Geologica Belgica Luxemburga International Meeting 2024

Celebrating the 150th Anniversary of the
"Société Géologique de Belgique"

11-13 September 2024

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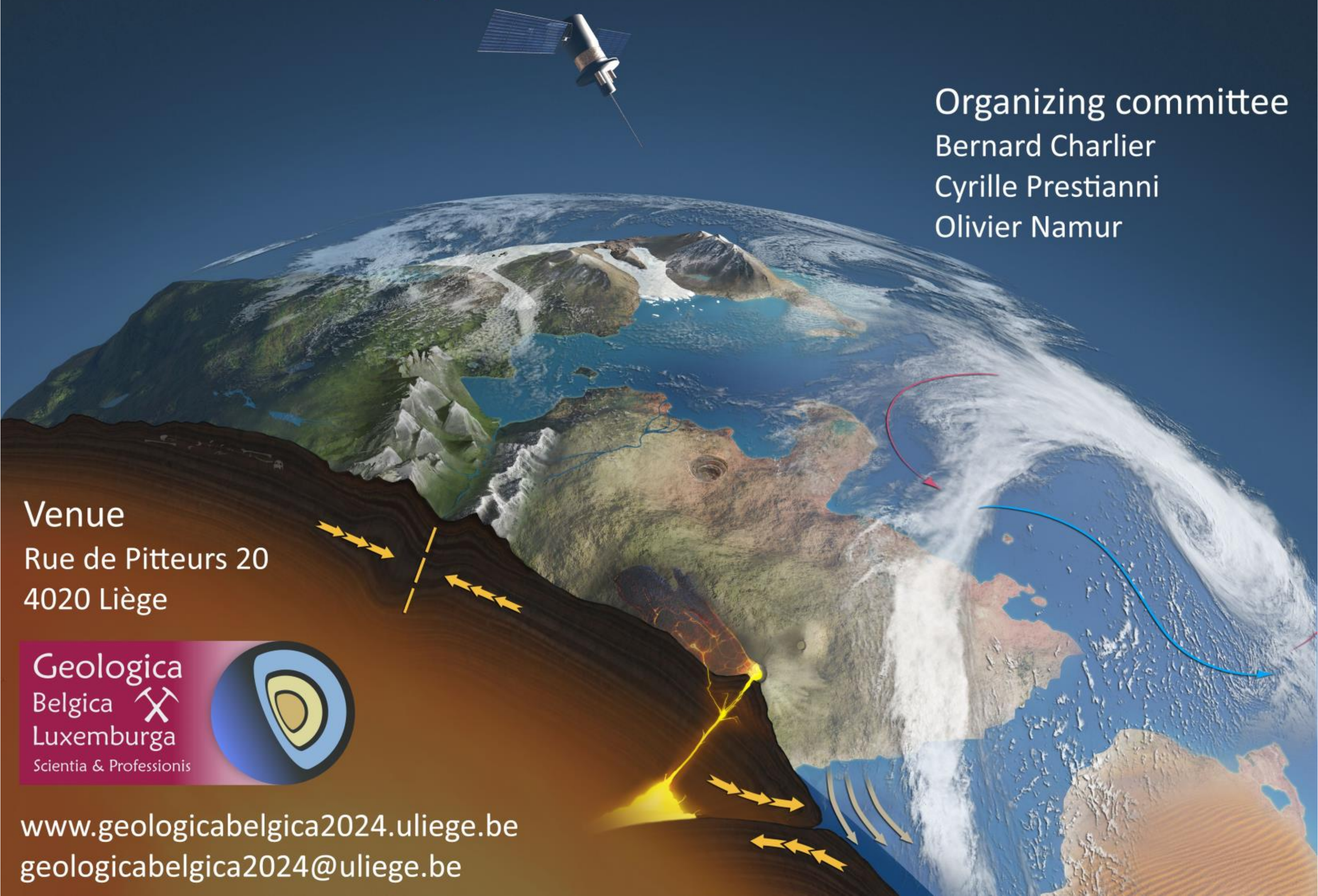

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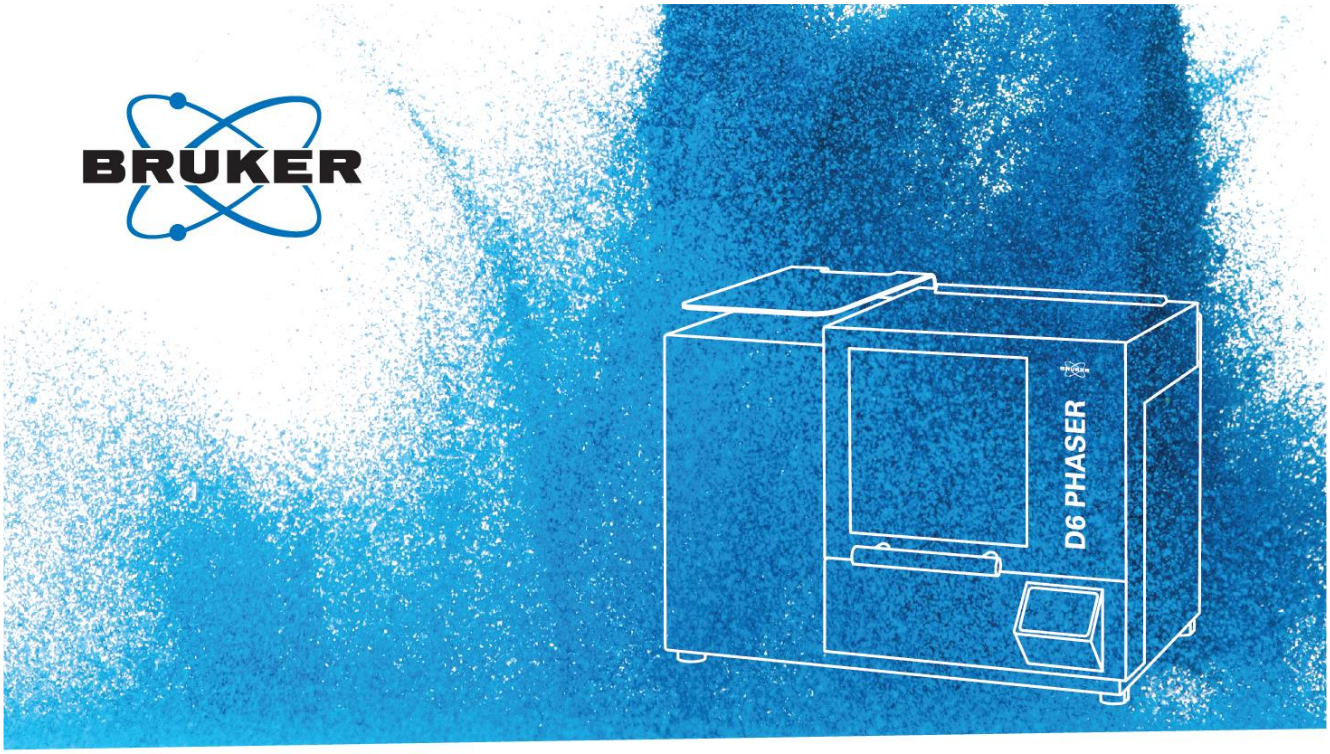

X-RAY DIFFRACTION

D6 PHASER – Benchtop XRD for the Analysis of Crystallite Sizes

Application Report 38

The D6 PHASER is ideally suited for rapid crystallite size analysis using powder X-ray diffraction. The analysis is based on the evaluation of the diffracted peak profiles. These show a characteristic broadening that increases as the crystallites become smaller. This broadening must be separated from the instrumental line broadening, which determines the upper limit of the crystallite size. The lower limit of the analysis is determined by the ability to separate broad, low intensity signals from the instrumental background.

Key characteristics of the D6 PHASER for this application include

- Angular resolution better than 0.03° 2Theta
- High X-ray flux, achieved by the 600 W or 1.2 kW generator, the compact goniometer radius, and the motorized divergence slit that illuminates a large and constant sample area at all measurement angles.
- Dynamic Beam Optimization (DBO) provides tight control of the instrument background to enable separation of broad peaks.

These features make the D6 PHASER an excellent tool for studying crystallite size in the chemical or pharmaceutical industries, where process parameters or material properties are closely related to crystallite size or surface area. Another typical application is LC analysis (ASTM D5187). It relates the Full Width Half Maximum to the quality of calcined anode coke used in the electrolytic smelting of metals.

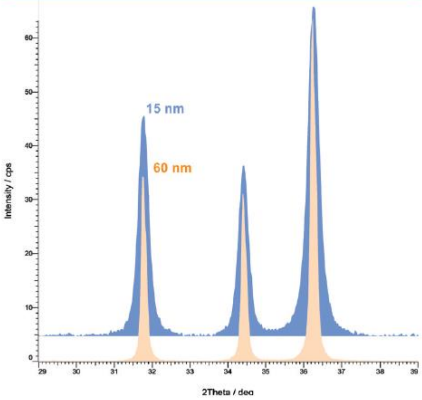

Figure 1
Two scans of NIST SRM1979 schematically showing the peak broadening for the smaller particles.

Figure 2
D6 PHASER equipped for Dynamic Beam Optimization (DBO) with Variable Divergence Slit (VDS), Motorized Air Scatter Screen (MASS) and LYNXEYE XE-T detector.

The instrument performance of the D6 PHASER for crystallite size analysis was verified by evaluating the NIST Powder Diffraction Line Profile Standard Reference Material SRM 1979 (Figure 1). Thin sample films were prepared on low background silicon sample holders. Data were collected in the configuration shown above and evaluated using DIFFRAC.TOPAS v7. Line shape analysis was performed similarly to the approach described in the NIST certificate, using Pawley fitting and the fundamental parameter peak model to deconvolute crystallite size from instrumental line broadening. The table below shows the excellent agreement of the crystallite size with the data from the certificate.

For the determination of isotropic crystallite sizes it is sufficient to evaluate a single peak in either DIFFRAC.EVA or DIFFRAC.TOPAS. The latter also allows to refine the directional dependence of the crystallites (or the shape of the crystallites) by evaluating the whole diffraction pattern (Figure 3).

	Sample A	Sample B
Certificate LVol / nm	31.65(46)	97.2(14)
Fixed Divergence Slit data	29.46(50)	107.2(16)
Variable Divergence Slit data	26.5(18)	104(1)

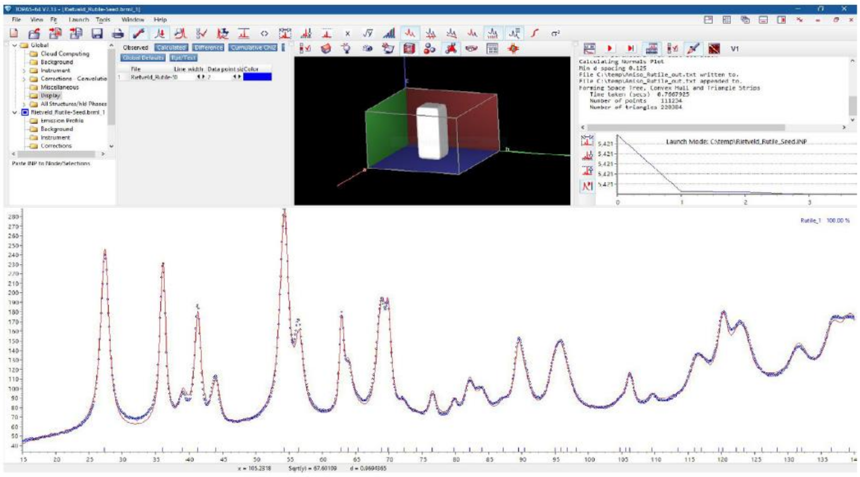

Figure 3
Crystallite size anisotropy of cuboidal rutile, TiO2, analyzed with DIFFRAC.TOPAS. The crystallization seeds show an x:z aspect ratio of about 1:2.5.

Data were collected with a D6 PHASER 1.200W, Cu radiation, no K-beta filter, 2.5° Soller collimators, primary variable divergence (constant illumination mode), motorized air scatter screen, scan range 15 to 140° 2Theta, total scan time 214 sec with the LYNXEYE XE-T detector in high resolution mode.

