pl
Afs,Qz
Afs
Qz
Opq
cl
Pl
100 µm


F
Afs
Opq
Qz
cl
100 µm

magma flow, emplacement, and subsequent deformation. The AMS fabric(s) at Wielisławka hill are defined by a mixture of silicate mineral fabrics and magnetic mineral fabrics (see Petronis et al., this volume). The spatially distributed AMS fabric measurements reveal three distinct fabric domains (see Petronis et al., this volume, Figure 1). The basal "nose" region exhibits flattened fabrics consistent with strain localization during interaction between the advancing magma and country rock. The central region contains shallow K_1–K_2 fabrics, suggesting sub horizontal magma transport during inflation, and a "roof" domain that displays steep K_1–K_2 fabrics consistent with sub vertical flow. The AMS and macroscopic fabrics largely record primary magma flow rather than later tectonic overprinting (see below). These observations support the interpretation of emplacement of the Wielisławka Rhyolite as an elongated, shallow emplaced intrusion that inflated beneath the surface and cooled as a simple domed body (see Petronis et al., this volume, Figure 1).

The paleomagnetic data reveal that the rhyolite preserves a stable characteristic remanent magnetization of southwest declination with two distinct inclination populations. One population is of southwest declination with a shallow negative or positive inclination. The second population yield a similar southwest declination, however, the inclinations are moderate to steep (>-40). The shallow inclination sites plot near the early Permian expected field direction, however, the remaining sites are considerably steeper. Spatially, we do not see a correlation between the inclination and location across the rhyolite and interpret the steep inclinations to reflect post-emplacement localized tilting (See Petronis et al., this volume).

Conclusion

The preserved field geometry and structures of the Wielisławka rhyolite provide compelling evidence for emplacement of the original body as a shallow-level, subvolcanic intrusion, within a few hundred meters of the Permian land surface. The lower part was emplaced through a broad, east-west aligned, upward-flaring fissure within the metasedimentary basement, whereas the upper part expanded into the overlying Permo-Carboniferous sedimentary rocks and was able to flow vertically and laterally. The top of the domal Wielisławka rhyolite, similar to a volcanic laccolith or cryptodome, could have up-domed or even locally breached the Permian land surface (cf. Goto & Tomiya, 2019; Goto et al., 2004). Magmatic flow foliation and cooling columnar joints together with magnetic fabrics and palaeomagnetic data indicate that the rhyolitic body grew by inflation as magma continued to flow into the developing structure, essentially in a single magmatic pulse. Petrographic and textural data indicate pre-emplacement partial crystallization of the rhyolite magma in a shallow reservoir, and emplacement-related quenching to glass, devitrification upon further cooling, as well as degassing and fluid migration. Mineralogical and geochemical results indicate strong post-magmatic, hydrothermal replacement of the primary igneous minerals by secondary phases as well as related intense changes in bulk-rock chemistry. The upper half of the original rhyolite body was subsequently removed by erosion.

Stop 2. Agates in silicic volcanogenic rocks near Nowy Kościół

leaders: P. Sarul, A. Pietranik

(51.0545444N, 15.8677558E)

Agate is one of the most widespread and diverse silica gemstones, occurring in a remarkable variety of colours, textures and internal structures (Götze et al., 2020). It consists predominantly of banded chalcedony (SiO_2), although macrocrystalline quartz commonly occurs intergrown with, or interlayered within, chalcedony bands (Götze et al., 2020). In silicic volcanic rocks, agates typically form as cavity fillings within lithophysae, spheroidal voids produced during volcanic cooling and degassing. Extensive eruptions of silicic lavas and ignimbrites took place across Central Europe during the Late Carboniferous and Permian, generating numerous agate-bearing volcanic successions in present-day Germany, Poland, Czechia and France (Götze, 2011).

In the "Land of Extinct Volcanoes" agates found in acidic volcanic rocks (rhyolites and tuffs) are abundant near Nowy Kościół, Gozdno and Sokołowiec. The Nowy Kościół area hosts one of the most important occurrences of agates associated with silicic volcanic rocks in the North-Sudetic Synclinorium. Agates occur within the Permian volcanic succession, where several rhyolitic and pyroclastic units form an extensive volcanic complex (Kryza & Kryza, 1982). The volcanic sequence consists of rhyolite lava flows and volcaniclastic deposits, including tuffs and tuff-lavas. Chalcedony mineralization is concentrated mainly in the upper portions of the pyroclastic units directly beneath the main rhyolite flows (Fig. 3A). It occurs in two principal forms: as agate-bearing nodules (lithophysae agates) within deeply weathered volcanic rocks (Fig. 3B) and as chalcedony veins cutting coherent rhyolites (Kryza & Kryza, 1982).

The weathered rocks are composed predominantly of clay minerals and forms a brownish-grey regolith with characteristic green and reddish patches. The primary character of these rocks is now largely obscured by alteration. Fresh volcanic rocks exposed locally within the weathered zone are represented by reddish-brown porphyritic rhyolites with massive to flow-banded textures. Phenocrysts consist mainly of quartz, partly altered feldspars and biotite. Agate nodules are particularly abundant within the weathered horizons exposed by former excavations. They typically display irregular to sub-ellipsoidal morphologies and range in size from a few centimetres to several tens of centimetres. Most specimens are translucent to opaque and display grey, bluish, reddish-brown or red colouration. In cross-section, most agate nodules typically exhibit a star-shaped pattern, though Uruguay-type agates (HS – horizontally stratified) or atoll-type agates also occur.