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Keynote Speakers

Developments in Earth Sciences education at Utrecht University, the Netherlands

Hans DE BRESSER

Department of Earth Sciences, Faculty of Geosciences, Utrecht University, the Netherlands

The Faculty of Geosciences at Utrecht University offers bachelor's degree programmes in Earth Sciences, Global Sustainability Science, Science and Innovation Management and Human Geography and Spatial Planning. In addition, the faculty houses a total of 16 master's degree programmes that allow students to specialize after having obtained their bachelor's degree, four of them focussing on Earth Sciences. The Earth Sciences bachelor is a three-year programme largely given in Dutch, consisting of a major of 135 EC and a so-called Optional Course Profile of 45 EC. Within this Optional Course Profile, students can choose courses form the complete University offer, either as a set of individual courses, or as a coherent package in the form of a minor. Taking part of an international exchange programme is also possible. The Earth Sciences masters are two-year English-spoken, selective programmes focussing on research.

The enrolment in the BSc Earth Sciences peaked in 2014 with an intake of 185 students, but has gradually decreased since, to 125 in 2022. For the current academic year 2023-2024, there has been a slight revival. The decrease fits with nationwide and worldwide trends. Possible reasons for this decrease include the current image that secondary school students have of the Earth Sciences. Many of them consider the Earth Sciences as an old-fashioned science, environmentally damaging and with insufficient emphasis on addressing societal problems. A recent survey among Dutch secondary school students confirmed that the Earth Sciences have an image problem, but also revealed low awareness of what the subject involves and what opportunities are available for graduates.

We concluded that a modernization of our programme was necessary, to reflect both the scientific advances of the last decades and the change in focus towards societal challenges. Shaping the new programme required quite a bit of discussion and hence time, but efforts were made to really get all teachers on board, as well as taking the student perspective into account. We have constructed a fully integrated, uniform first year, including modular fieldwork covering topics across the full breadth of the Earth Sciences. After the first year, students choose one out of four 'directions'. Each direction starts with its own set of foundation courses, followed by direction-related specialization electives. Seven skills learning lines are being implemented across the programme, providing the students with skills considered crucial for future Earth Sciences professionals. The students who started in September 2023 form the first cohort following the renewed BSc programme.

I my lecture, I will show how our Earth Sciences programmes is positioned in the overall programme structure of the Faculty of Geosciences, I will guide you along our modernization trajectory and the lessons learned, and share with you our first experiences. I'll also address the issue of how to use our renewal in improving the image that secondary school students have of the Earth Sciences, expecting a positive effect on enrolment.

Reading the magnetic record of rocks: interpretation and pitfalls

Mark J. DEKKERS

Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

It is well known that paleomagnetic data provide important kinematic constraints to geological reconstructions, in particular for reconstructions in the distant geological past. The magnetic signal stored in rocks is termed natural remanent magnetization (NRM); it resides in what is referred to as 'magnetic minerals': iron (oxy)(hydr)oxides or iron sulphides that occur in trace amounts in essentially any rock. The time-averaged Earth's magnetic field is a dipole field which enables calculation of the paleolatitude of rock formations from the inclination of the NRM stored in the rock; vertical-axis rotations can be derived from the declination of the NRM. Only fine-grained magnetic particles ensure an NRM which is stable over geological time scales: ideally, they consist of one or a few magnetic domains only. For meaningful paleogeographic reconstructions typically rocks are considered that carry what is referred as "primary NRM": the age of the NRM is the same as the age of the rock it is retrieved from. So, proving that the stable NRM of a sample collection is indeed a primary NRM is at the heart of any paleomagnetic study. And while this seems a rather straightforward task, the real world is harsh and bitter debates on the primary NRM of certain rock formations continue. The bitterness is partially fuelled by the perceived notion that when a rock does not carry a primary NRM – its NRM is reset by later geological processes, broadly referred to as remagnetization – it is utterly useless. Here, I will walk through the basic premises of how rocks get magnetized and strategies how to document a primary NRM. Then I focus on remagnetization as rocks are not immune to later geological processes, typically associated with orogenic action. So, remagnetized rocks are not utterly useless but contain information on 'geological action' during a given orogeny with implications for the paleolatitude of continent collisions and regional vertical axis rotations. In the talk I will illustrate these points with examples from the Indo-Asia collision and Variscan Europe.

Subduction initiation in the Atlantic and implications for the Earth's supercontinent cycle

João C. DUARTE

Instituto Dom Luiz (IDL) and Geology Department, Faculty of Sciences of the University of Lisbon, Portugal

On the 1st of November 1755, a giant earthquake struck off the coast of Portugal. It occurred on the morning of the All Saints' Day, when citizens were attending the mass. The roofs of the churches collapsed, and the thousands of candles started a fire that lasted for days. The survivors ran to the riverside, but forty minutes after the main shock three tsunami waves rose the Tagus River flooding the downtown. Thousands of people died, sending philosophical shock waves all around Europe. Today we do not yet know what caused the 1755 earthquake, but several works suggest that a new subduction zone may be forming off the coast of Portugal.

This is important because the initiation of subduction zones in Atlantic-type oceans marks the turning point of an ocean's life cycle (the Wilson cycle). However, the formation of new subduction zones in Atlantic-type oceans is challenging, given that it commonly requires the action of an external force, such as the slab pull from a nearby subduction zone. Notwithstanding, the Atlantic already has two fully developed subduction zones, the Lesser Antilles and the Scotia arcs. These subduction zones have been forced from the nearby Pacific subduction zones.

The Southwest Iberia Margin is another place where a new subduction system may just be forming in the Atlantic. In this case, likely associated with subduction zones from the Mediterranean. This is supported by geological and geophysical data and would explain the anomalous high-magnitude seismicity such as the Great Lisbon Earthquake of 1755. Recent geodynamic models further support this hypothesis.

The three Atlantic subduction zones have the potential to spread and connect in the future to form an ocean-wide Atlantic subduction system. This has implications for the evolution of the Earth's oceans and the supercontinent cycle itself. For example, it may imply that subduction zones are more likely to invade Atlantic-type oceans from oceans that already have subduction zones than to start new subduction along Atlantic-type margins. Subduction invasion may thus be a fundamental process in the recent geological evolution of the Earth.

SESSION 1 - MINERAL RESOURCES AND GEODYNAMICS

Conveners

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The mineral resource industry faces an immense challenge in meeting the surging demand for materials driven by the green and digital transition, on top of global economic development. While the industry is still far from adequately addressing these future demands, dedicated geological research is crucial to discover, reevaluate, and gain a comprehensive understanding of system earth and its natural resources. This session invites researchers who work on all aspects of geological research, possibly but not exclusively linked to the pursuit of mineral resources. Contributions may include advances in the understanding of magmatic or metamorphic processes, detailed mineralogy, geochemistry, and/or geochronology.

Since the intensification of mining activities worldwide necessitates the identification and resolution of social, societal, and environmental issues associated with exploitation, research contributions touching on the environmental and social governance (ESG) of mining are also welcomed.

The specific topics covered in this session include, but are not limited to:

- Critical and non-critical mineral deposits
- Mineral exploration and extraction
- Social, societal, and environmental considerations related to mining
- Metamorphic and magmatic geological processes
- Deformation within orogenic belts

Invited Speaker

Application of isotopic compositions in studying lateritic deposits

Hamed POURKHORSANDI* 1,2, Vinciane DEBAILLE 1, Sophie DECRÉE 3

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Intense weathering in wet tropical regions breaks down rocks into regolith, which can differ mineralogically and chemically from the original bedrock. This process leads to geochemical modifications, concentrating certain elements and forming supergene deposits. Analyzing isotopic compositions reveals insights into weathering processes and element concentration. This presentation focuses on using radiogenic Sr and Nd compositions to understand the concentration of rare earth elements in regolith. We will also explore the application of other isotopic systems, both radiogenic and stable.

Petrography, microtextures and lithium distribution in deformed LCT-type pegmatites and their host rocks from the Musha-Ntunga area (Rwanda)

Jolan ACKE 1,2*, Daniel KWIZERA 2, Renata BARROS 3,4, Christian BURLET 3, Simon NACHTERGAELE 5, Justin UWIRINGIYIMANA 6, Tobias FUßWINKEL 7, Stijn DEWAELE 2, Anouk BORST 1,8

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Lithium-Caesium-Tantalum (LCT-)type pegmatites in the Mesoproterozoic Karagwe-Ankole Belt of Central Africa are associated with granitic intrusive complexes which were emplaced around 1 Ga in metasedimentary sequences (Tack et al., 2010; Fernandez-Alonso et al., 2012). This study presents a detailed analysis of pegmatite drill core samples from the Musha-Ntunga area in East Rwanda, which show evidence of localized syn-to-post emplacement deformation. Petrographic and cathodoluminescence microscopy combined with elemental geochemistry (EPMA, LIBS and LA-ICP-MS) are used to study the mineral assemblages and microtextures, and the (re-)distribution of lithium within the pegmatites and surrounding host rock during the main paragenetic stages. These stages comprise magmatic crystallization, magmatic-hydrothermal metasomatism, sub-solidus deformation and low-temperature late stage alteration. Drill core mineral assemblages in the pegmatites are relatively consistent. Quartz, albite, microcline, muscovite, spodumene and montebrasite are major rock-forming minerals, while apatite, columbite-tantalite, cassiterite, lithiophilite, cookeite, eucryptite and beryl are present as minor phases. Five textural varieties of spodumene are identified. Coarse-grained subhedral type 1 often has narrow rims of symplectitic spodumene-quartz intergrowth (type 2). These first two types are interpreted to reflect primary magmatic crystallization. Type 3 and 4 on the other hand suggest magmatic-hydrothermal to hydrothermal recrystallization, often precipitating along albite grain boundaries. In some regions, spodumene has been intensely deformed, both in a brittle and a ductile manner. Under localized shear stress, large type 1 crystals have been deformed to sigma clasts (‘spodumene fish’) surrounded by bands of fine-grained spodumene laths (type 5), with interstitial apatite and quartz ribbons. Additionally, large elongated spodumene (type 1) grains can be fractured with microcline, albite, micas, cookeite and Li-phosphates (lithiophilite and montebrasite) filling the opened space. Book-shelf rotation and sliding along fracture or cleavage planes is also common, evidenced by offset twins in spodumene. Montebrasite occurs both as a late primary magmatic phase with spodumene, and as a secondary/late phase, recrystallizing during magmatic-hydrothermal alteration and deformation. Eucryptite, cookeite and lithiophilite are only observed as secondary minerals, replacing primary mineral assemblages. The elevated concentration of lithium in metasomatic tourmaline and micas within the metasedimentary host rock can act as an exploration tool for mineralized pegmatites.

Additionally, it indicates significant dispersion of lithium into the host rock during pegmatite emplacement and subsequent metasomatism. Lithium appears to be retained within the recrystallized spodumene during post-magmatic deformation. However, a decrease in spodumene grain size may affect ease of extraction.

Fernandez-Alonso M, Cutten H, De Waele B, Tack L, Tahon A, Baudet D, Barritt S.D (2012) The Mesoproterozoic Karagwe-Ankole Belt (formerly the NE Kibara Belt): The result of prolonged extensional intracratonic basin development punctuated by two short-lived far-field compressional events. Precambrian Research, 216–219, 63–86.

Tack L, Wingate M.T.D, De Waele B, Meert J, Belousova E, Griffin B, Tahon A, Fernandez-Alonso M (2010) The 1375 Ma "Kibaran event" in Central Africa: Prominent emplacement of bimodal magmatism under extensional regime. Precambrian Research, 180(1–2), 63–84.

Major-trace element and Sr-Nd isotope compositions of Sr-rich hydrothemal dykes in TTG gneisses of the Nyabessane greenstone belt (NW Congo Craton, Cameroon): Insights into fluid circulation in upper Archean crust

Joseph Martial AKAME 1*, Vinciane DEBAILLE 1, Wendy DEBOUGE 1, Jeroen De JONG 1, Camille FRANÇOIS 2

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The Mesoarchean (ca. 3.2 - 2.85 Ga) Nyabessane greenstone belt (NGB) in south western Cameroon includes variably deformed and metamorphosed granitoids, mafic to ultramafic rocks, gabbros, Sr-rich hydrothermal layers, and banded iron formation rocks. The Sr-rich hydrothermal mafic dykes intruded the Mesoarchean granitoids during the late Neoarchean magmatic stage at ca. 2.7 Ga (Akame et al., 2024). The Sr-rich hydrothermal mafic dykes were 1–20 cm wide and are mainly composed of epidote+chlorite+plagioclase + quartz ± diopside ± magnetite ± pyrite ± calcite±titanite. The Sr-rich hydrothermal dykes studied have rhyodacitic to dacitic compositions with 47-64 wt. % SiO_2, 0.66 ≤ wt. % MgO, 5.9–11.9 wt. % Fe_2O_3 (total Fe), 0.07–3.98 wt. % Na_2O + K_2O, 10.5–18.7 wt. % CaO, 15.2–18.6 wt. % Al_2O_3, 0.1–0.6 wt. % TiO_2, 2078–3930 ppm Sr and 12.7-397 ppm Ba. They show enriched-light REE (LREE) patterns (La/Sm_N = 8.9–75.2 and La/Yb_N = 8.95–75.22), positive Eu anomalies (Eu/Eu*=1.72–3.5), pronounced Sr-enrichment, and exhibit strong Rb, Ba, Nb- and Ti depletion suggesting post-emplacement alteration by fluids from the surrounding gneisses. Their higher Zr/Nb and lower Nb/Th ratios are similar to upper continental crust. Strontium-rich hydrothermal dykes, on the other hand, have La_N/Yb_N ratios similar to Archean TTG suites. These characteristics indicate involvement of crustal component in the petrogenesis of these dykes. The whole-rock Nd–Sr isotope data [($^{87}Sr/^{86}Sr$)(2.7 Ga) = 0.7081 to 0.7087 and εNd(2.7 Ga)= -4.4 to -2.5] of Sr-rich hydrothermal dykes are consistent with an involvement of older enriched crustal material. Petrographic observations show that epidote formed during the subsolidus hydrothermal alteration processes that involved these rocks. Epidote crystallization is the early stage of this process, followed by progressive enrichment of hydrothermal fluids in Sr and, and to a lesser extent in REE (Kropáč et al., 2024). This was probably responsible for the strong Sr enrichment in the Nyabessanes dykes, during the cooling stage of the cratonization in the NGB.

Akame, J.M., Oliveira, E.P., Debaille, V., Poujol, M., Schulz, B., Bisso, D., Humbert, F., Koah Na Lebogo, S.P., Zo'o Zame, P., 2024. Mesoarchean synchronous emplacement of TTG gneisses and potassic granitoids in the Nyabessane granite-greenstone terranes, NW Congo Craton (southern Cameroon): Zircon U Pb geochronology, petrogenesis and tectonic implications. Lithos 464–465, 107429. https://doi.org/10.1016/j.lithos.2023.107429

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A magnetic fabric study of the Neoarchean Bakkejord intrusion and associated mafic dykes (West Troms Basement Complex, northern Norway)

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The West Troms Basement Complex (WBTC) (Bergh et al., 2010, 2022; Myhre et al., 2013; Laurent et al., 2019) is a Precambrian outlier exposed west of the Scandinavian Caledonides in the coastal region of Tromsø (northern Norway) and considered as an autochthonous portion of the Baltic Shield farther east. It consists of Meso- to Neoarchean crust (ca. 3.0-2.6 Ga) affected by Paleoproterozoic rifting (ca. 2.4-2.0 Ga) and late- to post-Svecofennian magmatism and tectonism (ca. 1.8-1.6 Ga). The WBTC displays an oustanding diversity of lithologies, including crust-derived granitoids which are potential geodynamic markers. We present here the results of a fabric study, using the anisotropy of magnetic susceptibility technique, focusing on one of the WBTC granitoids, the Neoarchean Bakkejord intrusion (2711 ± 13 Ma; Myhre et al., 2013), a key structural element emplaced close to a probable 2.75-2.65 Ga active margin (Laurent et al., 2019).

The Bakkejord intrusion (outcrop surface ~100 km2) is in tectonic contact with Meso- to Neoarchean orthogneisses and Paleoproterozoic metasupracrustal belts. It is made of quartz diorite and quartz-poor tonalite and contains gneiss xenoliths of mostly granodioritic-tonalitic composition, metric to plurikilometric in size. The intrusion is cut by steeply-dipping and NW- to NE-trending dolerite dykes, dated at 2671 ± 1 Ma (Myhre et al., 2013), which make up ≥50% of the rock volume at many places. The quartz diorite–tonalite and the dolerite display a concordant penetrative foliation, also parallel to the foliation/banding of the gneiss enclaves, with a mean orientation of 173W85 (n = 63). The igneous texture of both the Bakkejord intrusion and dolerite dykes is globally preserved, but the rocks display microscope evidence of deformation, recovery and recrystallization, as well as greenschist-facies metamorphism and likely retrograde conditions, possibly after an amphibolite-facies metamorphic phase.

The bulk magnetic susceptibility varies from 238.5 to 3252.0 x 10-6 SI, with a mean value of 556.8 ± 366.4 x 10-6 SI (n = 39) in the Bakkejord intrusion and 1111.5 ± 521.7 x 10-6 SI (n = 20) in the dolerite dykes. Thermomagnetic measurements, controlled by petrographic observations, indicate that this susceptibility is dominated by paramagnetic minerals (mostly biotite and hornblende) and a ferromagnetic component (a Ti-poor titanomagnetite with ~1-10 mol% of ulvospinel) whose contribution ranges from ~10 to 70-75%. The magnetic foliation is close to the foliation measured in the field and the magnetic lineation is dominantly gently plunging to the NNW, respectively with mean orientations of 177W75 and 165NNW32 in the Bakkejord intrusion (n = 39), 161WSW52 and 153NNW14 in the dolerite dykes (n = 20).

The fabric of the Bakkejord intrusion and associated mafic dykes is concordant with the main regional structural pattern of the surrounding metamorphic rocks, inherited from the first of three successive late-Svecofennian tectonometamorphic phases, an ENE-WSW crustal contraction which caused nappe stacking, in amphibolite-facies, prograde conditions (Armitage & Bergh, 2005; Bergh et al., 2022). Not surprisingly, the Bakkejord intrusion has therefore retained no memory of the syn-emplacement, Neoarchean tectonism, but is rather a valuable marker of the late-Svecofennian deformations.

Armitage, P.E.B., Bergh, S.G. (2005). Structural development of the Mjelde-Skorelvvatn Zone on Kvaløya, Troms: a metasupracrustal shear belt in the Precambrian West Troms Basement Complex, North Norway. Norwegian Journal of Geology 85: 117-132.

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Trace-element behaviour in tourmalines from Minas Gerais, Brazil

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In the last century, Brazil became an important producer of high-quality tourmalines in the world. Most of these minerals formed within the granitic pegmatites of the Eastern Brazilian Pegmatite Province, in the mining State of Minas Gerais, located in the south-eastern part of the country. Minerals of the tourmaline supergroup are constituted by rhombohedral borosilicates with a R3m space group, and a general formula $XY_3Z_6[T_6O_{18}](BO_3)_3V_3W$ (Hawthorne and Henry, 1999).

Seventeen tourmaline crystals from eight pegmatite deposits spread across the province have been analysed by electron-microprobe and LA-ICP-TOF-MS, in order to provide accurate data about the major and trace element concentrations in each crystal. Compositions usually vary along the elbaite-schorl solid solution, with sometimes compositional and optical zonings between both end-members.

Some elbaite-schorl samples from different deposits show similar trace element concentrations, thus implying that some deposits certainly formed under the same geological conditions. One sample from the Lavra do Urucum pegmatite (KF-081) shows a rossmanite composition, with the Y group of sites occupied by two Al and one Li cations. Another sample from the same pegmatite (WR-045) is significantly enriched in REE and Ca, with values reaching 30 ppm La, 56 ppm Ce, 6 ppm Pr, 18 ppm Nd, and 1.90 wt. % CaO. Such a composition shows an evolution towards liddicoatite, which has also been observed in a Mozambican sample from the Mavuco pegmatite. The similar geochemical signature of these two crystals is currently under investigation.

In order to constrain the cation distributions on the different crystallographic sites of these samples, the tourmalines were investigated by single-crystal X-ray diffraction methods. Measured unit-cell parameters, between 15.82 Å ≤ a ≤ 15.93 Å and 7.09 Å ≤ c ≤ 7.13 Å, are consistent with elbaite-to-schorl compositions. Refined site populations have been calculated from the structural data and are similar to the assigned site populations given by the electron-microprobe analyses. Mean bond lengths determined through the structure refinement are also consistent with the calculated bond lengths, and bond-valence sums obtained for the different sites are close to the ideal theoretical values. A detailed examination of polyhedral distortion coefficients indicates an inverse correlation between the distortions of the Y and Z sites. Concerning the Z site, the highest distortion values are observed for schorl-rich compositions.

These preliminary data, coupled with those obtained on similar samples from Mozambique, will certainly allow to better understand the crystal-chemical control on trace-element distribution in these complex pegmatite minerals.

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3D automated mineralogy reveals the paragenetic history of mineralized pegmatites in the Karagwe-Ankole Belt

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The Mesoproterozoic Karagwe-Ankole belt (KAB) in Central Africa hosts important mineralized Lithium-Caesium-Tantalum (LCT) pegmatites enriched in Sn, Nb, Ta and W. It is expected that research on pegmatites will remain crucial as many of the searched-for critical elements in clean energy technologies are associated with LCT pegmatites. Notwithstanding many decades of geological research on mineralized pegmatites, the exact processes and formation conditions that lead to the concentration of these critical elements are yet not fully understood. Therefore, the detailed documentation of the textural variability of the pegmatite-forming minerals in naturally occurring deposits is necessary for the verification of the crystallization response in experimental simulations and to contribute to fundamentally new concepts about how the concentration of critical elements is controlled by the fluxing components.

Using a combination of scanning electron microscopy (SEM)-based automated mineralogy systems with X-ray computed tomography (μCT), we investigated the mineral relationships in a three-dimensional (3D) space. The textural complex and mineralogical diverse assemblages could now be fully studied in 3D which offered new insights regarding their crystallography and spatial association. The 3D automated mineralogy assisted in the identification of minerals (e.g., identification of Fe-Li mica and the inclusion of a barite veinlet in a muscovite grain) and the localization of key mineral assemblages that further helped to refine the paragenesis of mineralized pegmatites in the KAB.

A stage of albitization followed the primary crystallization and muscovite was found to probably play a role in the fluid migration and the subsequent precipitation of ore minerals. An important observation from μCT data is a mineral assemblage of quartz-albite-tourmaline-muscovite that revealed a stage of tourmaline crystallization between two stages of albitization. The Cornish Type ' cassiterite originating from greisen pockets confirmed the suggested hydrothermal formation conditions. A first-time description of oriented zircon and the association with flat tabular columbite-tantalite pointed to the importance of local magmatic-hydrothermal conditions.

This presentation emphasizes the possibilities of using 3D automated mineralogy for the identification of minerals and their position in the paragenetic history of mineralized pegmatites and by extension of other complex ore deposits.

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Fluid characterisation of the orogenic gold mineralisation at Imonga (Maniema, DR Congo)

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The Western Domain (WD) of the Karagwe-Ankole Belt (KAB), located in the metallogenic province of the Great Lakes region in Central Africa, is known to be rich in Nb-Ta-Sn-W-Li-Be-Au. The magmatic-hydrothermal Nb-Ta-Sn-W deposits in this region have been extensively studied. However, the characteristics and source(s) of the Au mineralising fluids remain largely unknown. In order to gain a better understanding of the gold mineralising fluids in this metallogenic province, the Imonga prospect (Maniema, eastern Democratic Republic of Congo) was selected for a detailed petrographic and an extensive fluid inclusion study.

The metasedimentary and magmatic host rocks at Imonga were deformed, underwent metamorphism to the greenschist facies, and were intensively altered. In total four vein generations were recognised. Most important for the orogenic gold mineralising fluid study are: (1) the post-foliation, mineralised second vein generation consisting of quartz and ferroan-dolomite with deformation textures (crystalplastic quartz deformation and crack-seal mechanism), and (2) the mineralised third vein generation composed of ferroan-calcite and quartz.

The fluid characteristics as well as the source and conditions, were studied by means of fluid inclusion petrography, microthermometry, Raman spectroscopy, LA-ICP-MS and modelling. The mineralising fluid has a low saline H_2O-NaCl-KCl-CO_2-N_2-CH_4 composition. The CO_2-dominant (70-100mol%) gaseous system with large variations in N_2-content (0-30mol%), and minor CH_4 (0-6mol%) is compatible with a metamorphic origin of the mineralising fluid, which underwent varying degrees of fluid-rock interaction. The presence of H_2S in the fluid may indicate Au was transported as a reduced sulphur complex. Further characterisation of the mineralising fluid results in a salinity ranging from 3.09 to 6.98 eq.wt% NaCl and a density ranging between 0.74 and 0.94g/cc.