Agates from Nowy Kościół are interpreted as products of hydrothermal alteration and subsequent weathering of silicic volcanic rocks (Kryza & Kryza, 1982). Similar agates occur in Permian rhyolites of the North Saxonian and Sub-Erzgebirge basins in Germany, where studies indicate that silica mineralization developed within lithophysal cavities formed during cooling and degassing of rhyolitic lavas and ignimbrites (Götze et al., 2016, 2023). The agates are composed predominantly of chalcedony and quartz and commonly display red colours related to finely dispersed iron oxides. Textural relationships, including banded chalcedony, macrocrystalline quartz, pseudomorphs after pre-existing minerals and multiple generations of silica, indicate a complex, multi-stage history involving primary hydrothermal mineralization followed by dissolution, replacement and repeated silica precipitation. Geochemical studies show that agates are generally depleted in most trace elements relative to their host rocks, although enrichment in elements such as B, Ge and U has been reported

from some German occurrences. These geochemical signatures have been interpreted as evidence for interaction with magmatic volatile-rich fluids capable of transporting silica and trace elements. Together with fluid-inclusion data indicating minimum formation temperatures of approximately 130-180 °C, these observations suggest that agate formation began during the late stages of volcanic activity and continued during subsequent hydrothermal alteration and weathering of the volcanic succession (Götze et al., 2016, 2023).

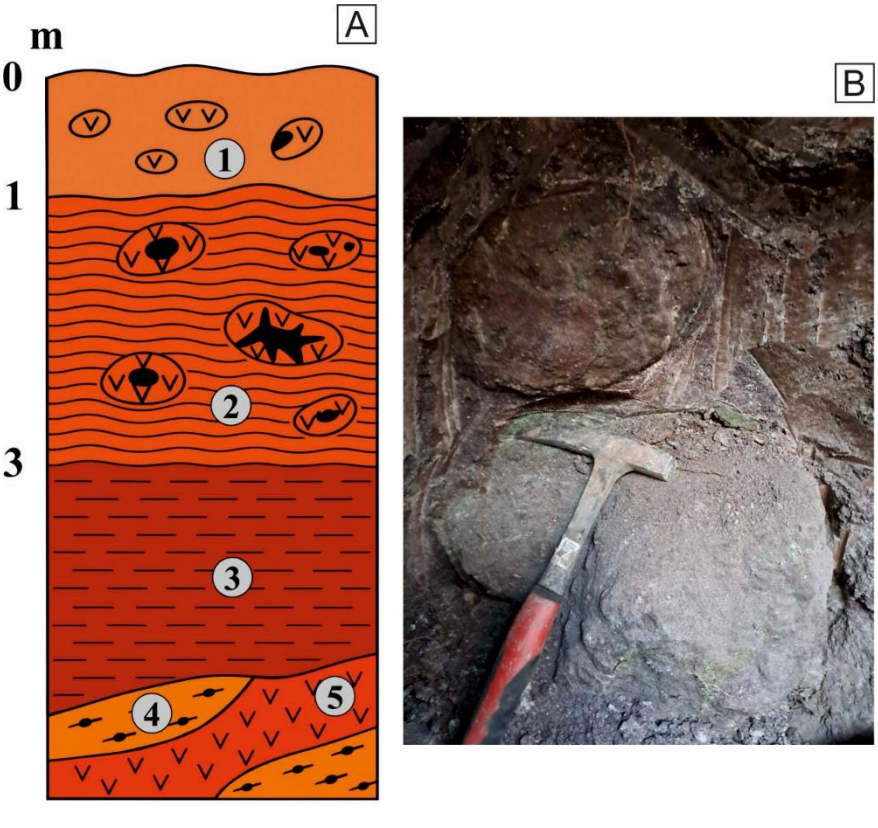


Figure 3. A. Geological profile of the agate-bearing zone near Nowy Kościół ("Piekiełko" field): 1 - Weathered felsic volcanic rocks with agate-bearing lithophysae; 2 - Rhyolitic tuff with agate-bearing lithophysae; 3 - Rhyolitic tuff; 4 - Volcanic agglomerate; 5 – Rhyolite. (Lewczuk, as cited in Janeczek et al., 1991). B. Lithophysal agate in the weathered felsic volcanic rock. Photo: Piotr Sarul.

Stop 3. Agate museum at Nowy Kościół

leader: P. Sarul

(51.071671N, 15.864915E)

Piotr Sarul is the founder of the local Agate Museum in Nowy Kościół. He has been involved with agates for more than 35 years and specializes mainly in Polish agates, particularly those found in the vicinity of Nowy Kościół. He has also assembled an impressive collection of specimens from around the world. His collection comprises several

thousand specimens. The museum exhibitions primarily feature local agates. The largest agate discovered in the area weighs more than 200 kg.

Currently, Piotr Sarul conducts geological workshops for families with children as well as for primary and secondary school students. Adjacent to the museum is a small lapidary workshop where visitors can cut, grind, and polish minerals.

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