By LA-ICP-MS analysis of individual fluid inclusions, the elemental fluid composition was determined and compared with a constructed framework describing the composition of sedimentary, metamorphic and magmatic fluids. The low concentrations of Rb-Cs-Sr-Ba are a clear indication that the mineralising fluid has a metamorphic origin without any evidence for a magmatic contribution. The obtained concentrations and molar ratios of other elements (e.g. Mg-K-Ca-Mn-Fe), equally indicate a metamorphic fluid origin. Au was both quantitatively and qualitatively observed in the petrographic and geochemical data.

The temperature formation window is modelled to range from 350 to 400°C based on several proxies (e.g. crystalplastic quartz deformation, andalusite formation and total homogenisation temperature of the fluid inclusions), with at 350°C an upper lithostatic pressure limit of 250MPa and a lower (sub-)hydrostatic pressure limit of 75MPa. These pressures correspond to a burial depth range of 7.6 to 9.6km. Additionally, this pressure variation and petrographic observations of a crack-seal mechanism, point towards cyclic fluctuations in fluid pressure, favouring the fault-valve activity model typical for orogenic gold deposits. Precipitation of the gold-sulphur complexes could have occurred through destabilisation by interaction with the iron bearing host-rock and/or the fault-valve activity.

Based on all obtained results, the orogenic gold mineralising fluid at Imonga is interpreted to have a purely metamorphic origin. Furthermore, in contrast to the Sn-W vein mineralisation in the WD, no indication of any magmatic-hydrothermal contribution is observed.

The Falklands Islands / Malvinas did not rotate more than ~60° during rifting and opening of the South Atlantic Ocean

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All plate-tectonic reconstructions show that, prior to South Atlantic opening, the Falkland Islands / Malvinas (FI/M) occupied a position somewhere along the east coast of South Africa. Based on geological similarities with South Africa, Adie (1952) already proposed a rotation of ~180° of FI/M during rifting and opening of the South Atlantic Ocean. The similarities have been documented in detail (e.g., Stanca et al., 2019). Early paleomagnetic work by Taylor & Shaw (1989), based on dykes of unknown age, seemingly confirmed Adie's (1952) proposal, and this in turn resulted in suggestions of a late Jurassic or early Cretaceous rotation of a Falkland Islands microplate (see Stone et al., 2009 and references therein). Up to ~60° of this rotation can be attributed South Atlantic opening, but the remaining ~120° rotation remains enigmatic (e.g., Stone et al., 2009).

There are two points of concern regarding a post-Triassic South Atlantic rotation model for FI/M. 1) None of the existing plate-tectonic models offers a solution for the remaining ~120° rotation during rifting/opening of the South Atlantic Ocean. 2) Despite later (post-1990) accurate dating of individual dykes, more recent paleomagnetic work on FI/M, often in publications with ties to the original paleomagnetic study authors, are rather disappointing (e.g., anomaly fitting - a possible fit - instead of proper paleomagnetic work; see Stone et al., 2009).

Geognostics has a global plate-tectonic model (220 – 0 Ma) and maps depth-to-basement across the globe, using a bottom-up approach. In this approach, basins are interpreted from the bottom-up, starting from the foundations (basement terranes), using gravity and magnetic data calibrated with conventional geological data (i.e. wells, cross section data, outcrop). In this integrated workflow, areas are first interpreted in terms of basement terrane nature, which is then combined with (hand-contoured) Moho and depth-to-basement mapping, basement composition interpretation and plate-tectonic reconstructions. This integrated bottom-up basin interpretation ultimately serves as input into Geognostics geothermal model in which the heat source plays the key element instead of the measured surficial result.

Using the Geognostics SEEBASE® depth-to-basement approach, combined with Geognostics Plate Model (GEM), an entirely different scenario comes forward, in which the mirrored geology between FI/M and the Cape Fold Belt (e.g., Stanca et al., 2019) is not due to passive block rotation during South Atlantic rifting and spreading, but instead is re-interpreted as a "Variscan" orocline. In this model, the eastern offshore part of the Cape Fold Belt contains the anticlinal hinge, transposed by the Abrulhas – Malvinas Transform Fault, whereas FI/M occupies the adjacent oroclinal hinge zone.

Implications of this model are:

- FI/M represents the opposite limb to the Cape Fold Belt as part of a Late Permian – Triassic orocline.

- The competent appearance of FI/M is not a reflection of a craton but instead is due to an intruded and mineralised oroclinal hinge zone of a hot orogen (cf. Bohemian Massif).
- The folded fabric of the orocline controlled basin development (e.g., Pletmos, Algoas and Gamtoos basins in South Africa and Malvinas, San Julian and southern North Falkland basins in Argentina).

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Geochemical and mineralogical variability in weathering profiles of the Paleoproterozoic manganese ore of the Franceville basin (Gabon)

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The Franceville basin (SE Gabon) hosts the world's largest supergene manganese deposit, supplying 39% of the manganese used in the European economy. The protolith of the Mn-ore is Paleoproterozoic unmetamorphosed Mn-rich carbonate-bearing black shale (Franceville Fm, FB1c) that has undergone weathering processes, forming a Mn-rich laterite. Mn-rich weathering profiles occur only on the top of plateau-like erosional highs and exhibit variable thicknesses (2-20 m). The Mn-ore profiles display a common structure, with the following units (from bottom to top): (i) unweathered black shale, (ii) transitional clayey zone, (iii) massive Mn ore, 0.1-0.5 m-thick, (iv) platy Mn ore, 0.5-9.0 m-thick, (v) transitional blocky zone, (vi) pisolith zone, and (vii) humic soil horizon. This study aims to reveal the factors that controlled the uneven distribution of the Mn resources across the Franceville basin and processes leading to the formation of the layered structure of the Mn-ore profiles.

We targeted six cross-sections in mined (Biniomi, Bangombé, Okouma) and non-mined (Franceville) areas to identify mineralogical, petrographic, and geochemical variations along each weathering profile. Preliminary results show that most elements are enriched in the weathering profile compared to the Mn-carbonate protore, with exceptions for Na, P, and SiO_2. This enrichment likely results from the loss of organic matter and CO_2 during weathering. Decarbonization process likely accounts for the 2 to 3-fold increase of Mn, Al, Co, Fe, Pb, and Zn in the residual, weathered ore. However, elements are unevenly distributed between the various units. Manganese is mostly concentrated in the lower part of the profile, in platy and massive ore horizons. The main Mn-minerals identified are pyrolusite, nsutite, cryptomelane, and lithiophorite. Manganite occurs in the massive Mn ore alongside pyrolusite and a coating of neoformed rhodochrosite. Variable Mn oxidation states in these minerals (Mn^{2+} to $^{4+}$) probably witness changes in the redox conditions prevailing within the weathering profile. Co (up to 2800 ppm), Ni (up to 3000 ppm), Zn (up to 2400 ppm), and Cu (up to 2100 ppm) are concentrated at the base of the platy zone, and carried/trapped within lithiophorite (as indicated by SEM-EDS analyses). Barium (up to 1.8 wt.%) is concentrated on top of the platy zone and in the pisolith zone and is hosted by cryptomelane. Al, Fe, Si, P, Ca, and Ti content increases through the pisolith and humic horizons and are expressed by an increase in gibbsite, kaolinite-halloysite, goethite, and hematite, with disseminated anatase and neoformed apatite. The transitional clay horizon underlying the Mn ore horizons is barren of metals. These results point to different redox states that can be linked to the placement and movements of the water table within the profiles. This in turn has implications on the valence of elements and their recombination in neoformed Mn-rich minerals. The high amount of carbonaceous material in the protore and the preserved sub-horizontal stratification across the basin probably account for the slow downward progression of meteoric fluids and poor carbonate dissolution of the Paleoproterozoic protore. Therefore, in the present state of knowledge, these profiles are considered immature and geologically "young" (i.e. likely Cenozoic. Ar dating of Mn ore is in progress).

Lithostratigraphic correlations between the Supergroups of the Kivu (RDC) and Akanyaru (Rwanda, Burundi), Karagwe-Ankole belt

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The Karagwe-Ankole Belt (KAB) forms the basement of the Great Lakes region of Central Africa. It comprises stratigraphic series, metamorphic complexes and magmatic intrusions mainly of Mesoproterozoic age, as well as Paleoproterozoic rocks and younger Neoproterozoic series. These units are relatively well known in Rwanda, and, to a lesser extent, in Burundi, where they have been mapped at the 1/100.000 scale. In contrast, in the Kivu and Maniema regions of East DRC, they are less known and occur in disconnected areas. The existing knowledge (mainly from the 1930-1950 period) has been compiled in a 1/500.000 scale map (Laghmouch et al. 2018).

In the frame of recent investigations in the Kivu and Burundi, and using also new results from the revision of the geological map of Rwanda, we have re-examined the geological evolution of this region by proposing new lithostratigraphic correlations between the Eastern and Western sides of Lake Kivu. East of the lake (Rwanda, Burundi), the Mesoproterozoic formations are assembled in the Akanyaru Supergroup and west of the lake, in the Kivu Supergroup. The Neoproterozoic Itombwe Supergroup, well defined in the Kivu side, is also present in Rwanda, showing that his extension is not limited to the Itombwe ‘syncline’, but that it was deposited over a wider region.

Certain formations identified in Rwanda can be correlated with similar formations in Kivu. Among others, the Sakinnyaga quartzites are clearly equivalent to the Bangwe quartzites in Kivu. In Rwanda, the Sakinnyaga quartzites form the youngest Mesoproterozoic formations, while in Kivu, they are overlain by two additional formations (Mukubio and Mughera). On the other part, the Cyurugeyo formation, well known in the Kibuye region of au Rwanda and which comprise quartzites, pelites, dolomitic limestones and meta volcanics form a characteristic sequence which can be recognised even after locally high metamorphism. Rock series with similar characteristics are observed in the Idjwi Island in the middle of Lake Kivu, North of Kalehe up to Sake on the western border of Lake Kivu and in SW Burundi.

The lithostratigraphic evolution is constrained by ages obtained on detrital zircons in sediments, and also by geochronological ages on magmatic intrusions and metamorphic minerals. Deposition of the Kivu and Karagwe-Ankole Supergroups ended in the late Mesoproterozoic by a major tectonic event related to Rodinia amalgamation (1080-1040 Ma). This was followed by the massive intrusion of tin-bearing granites (1040-920 Ma) causing contact metamorphism and metasomatism of the intruded metasediments. The tin-tantalum-tungsten mineralisations are hosted by late phase pegmatites, quartz veins and greisens (Kalikone et al., 2023).

The subsequent fragmentation of Rodina during the Neoproterozoic (825-710 Ma) is marked by alkaline magmatism, of which the Kahuzi-Biega alkaline massif that we dated at 825-814 Ma. Breakup intensified in the Cryogenian with the deposition of the Itombwe glacial series in N-S elongated rift basins (710-625 Ma). A second major thermo-tectonic episode related to the Pan-African amalgamation of Gondwana caused the N-S folding of the Itombwe series and reactivated also the Mesoproterozoic series under green-schist-facies metamorphism (620-545 Ma). The Pan-Africain deformations ended in the early Paleozoic (545-520 Ma) by ductile to brittle shear zones associated to ferruginous fluids, causing Au remobilisation.

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The Gamaye pluton: a tectonic marker of the early Eburnean (Birimian) orogeny in the Kédougou-Kéniéba Inlier (West African Craton)

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The Gamaye pluton belongs to the Paleoproterozoic Kédougou-Kéniéba Inlier (KKI), in the West African Craton. It crops out as a N-S elongated body, with dimensions of ~24 x 9 km, east of a major crustal discontinuity, the sinistral, transcurrent Senegal-Mali Shear Zone (SMSZ). Also, as for other granitoids in the KKI, it displays spatio-temporal relationships with world-class gold mineralizations (Lawrence et al., 2013). The pluton is made of a dominant, fine- to medium-grained and locally porphyritic leucocratic biotite granite, associated with a subordinate, fine- to very-fine grained mesocratic granite. Apatite U-Pb geochronology yields, for the main leucocratic facies, a date with relatively large uncertainties (2160.0 ± 34.8), interpreted as the emplacement age of the pluton. An older apatite U-Pb age of 2294.6 ± 68.3 Ma, obtained for the mesocratic facies, is likely related to an inherited, early Paleoproterozoic component, as found in other granitoids of the KKI through zircon U-Pb geochronology (e.g. Lambert-Smith et al., 2016). The mesocratic and leucocratic facies are both mylonitized close to the western margin of the pluton, in a roughly N-S-trending, sinistral transcurrent strike-slip shear zone, possibly a satellite of the SMSZ. Outside this high-strain zone, microstructures show that the Gamaye pluton has also undergone solid-state deformation and dynamic recrystallization of variable, but weak intensity. Measurements of the anisotropy of magnetic susceptibility, conducted on 54 samples, reveal paramagnetic signatures with bulk susceptibilities lower than 0.5×10-3 SI and a variation of the magnetic fabric shape, from oblate to prolate, towards the western mylonitic zone. The magnetic lineations are gently-plunging and oriented quite regularly, with a weighted mean orientation of N195°E/3°S. The magnetic foliations (weighted mean orientation of N24°E/23°E) are organized around a zone axis parallel to the average magnetic lineation, a feature commonly observed in granitoids, especially in synfolding plutons (Bolle et al., 2018; and references therein). At a larger scale, S1 cleavages in the metasedimentary host-rocks of the pluton and related to the oldest Eburnean tectonic event recorded in the KKI (a contraction phase, D1) are also organized around an axis parallel to the average magnetic lineation. The fabric data demonstrate emplacement of the Gamaye pluton during a transpressive tectonic phase (D2), responsible for folding of the S1 cleavage in the country rocks, as previously proposed (Pons et al., 1992) and the U-Pb geochronology places therefore a time constraint on D2 which could be older than formerly thought (2080-2120 Ma according to Masurel et al., 2017).

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New possible end-members in the ardennite group

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Ardennite is a rare Mn-rich aluminium silicate originally found in Salmchâteau, Stavelot Massif, Belgium, during the second half of the 19th Century. Samples were simultaneously investigated by A. von Lasaux and F. Pisani leading to some controversies between the two scientists as they initially considered the mineral as vanadium-bearing (von Lasaulx, 1872; Pisani, 1872), and then as arsenic-rich (Pisani, 1873). Nowadays, two distinct species were defined: ardennite-(As) with the ideal formula $Mn^{2+}{}_4Al_4(AlMg)(AsO_4)(SiO_4)2(Si_3O_{10})(OH)_6$ and with type-locality Salmchâteau (Belgium), and ardennite-(V) with the ideal formula $Mn^{2+}{}_4Al_4(AlMg)(VO_4)(SiO_4)_2(Si_3O_{10})(OH)_6$ and with type-locality Sparone (Piedmont, Italy, Barresi et al., 2007). During the past years, new occurrences of ardennite were discovered in the southern part of the Stavelot Massif, initiating the crystal-chemical investigation of eleven Belgian ardennite samples originated from various localities or mineralogical and petrographic associations.

Chemical compositions obtained from electron-microprobe analyses are in good agreement with single-crystal structure refinements. An heterovalent substitution mechanism involving the T4 and M3 sites, $T4Si^{4+} + M3(Al, Fe)^{3+} \leftrightarrow T4(As, V, P)^{5+} + M3Mg^{2+}$ clearly occurs. Due to the various multiplicities of the M3 and T4 sites, 4 and 2 respectively, a valency-imposed double-site occupancy on M3 is necessary to preserve charge-balance (Hatert and Burke, 2008) in the ideal end-member formulae of ardennite-group minerals. The $As^{5+} \leftrightarrow V^{5+}$ homovalent substitution on the T4 tetrahedral site explains the existence of a complete solid solution between ardennite-(As) and ardennite-(V), while the incorporation of Si^{4+} and P^{5+} seems to be more restricted. Solid solutions towards the potential new species "ardennite-(P)" and "ardennite-(Si)" appear to be relatively limited although some samples show significant enrichments, with up to 0.28 P^{5+} atoms per formula unit (apfu) and 0.74 Si^{4+} apfu. Therefore, the existence of possible Si-rich and P-rich end-members is discussed.

The existence of both As- and V-bearing species in the original samples from Salmchâteau is certainly at the origin of the disagreement between A. von Lasaulx and F. Pisani, who decided to give different names to these minerals. Ardennite was named by von Lasaulx (1872) for the Ardennes mountains were the mineral was found, and dewalquite was named by Pisani (1873) for the famous Belgian geologist Professor Gustave Dewalque from the University of Liège (1826-1905). Nowadays, only the name ardennite is retained.

Our second nomenclature suggestion for the ardennite group concerns the revalidation of the name dewalquite. Indeed, since the early samples of the V-rich variety were named ardennite by von Lasaulx (1872), and since the presence of arsenic was first demonstrated by Pisani (1873) on samples that he named dewalquite, it seems logical to rename ardennite-(V) as ardennite, and ardennite-(As) as dewalquite. However, if a suffix-based nomenclature is preferred for the group, we could define dewalquite as a new root-name, corresponding to a V^{3+}- and Si-rich species recently observed in Arbrefontaine. These decisions, however, have to pass through the IMA Commission on New Minerals, Nomenclature, and Classification for validation.

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Elucidating deformation of continental interiors and passive margins: insights from apatite fission-track thermochronology in Southeast Brazil and Peninsular India

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The theory of plate tectonics revolutionized our perception of the Earth's lithosphere as a dynamic and complex system divided into tectonic plates. The Wilson cycle further enhances this theory by detailing the lifecycle of ocean basins, from their formation through rifting and spreading, to their eventual destruction via subduction and continental collision. This framework elucidates crucial geological processes at plate boundaries that reshape our planet's surface. However, the theory primarily focuses on tectonic activity at plate margins and struggles to account for deformations observed in continental interiors, far from these boundaries. We employ low-temperature thermochronology, specifically apatite fission-track (AFT) analysis, to elucidate the timing, controls, and magnitude of intraplate deformation events. This technique reconstructs the cooling of minerals as they are exhumed from the hotter (c. 120 °C), deeper parts of the crust, to the cooler surface, thus providing a timeframe for rock uplift and exhumation through the analysis of their thermal history. A total of 135 samples were analyzed from the (Pre)Cambrian terrains of Southeast Brazil and Peninsular India, regions traditionally considered stable since their formation within the Gondwana supercontinent. In Southeast Brazil, the study emphasizes the role of geological inheritance in continental deformation by examining three geological terrains: the Brasília Orogen, the São Francisco Craton, and the Araçuaí Orogen. The study in Peninsular India focuses on comparing the eastern and western passive margins that developed following the breakup of Gondwana. We specifically look into the Dharwar Craton and the Southern Granulite Terrain. In our analysis of the datasets, we demonstrate that the Gondwana basement was heterogeneously exhumed, diverging from traditional models of stable platforms. The exhumation, largely controlled by geological context, lithospheric properties, and structural inheritance, suggests the need to update Wilson cycle models to incorporate these new findings on the partitioning of intracontinental deformation. Additionally, we compare the elevated escarpments of Southeastern Brazil and Western India, exploring why their AFT results differ in relation to their uplift. In Brazil, the data correlates the uplift with post-rift events, whereas in India, the AFT data does not provide clear constraints on the timing or drivers of uplift. Despite this work making significant progress, future research employing multi-method approaches and focusing on additional key study areas is strongly recommended for a more comprehensive understanding of intraplate deformation triggers, mechanisms, and controls over geological time.

Evolution of geodynamics during the Precambrian in Central Africa

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One of the great enigmas of geodynamics is to know when rigid modern plate tectonics, as we understand it today, began on Earth and what geodynamic processes existed on ancient Earth. To solve this, we need to constrain the evolution of these processes over time, and better understand lithospheric dynamics in terms of burial, exhumation, and the speed of these processes. In order to answer these questions, (Ultra) High Pressure and Low Temperature ((U)HP-LT) metamorphic rocks provide exceptional clues to geodynamic processes, as these rocks indicate the existence of "modern-style" subduction, implying the burial of a lithospheric panel into the mantle and, therefore, functional plate tectonics.

The African continent, with its abundant Precambrian rocks, represents a key area for better constraining the evolution of Precambrian geodynamics. The oldest evidence of UHP eclogite are found there, highlighting the existence of "modern" tectonics (burial of a rigid slab at great depth, ca. 611 Ma; Caby, 1994) linked to Pan-African events during the formation of the Gondwana supercontinent. In addition, the oldest occurrences of HP/LT eclogites are recorded at the edges of the Congo and Tanzania cratons, marking the beginning of a proto-subduction and then plate tectonics on Earth (ca. 2.1 Ga; Möller et al., 1995; François et al., 2018, Loose & Schenk, 2018) and are linked to the Eburnean events during the formation of the Columbia/Nuna supercontinent.

As part of the IGCP 667 Project "World Map of Orogens" (François et al., 2022), an extensive compilation of orogens and their main markers in Africa has been carried out. In the Democratic Republic of the Congo, we investigated additional samples of Paleoproterozoic metamorphic rocks from the Kimeza orogen in the Central Kongo (ca. 2 Ga) and in the Kasaï Block (from 2.5 to 1.9 Ga; Fernandez-Alonso e al., 2017). Overall, we emphasize that the transition from ancient to modern tectonics occurred gradually, as a function of the progressive cooling of the mantle and the resulting deepening/steepening of the subduction process.

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Variscan backthrusting on the northern border of the Rocroi Inlier (Belgium): the 'pop-up structure' stage of the Dinant Synclinorium

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The studied region encompass the northern part of the Cambrian Rocroi Inlier and the Devonian cover of the southern border of the Dinant Synclinorium. The base of this work consists of a detailed geological mapping of the Belgian part of the region performed in the framework of the new geological map of the Walloon Region at the scale of 1:25 000 (Geological Survey of Wallonia, SPW, Jambes, Belgium).

The whole belongs to the Ardenne Allochthon and is therefore carried northwards through the Midi Fault or its equivalent at depth. The Cambrian rocks are recognized over about 1400 meters thick. They mainly show quartzites and dark slates belonging to the Revin Group, and quartzites and green or purple slates of the Deville Group in the eastern part of the study area. The Lower Devonian series is about 2000 meters thick. It is made up of a stack of alternately sandstone and slaty shales formations. These series overlie the Cambrian Formations with an angular unconformity that is complicated by the existence of back-thrust faults: the Fépin and Lahonry faults.

These faults present a northwards dip, and therefore a southwards vergence. The Fépin Fault causes the base of the Devonian (Fépin Formation) to slide over the less competent Cambrian formations. The Lahonry Fault splits the Cambrian-Devonian contact as well as the Devonian basal layers. The Macquenoise Fault, for its part, is located at the base of the Oignies Formation. It carries the same Formation and the overlying rocks, to the south, on the incompetent siltstones and shales of the Mondrepuis Formation.

In a larger extent, this back-thrusting contributes to the upwards expulsion of the essentially Upper Paleozoic terrains, between, on the one hand, the Variscan Front (Midi Fault) accompanied by a certain number of other overlapping faults with northwards vergence (e.g. the Yvoir Fault) and, on the other hand, the Rocroi Massif. This large 'pop-up structure' probably occurred early in the evolution of the Variscan compression. A north-verging deformation was superimposed during the later shortening of the structure.

The back-thrusting is facilitated by varying competences between the different formations, but above all by the fact that the isotherm of 300-(350) °C must have been situated (at the beginning of Variscan contraction) in the vicinity of the top Lower Paleozoic (Ardennian) unconformity.

This simplifies the interpretation of a certain number of facts that have been known for a long time. For example, the existence of a stepped structure, constituted by north-verging tight chevron-folds with horizontal hinge lines and moderately inclined axial surfaces, located on the southern edge of the Dinant Synclinorium, which would paradoxically correspond to retro-folds initiated on the hanging-wall of the Fépin and Lahonry backthrusts.

Mineralogical, petrographic and geochemistry study of the Musha-Ntunga pegmatite mineralisation in Eastern Rwanda

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Pegmatites are intrusive magmatic rocks with typically very coarse-grained minerals. As they tend to form from the last portion of a magmatic melt, they can contain significant mineralisation of (incompatible) critical metals, including lithium, tin, tantalum, and niobium (London, 2018). The demand for these critical metals, particularly lithium, has been increasing due to an ongoing energy transition aiming at achieving net zero carbon emissions by 2050. Therefore, a comprehensive understanding of the genesis and evolution of rocks containing these metals, especially pegmatites, is crucial to ensure a constant supply of these critical metals.

The Musha-Ntunga area in eastern Rwanda, part of the Mesoproterozoic Karagwe-Ankole belt (KAB), contains Li-Sn-Ta-Nb mineralised pegmatites and Sn-mineralised quartz veins. This mineralisation is associated with widespread G4 granitic magmatism, which intruded the KAB metasediments forming intrusive rocks around 1 Ga (Tack et al., 2010; Fernandez-Alonso et al., 2012). In the Musha-Ntunga area, both pegmatite and quartz vein mineralisation occurs associated with the Lake Muhazi granitic pluton. The emplacement of the mineralisation is structurally controlled and is related to the reactivation of pre-existing discontinuities due to the regional stress regimes (Hulsbosch et al., 2017). As other pegmatite fields in the KAB, pegmatites in the Musha-Ntunga area often exhibit a regional zonation that may be attributed to a single path of fractional crystallisation of a granitic melt. This fractional crystallisation results in the progressive enrichment of incompatible elements such as Li, Rb, Cs, Nb, Ta, and Sn (Hulsbosch et al., 2013).

This research aims to characterise a representative Li-mineralised pegmatite intrusion and its interaction with the host rock. Fresh, unweathered drill core samples have been studied using optical microscopy, Cold-CL microscopy, Raman spectroscopy and X-ray diffraction to identify the paragenesis of the pegmatite and the host mineralogy. ICP-OES and ICP-MS were applied to determine changes in the host rock geochemistry related to the intrusion and evolution of the pegmatites.

We are able to divide the crystallisation history of the studied pegmatite into three stages. Primary minerals (stage 1) are interpreted to be associated with the magmatic phase of pegmatite crystallisation, i.e. they crystallised as primary minerals from a Si-saturated and H_2O-rich melt. The minerals include microcline, albite, quartz, muscovite, spodumene, columbite-tantalite, cassiterite, fluorapatite and monazite. Secondary minerals (stage 2), such as albite, muscovite, quartz, and cassiterite, are linked to the (magmatic-)hydrothermal phase of pegmatite crystallisation, characterised by (magmatic-)hydrothermal overprinting of primary minerals. Later secondary minerals consist of kaolinite, chlorite, and goethite, interpreted to have formed during more recent - potentially supergene - alteration.

While tourmaline is the dominant metasomatic alteration mineral observed with muscovite, a geochemical dispersion halo of at least 5 m, enriched in Cs, Rb, Sn, and Zn is identified in the host rock adjacent to the selected pegmatite intrusion. This suggests that residual fluids enriched in incompatible elements, released during the pegmatite crystallisation, flushed the host rock. The enrichment of these incompatible elements indicates the extreme fractionation of the studied pegmatite.

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Perspective of exploration of base metals in the Central Africa Copperbelt: A case study of copper deposits in the Nguba Group

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The Central African Copperbelt hosts world class Cu-Co deposits within the Neoproterozoic Katanga Supergroup. The discovery of the Fishtie Cu deposit in the Zambia Copperbelt (ZCC), and the giant Kamoa-Kakula in the Katanga Copperbelt (KCB) within the Mwale Formation of the Nguba Group demonstrate the potential of the Nguba Group as new exploration target. Most of these deposits are, however, not exposed and are only located along fault zones crosscutting the Nguba, Kundelungu and Biano Groups (Mambwe et al. 2023).

Previous works demonstrated that the Cu mineralization at Kamoa-Kakula is associated with hydrothermal potassic and magnesian alteration, however, without any structural control on the mineralization (Schmandt et al., 2013). Recent exploration work in the underground mine demonstrates also a structural control on the Cu mineralization at Kamoa-Kakula, as described before at the Shanika syncline and the Kamakonde Cu occurrences at the Tenke Fungurume Mining District (TFMD) in the KCB and at the Fishtie Cu deposit in the ZCB (Mambwe et al., 2017; Twite et al., 2020, Turner et al., 2023).

Structural analysis in the Mines Subgroup at TFMD indicate pre-folding, and both syn-folding and post-folding Cu-Co mineralization related to the Lufilian orogeny. These mineralization stages have also been recognized in the rocks of the Nguba Group at Kamoa-Kakula. The pre-folding mineralization consists of disseminated Cu sulphides in the matrix of diamictites, siltstones and gravity flow breccia. Syn-folding mineralization consists of Cu mineralization along a foliated zone and strain shadows developed during the main stage of the folding. The post-folding mineralization is recognized at Kamoa-Kakula as centimetric to metric (up 1 m) quartz veins with chlorite, containing pyrite, chalcopyrite, bornite and chalcocite crosscutting parasite folds.

A regional low angle (<30°) thrust-fault affected the footwall of the diamictite. This fault is exposed as a fault breccia that contains Cu mineralization. Several centimetric up to metric faulted folds and dejected folds were related to this thrusting that can be related to the tectonic inversion during the D1-Kolwezian phase (Mambwe et al., 2023). In addition, a thrust breccia at Kamoa-Kakula is made up of mega-fragments belonging to the Mwale Formation and Mwashya Subgroup. Faults interpreted as syn-sedimentary occurring with the gravity flow breccia were reactivated by the compressional inversion and subsequent extensional tectonics of the Lufilian orogeny (Mambwe et al., 2023). Structural analysis coupled with fluid flow modelling constitute a key for identifying new exploration targets in the CACB, especially in the Nguba Group. Finally, the potassic and magnesian alteration described at Kamoa-Kakula, Shanika syncline and Kamakonde at TFMD and Fisthie are associated with the mineralization, but apparently do not control it.

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Bulk composition of fast-spreading oceanic crust providing intrinsic insights on hydrothermal circulation processes (Hess Deep)

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Mid-ocean ridge (MOR) melts form during adiabatic mantle melting and migrate upwards to form new oceanic crust. The nature of the lowest oceanic crust remains unknown due to poor in-situ accessibility. We collected samples of cores recovered during the IODP Expedition 345 to the Hess Deep Rift (HDR), which include lower crustal cumulates from the East Pacific Rise (EPR) and primitive basalts from the Cocos–Nazca Rift (CNR). In Deasy et al. (2021) we presented average major and trace element compositions of these cores using a new channel sample strategy (Wintsch et al., 2022) , representing the first systematically measured chemical and mineralogical compositional dataset of in-situ, fast-spreading lower oceanic crust. This dataset was compiled with available analyses of gabbros, dikes, and lavas from across the HDR to calculate the average bulk composition of fast-spreading oceanic crust (produced at the equatorial EPR). Because fast spreading oceanic crust is considered to be relatively homogeneous in space and time, this new average bulk composition is of fundamental importance for modeling and understanding large-scale geodynamic processes (e.g., subduction factory).

However, this new data set not only casts light on ongoing primary global geodynamic processes but also provides direct insight into water-rock interactions within lower oceanic crust from fast-spreading centers. Hydrothermal alteration of igneous crust is one of the most conspicuous products of water–rock interactions. Despite evidence from high-temperature black smokers and from ophiolites, the lack of data from in-situ lower oceanic crust has hindered progress in understanding major geochemical consequences of rock-water reactions, and hence Earth’s complex physical, chemical, and geobiological cycles. To fill this gap, we report on high- and low-temperature metamorphic alterations in the lower EPR crustal cumulate rocks. The distribution and abundances of the alteration minerals show a multistage sequence of reactions with falling temperature as these gabbros and troctolites traveled east from the EPR toward the HDR. The high temperature alteration stage near the EPR was driven by the ingress of small amounts of aqueous fluids to produce green spinel (Nozaka et al., 2016), corundum, amphibole, talc, and chlorite at ~750-400°C. Subsequent lower temperature alteration included more substantial hydration and included intervals of serpentinization (Nozaka et al., 2017), prehnitization and epidotization. The hydration was facilitated by increasing permeability provided by vein networks. Finally, clay minerals and zeolites formed during shallow faulting at the HDR. The stages of alteration are not only separate in time but their effects localized in space, with the primary mineralogy everywhere at least partially preserved. Moreover, the alteration products are neither in equilibrium either with each other nor with the magmatic minerals.

These observations indicate that, whereas water molecules do penetrate the lower crust to induce metamorphic reactions and small-scale mobilization of elements (e.g., Kummerow et al., 2020), at high temperatures any water molecules that reach the lower crust are fixed in new mineral structures.

Consequently, hydrothermal fluids, as sampled at MOR events, cannot have originated from these depths, but paradoxically, significant alteration and hydration of the lower crust by high-temperature metasomatic reactions could be common near spreading axes. This and concomitant hydrothermal cooling need to be included in any models of deep oceanic crustal growth and geochemical cycling.

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In-situ high-temperature hydrothermal alteration of fast-spreading lower oceanic crust at the East Pacific Rise, Hess Deep

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Despite evidence from high-temperature black smokers and from ophiolites, the lack of data from in-situ lower oceanic crust has hindered progress in understanding major geochemical reactions, and hence the complex physical, chemical, and biological cycles. To fill this gap, we report on high- and low-temperature metamorphic alterations in drill cores from the lower crust at the East Pacific Rise. First, we define the composition of fast spreading (lower) oceanic crust, including average composition and error estimates for the upper volcanic and lower plutonic sections . With these samples we confirm that hydrothermal green spinel, corundum, and diaspore forms in situ at lower crustal levels. Geothermometry at 2 kilobars yields formation temperatures of 650– 750 °C for spinel + pargasite, 410–690 °C for tremolite-hornblende + chlorite, 400–710 °C for corundum, and <400 °C for diaspore. The suggestion of CaO and Na_2O loss via aluminous spinel replacement of magmatic plagioclase is confirmed by comparison of bulk compositions of variably altered gabbro and troctolite. Major element transfer is further supported by reactive hydrothermal experiments that show the high solubility of rocks in supercritical multicomponent aqueous solutions. However, these experiments also illustrated that elemental mobility will not be recorded in hydrothermal fluids reaching the surface due to intervening, lower temperature mineral dissolution and precipitation reactions. As a result, fundamental hydrothermal alteration reactions and fluxes can be underestimated by the compositions of fluids in high-temperature vents. Based on our high-temperature alteration studies of the lower oceanic crust we conclude that (1) the concentrations of aluminous phases in the lower oceanic crust are presently underestimated, and (2) chemical modification of the lower oceanic crust due to high-temperature hydrothermal metasomatic reactions could be common near spreading axes, which (3) suggests that the lower crust may cool too quickly to support a glacial model for lower crustal formation.

Mineralogy of the supergene Cu-Pb-Zn Bou Skour deposit (Anti-Atlas, Morocco)

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The Cu-Pb-Zn Bou Skour deposit is situated in the Eastern part of the Anti-Atlas belt, approximately 50 km to the east of Ouarzazate city, in the Sidi Flah – Bou Skour inlier. The deposit is divided into five ore bodies referred to as, from north to south: "Panther," "Chaigne," "Anne Marie," "Chapeau de fer," and "Patte d'Oie." The latter is economically the most attractive ore body with copper-bearing sulfide mineralization occurring in the Cryogenian to Ediacaran andesitic to granodioritic rocks, locally intruded by a series of rhyolitic and doleritic dyke swarms.

Subjected to atmospheric conditions, sulfide-bearing mineralization undergoes rapid oxidation through weathering processes generating secondary mineralization depending on (i) pH-Eh changes, (ii) enriched metals in the fluid, and (iii) the involved neutralization minerals (carbonates or silicates). In the Bou Skour deposit, the primary assemblage mostly consists of chalcopyrite, pyrite, galena, sphalerite, arsenopyrite and tennantite/tetrahedrite. The resulting acidic fluids derived from the oxidation of primary sulfides are neutralized by gangue minerals such as dolomite, calcite, and chlorite. This, combined with the large diversity of primary mineralogy, results in a diverse secondary mineral assemblage consisting of (i) secondary sulfides (chalcocite, covellite/digenite/djurleite), (ii) sulfates (brochantite), (iii) arsenates (duftite, olivenite), (iv) silicates (hemimorphite, chrysocolla), (v) carbonates (azurite, malachite, smithsonite) and (vi) Fe-Mn oxides. The different parts of the weathering profile are not clearly defined, the different levels merge and overlap.

Mineralogical characterization and emplacement of the giant Manono-Kitotolo pegmatite system, Democratic Republic of the Congo

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The Manono-Kitotolo pegmatites in the Democratic Republic of Congo represent the largest known Lithium-Caesium-Tantalum (LCT-) pegmatite system in the world, stretching at least 13.5 km in length, with a thickness of 250-300 m and an unknown extent at depth (Dewaele et al. 2016). They consist of a series of flat-lying to steeply dipping subparallel sheet-like bodies, which include the Roche Dure, Kyoni, Mpete, and Tempete pegmatites within the southwestern Kitotolo sector, and Carrière De L'Est and Malata in the northeastern Manono sector. The alluvial and eluvial parts of the pegmatites were industrially mined for cassiterite between 1915 and 1985. Recent exploration led to a resource estimation of 842 million tonnes at 1.61 wt% Li_2O, 709 ppm Sn, and 37 ppm Ta (AVZ Minerals Limited, 2024).

Here, we present new geological, mineralogical and petrographic data obtained from fieldwork and drill core samples. The latter samples present three cross-sections through the pegmatite system (two at Roche Dure and one at Carrière De L'Est). Spodumene is the dominant Li-bearing phase throughout the pegmatites, occurring dominantly as white prismatic crystals, locally with rims of symplectitic spodumene-quartz intergrowths (SQI). It occurs less often as randomly oriented tabular crystals, and very locally as coarse grained SQI (Fig. 1). Prismatic spodumene typically shows unidirectional growth textures perpendicular to the outer pegmatite contacts. Columbite-tantalite group minerals (CGMs) and cassiterite are inferred to be early to late magmatic. Cassiterite is, however, also commonly found in muscovitized/greisenized and albitized areas. Accessory minerals include apatite, triphylite-lithiophilite, Ca-Mn-Fe phosphate alteration assemblages, garnet and tourmaline. The system appears to have a relatively Mn-Fe rich trend, allowing the crystallization of Li-Mn-Fe phosphates (rather than Li-Al-phosphates), Fe-rich tourmalines classified as schorl, Mn-rich apatite, and muscovite with ~2 wt% FeO content.

Meter-scale layering is visible from distance in outcrop, and fine aplite layering observed locally in outcrop. In the drill cores, alternations between greisen, aplite, K-feldspar, albite-, and spodumene-rich intermediate zones can be recognized. The classic internal zonation has thus not been recognized. Instead, a textural and mineralogical zonation appears to be repeated many times over a meter- to decimeter-scale. Furthermore, primary zoning is partially obscured by overprinting metasomatic alteration, i.e. albitization followed by greisenization. Geochemical assays of the core (AVZ Minerals Limited, 2023), at 50 cm sampling intervals, show multiple 'high-grade' Li zones, where Li_2O content exceeds 2%. These high-grade bodies appear to dip parallel to the overall pegmatite and may represent the intermediate zones of individual pegmatite sheets.

Based on these observations, we postulate that this world-class pegmatite system was formed through incremental emplacement of many smaller pegmatite bodies. Historic and recent age dating (Dewaele et al. 2016, Cahen & Ledent,1979) indicate a temporal discrepancy between nearby granite and the pegmatite, which does not support a genetic link. If the pegmatites are the result of extreme fractional crystallization, this implies a large granitic body hidden at depth. Alternatively, pegmatite melts may have been periodically formed by partial anatexis of an earlier granite, such as proposed in the two-stage melting model of Koopmans et al. (2023). Further geochemical and geochronological data are required to test these two models.

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AVZ Minerals Limited (January 2024). ASX Announcement: Manono Project Mineral Resource increases 47% to 842Mt. https://shorturl.at/aglE2 3 AVZ Minerals Limited (May 2023). Geology, downhole surveys and assays for the three drill holes across the pegmatites (Internal communication).

Cahen L, Ledent D (1979) Précisions sur l'âge, la pétrogenèse et la position stratigraphique des granites à étain de l'Est de l'Afrique centrale. Bull. Soc. Belg.

Koopmans L, Martins T, Linnen R, Gardiner N J, Breasley C M, Palin R M, Groat L A, Silva D, and Robb L J (2023) The formation of lithium-rich pegmatites through multi-stage melting. Geology, 52(1): 7–11

Figure 1: A. Prismatic spodumene showing unidirectional growth direction, perpendicular to the outer contacts of the core B. Tabular spodumene. C. Coarse quartz-spodumene intergrowths (SQI).

Data for sustainable raw materials management

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In Flanders (Belgium), sustainability principles have been taken into consideration in extraction activities for a long time. More specifically, the following was established by Decree in 2003: "The basic objective of the surface minerals management policy is to sustainably supply the mineral resources necessary to meet the current and future demand of society for materials." To achieve this, long-term planning of raw materials management, based on data, is absolutely essential.

Near-surface mineral resources, such as clay, sand, loam and gravel, are exploited by means of open pit methods. To collect data on the quantities required for industry, the Flemish Government has developed a monitoring system. Producers, traders and consumers of raw materials are periodically surveyed about their production, trade and consumption volumes of both mineral resources and all their alternatives, whether they are excavated geological layers from infrastructure projects, recycled granulates, slags or other alternatives. The differentiation between local and imported raw materials is being made, as well as a distinction on the level of application, e.g. for concrete, foundations, ceramics etc. The monitoring results show important differences between the individual mineral resource types in terms of availability of alternatives, partly due to quality requirements, and import dependence.

The monitoring system is combined with a long term vision on research, both in-house and commissioned by the Flemish Government. Examples of recent outsourced research are a study on future availability of raw materials from abroad (Van den Abeele et al., 2019) and the development of a stock-flow model (Goelen et al., 2023). With this information, estimations of the future demand of each mineral resource can be made, taking into account the principles of circular economy. Data on reserves in the areas designated for mineral extraction are also collected, based on geological models and reported extracted volumes. All this information allows to propose future actions in the General Surface Mineral Resources Plan (AOD).

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Goelen T, Van den Abeele L, (2023) Stock & flow model voor grof zand, grind & steenslag, studie uitgevoerd in opdracht van het Vlaams Planbureau voor Omgeving.

Microthermometric and geochemical analysis of fluid inclusions of the Tenke-Fungurume Mining District (Democratic Republic of Congo) and their contribution to understanding the Katanga basin evolution

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Sedimentary basins are an important source of many base metals, and their percolating fluids are intricately associated with metal transport – which can begin from deep crustal levels – and deposition. Basinal brine migration, both on a regional and local scale, is generally related to the origin of many significant deposits of Pb-Zn, Ag-Pb-Zn(-Cu), U, Ba, and F. In the Central African Copperbelt, one of the largest sediment-hosted, stratiform to stratabound Cu-Co provinces in the world, numerous studies have been performed regarding the economic potential of different metals and the genesis of the mineralization. A well-accepted model of the Copperbelt involves at least two main stages of ore formation (Dewaele et al., 2006; El Desouky et al., 2009). Each of these two stages has a distinct signature of fluid salinity and temperature, the first associated with diagenesis of the sediments and the second taking place subsequently during deep burial and orogenesis.

The Tenke-Fungurume mining district (TFMD), located in the northern part of the Katanga Copperbelt, DR Congo, hosts numerous mineralized carbonate-quartz veins that characterize the pre-, syn-, and post-folding events related to the Lufilian Orogeny (Mambwe, 2023), a major tectonic event that occurred during the Pan-African orogeny. Pre-folding veins formed before folding and cleavage development and include bedding-normal, bedding-parallel, and stylolite-associated veins. Syn-folding veins were formed during the folding stage of tectonic deformation and consist of saddle reef and fracture-filling veins, hairline veinlets and bedding-parallel shear veinlets. Post-folding veins occur after the main deformational stage and are characterized by irregular orientations and cross-cut earlier vein generations and folds. All these vein types contain associated sulfide mineralization including chalcopyrite, bornite, and carrollite.

Microthermometric and geochemical analyses, along with detailed cathodoluminescence petrography of dolomite and quartz crystals were performed to understand the type II fluid (cf., El Desouky et al., 2009) evolution throughout those stages. Primary fluid inclusions record a large range of T_h (101-372°C) and salinity (36.4-65.0 wt.% NaCl + KCl eq.) for all stages, which cannot be differentiated according to these signatures. Crush-leach analysis of carbonate and quartz leachates yielded Cl/Br and Na/Br ratios pointing to fluids originating from the progressive evaporation of seawater followed by the dissolution of evaporates at high temperatures and deep fluid-rock interactions (Fig. 1a; cf. Heijlen et al., 2008; Selley et al., 2018). However, the fluid composition identified in the pre-, syn-, and post-folding events in the TFMD indicates complex geochemical signatures, as observed with laser-ablation ICP-MS analyses from individual fluids inclusions. Samples from the aforementioned tectonic stages do not record compositions that aid in the distinction of each event, as their element content is remarkably similar (Fig. 1b). High contents of Cu, Co, Ba, Zn, and Pb relative to Na were measured in all stages, suggesting mineralization was not restricted to any of them, and that the hydrothermal system probably operated during a large part of basin evolution and deformation.

Dewaele S, Muchez P, Vets J, Fernandez-Alonzo M, Tack L (2006) Multiphase origin of the Cu–Co ore deposits in the western part of the Lufilian fold-and-thrust belt, Katanga (Democratic Republic of Congo). Journal of African Earth Sciences (46): 455-469. El Desouky HA, Muchez P, Cailteux J (2009) Two Cu–Co sulfide phases and contrasting fluid systems in the Katanga Copperbelt, Democratic Republic of Congo. Ore Geology Reviews (36): 315-332. Heijlen W, Banks DA, Muchez P, Stensgard BM, Yardley BWD (2008) The Nature of Mineralizing Fluids of the Kipushi Zn-Cu Deposit, Katanga, Democratic Repubic of Congo: Quantitative Fluid Inclusion Analysis using Laser Ablation ICP-MS and Bulk Crush-Leach Methods. Economic Geology (103): 1459-1482. Mambwe MP (2023) Sedimentological, stratigraphic and metallogenic study of the Katanga Supergroup in the Tenke Fungurume Mining District (Katanga, DRC). PhD Thesis, KU Leuven, 349 p. Selley D, Scott R, Emsbo P, Koziy L, Hitzman MW, Bull SW, Duffett M, Sebagenzi S, Halpin J, Broughton DW (2018) Structural Configuration of the Central African Copperbelt: Roles of Evaporites in Structural Evolution, Basin Hydrology, and Ore Location, in Arribas RAM and Mauk JL, eds., Metals, Minerals, and Society, 21, Society of Economic Geologists (SEG): 115-156.

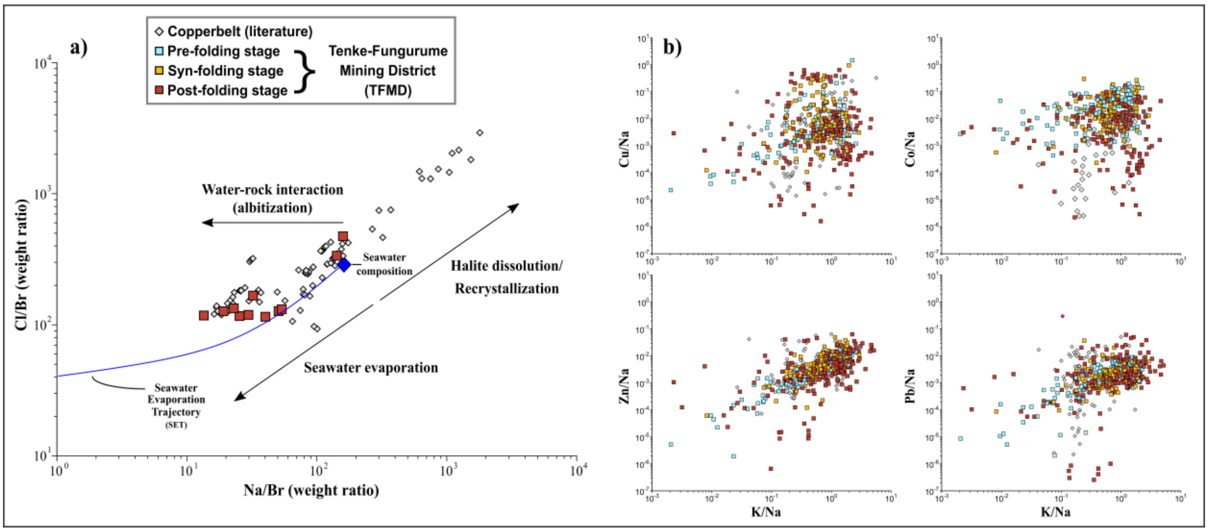

Fig 1. a) Na/Br vs. Cl/Br weight ratios of fluid inclusion leachates from samples of the post-folding stage; b) Diagrams of K/Na and element-to-Na ratios from fluid inclusions analysis in samples from this study. Comparison with literature data includes r

Syn- to late orogenic fluid evolution in the High Ardenne slate belt (Herbeumont, Belgium)

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Near Herbeumont (Belgium), two distinct types of quartz veins can be identified. Firstly, synorogenic veins were identified within the top-to-north Herbeumont shear zone (Schavemaker et al. 2012), reflecting the main compressional stage of the Variscan orogeny. Secondly, discordant veins were observed within a top-to-south extensional shear zone, attributed to the late orogenic gravitational collapse of the High Ardenne slate belt. These discordant veins are further classified into two types: Type I, where the foliation-parallel shear continues across the 'precursor vein', and Type II, where the shear zone displaces at the level of the 'precursor vein' and is transferred across the 'precursor vein' (Van Baelen & Sintubin 2022).

The veins were examined by a petrographic analysis and the fluid inclusions were analyzed using microthermometry and Raman spectroscopy. The characterization of the fluid inclusions within these quartz veins enables to constrain the evolution of the metamorphic fluids circulating in the High Ardenne slate belt in the later stages of the Variscan orogeny.

Synorogenic veins contain aqueous fluid inclusions (H_2O-NaCl-(CO_2-N_2-CH_4)) with an average salinity of 5.2 eq. wt% NaCl and a very low amount of gaseous content. Microthermometry indicates metamorphic conditions ranging from 335°C to 390°C and 245 MPa to 250 MPa. Both Type I and Type II veins show an H_2O-NaCl-CO_2-N_2-CH_4 system, with Type II veins displaying an increased presence of N_2. Average salinity for Type I is 4.5 eq. wt% NaCl, while Type II records 3.7 eq. wt% NaCl. Pressure-temperature conditions show Type I veins formed within a range of 305°C to 380°C and 220 MPa to 270 MPa, while Type II veins formed between 280°C to 380°C and 200 MPa to 270 MPa. Late orogenic discordant veins exhibit high gaseous content in their fluid inclusions, which can be attributed to exhumation releasing the gaseous components in addition to a low saline fluid. In a closed fluid system, as is the case for the High Ardenne slate belt, gaseous species have multiple origins (Kenis et al. 2005). CO_2 is derived from decarbonization of organic matter, while CH_4 is derived from the maturation of organic matter. The relatively high N_2 content can partially be due to maturation of organic matter. However, during retrograde metamorphism, N_2 is often the result of the release of nitrogen from NH_4-rich phyllosilicates. A retrograde metamorphic trajectory can be fitted, from synorogenic veins to discordant veins, which correlates well with the increase in N_2 content.

Pressures ranging from 200 MPa to 270 MPa correspond to depths of 8 to 10 km. The occurrence of large blocky quartz crystals indicates growth in fluid-filled open cavities. The existence of open cavities at 8 to 10 km depth can only be the result of very high, up to supralithostatic, fluid pressures, typical for periods of tectonic inversion (Depoorter et al. 2014).

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The Critical Raw Materials Act in Flanders: preliminary research on REE-content of coking coal

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In 2023, the European Commision published its fifth list of “Critical Raw Materials”, i.e. raw materials with high economic importance and high supply risk for the European Union. Alongside this list of 34 critical and strategic minerals (CRMs and SRMs), a first proposal for the “Critical Raw Materials Act” (CRMA) was released. This European regulation establishes a framework for ensuring a secure and sustainable supply of the critical raw materials and was recently approved and signed by the European Parliament. The regulation sets benchmarks regarding the extraction, processing and recycling capacity within the EU, as well as for a diversification of import from third countries. Regarding extraction, it is the aim to be self-sufficient for at least 10% of the EU annual consumption of SRM, to the extent that the Union’s reserves allow this (European commission, 2024).

The only critical raw material (currently) known of relevance in Flanders is coking coal, in the province of Limburg. The coal mines in Flanders have been closed since 1992, but vast reserves are still present in the subsurface (e.g., Gullentops & Wouters, 1996). Additionally, some coalbasins, e.g. in Poland, the US and China, have shown to be locally enriched in Rare Earth Elements and other SRMs and CRMs (e.g., Dai & Finkelman, 2018; Zhang et al., 2024). So far, only limited research on the responsible minerals, processes and conditions of enrichment has been done.

A full geochemical analysis (major, trace, rare earth elements) has been carried out on 62 samples (27 coal samples, 35 sediment samples) from four boreholes in the eastern Campine Basin (Flanders), covering the whole Westphalian stratigraphy. Flemish coal samples show a higher total REE-content than the surrounding sediments (537 ± 409 ppm vs 191 ± 68 ppm, figure 1), mainly manifested in the light REE La, Ce and Nd. The observed REE-content is also high compared to literature values for coal (18 – 634 ppm, average of 262 ppm). Additionally, the Flemish coal is relatively enriched in Ga, Ge, Be, V and the metals Co, Ni, Cu, Zn and Pb.

Coal and sediment samples show distinct geochemical characteristics regarding the REE (figure 1). In the sediment samples, a strong correlation between the REE and Al, Th, Ti, V and Y is observed, as well as a less strong correlation for Na and Nb. This suggests adsorption of the REE in clay minerals such as kaolinite and possibly loparite. Coal generally has a higher geochemical variability, but the REE show positive correlations with P, Th and Y, indicating the occurrence of REE can be hosted in phosphates like monazite or xenotime. No correlation with ash content, Zr and Ca is observed, ruling out an important contribution of organic material, apatite or zircon. Future work will focus on the geochemical and petrographical results in view of the Westphalian stratigraphy as well as the relation between coal and surrounding sediment, in order to identify possible leaching processes or trends in sediment composition.

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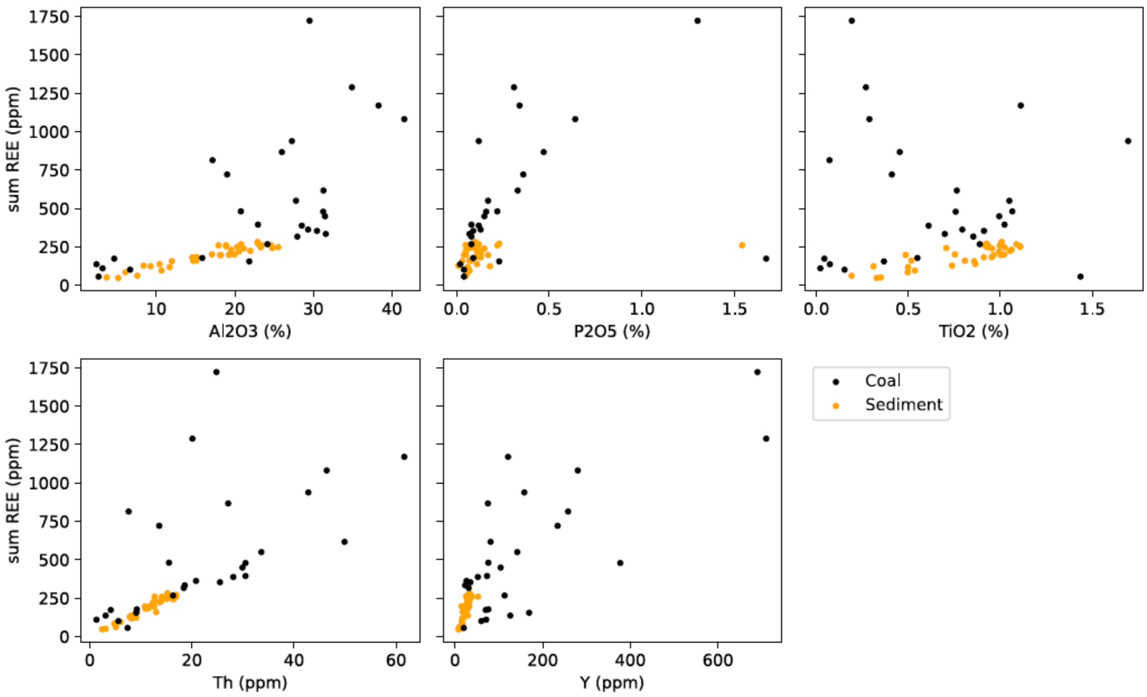

Figure 1: geochemical composition of Westphalian coal and sediment in the Campine Basin, Flanders (selection)

Investigating the origin of REE mineralisation in the Korsnäs Pb-REE deposit, Finland: Magmatic Carbonatite Dikes or Hydrothermal Veins?

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Rare Earth Elements (REE) are crucial ingredients for renewable energy technologies such as wind turbines and electric vehicles. In the pursuit of new sources of REE, carbonatites and alkaline rocks are a primary target for research and exploration. This study focuses on a new exploration project in Finland, which is revisiting a former lead mine at Korsnäs, Finland. The deposit consists of white calcite veins rich in sulphides, with elevated REE contents in surrounding skarn-like rocks, that crosscut a migmatitic mica gneiss. The elevated content of REEs in Korsnäs has been known since the 1970s, as evidenced by a small 'lanthanide dump' near the historic Pb mine. Yet the origin of these REE-rich sulphide-carbonate rocks remains a matter of debate. These rocks occur as a network of veins in an area of 10 km2. They are hosted by a north-south trending fracture zone dipping eastward at an angle of 40° to 60°. The veins range from only a few centimeters in width to several meters with the largest reaching 30 meters in width with a length up to 1.5km down to a depth of 350m (Al-Ani et al. 2018). Some have referred to the calcite veins as magmatic carbonatitic dikes (Sarapaä et al. 2013). In contrast, others suggested a meteoric origin for the fluids that precipitated these carbonate veins based on stable isotopic signatures of oxygen and carbon (Torppa and Karhu, 2013). An intrusive or hydrothermal origin appears to be obscured by a later stage of metamorphism, thus forming skarn-like assemblages.

This study aims to uncover the origin of the Korsnäs REE-Pb deposit and identify where and in which minerals the REEs have accumulated. Microscope and SEM observations on samples obtained from 60-year-old cores stored by the Geological Survey of Finland (GTK) have shown that while the carbonate veins themselves do not contain a significant amount of REEs, the contact between the carbonates and the silicate host rock does. The carbonate veins consist of coarse calcite crystals with sulphide mineral droplets (pyrrhotite, galena, pyrite). In the skarn-like assemblages, both calcite and dolomite form the bulk of the rock together with quartz, Ba-rich feldspars, pyroxenes, scapolite, and accessory titanite, monazite and fluorite crystals. Most of the REEs are hosted in monazite crystals. These occur both as discrete crystals, but also as fine-grained inclusions disseminated within larger apatite crystals (Fig. 1). The latter is especially true for rocks that have undergone severe alteration or metamorphic replacement. Those which have been altered also often contain barite as a vug-filling phase. Other REE minerals identified include calcioancylite and britholite. Geochemical assay data of the drill cores provided by Prospech Ltd show REE grades above 3,000 ppm for 35 out of the 49 drill cores sampled (Prospech Limited, 2024a), with samples containing up to 49,324 ppm (Prospech Limited, 2024b).

The petrography and mineralogy of the studied rocks potentially support an origin of a metamorphosed carbonatite. The geochemical data also show a similar pattern to other carbonatites, more specifically, post-collisional carbonatites. This would suggest that the stable isotope study that has been conducted in the past, was influenced by later hydrothermal overprinting, potentially during low-grade regional metamorphism.

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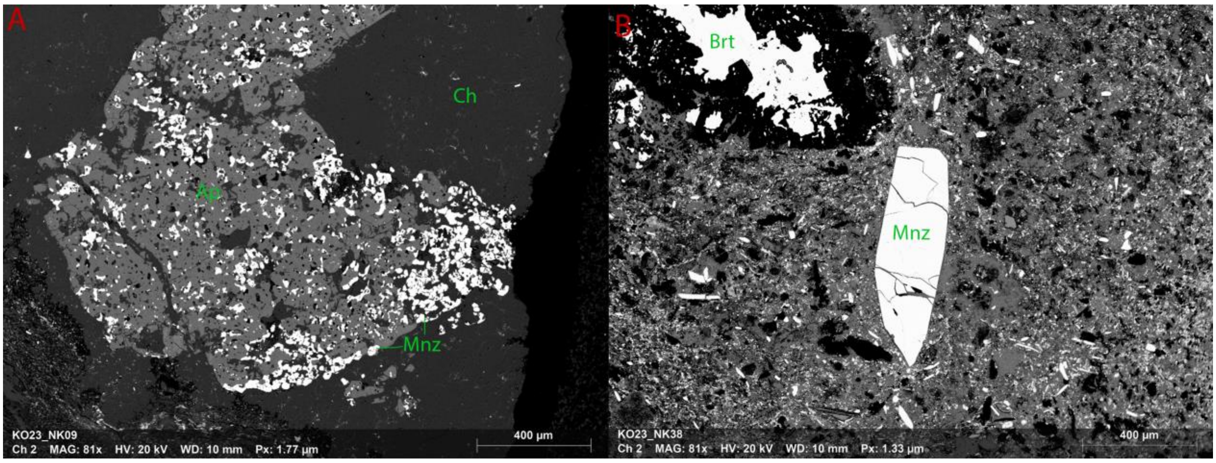

Figure 1: A) SEM image of monazite (Mnz) inclusions in apatite (Ap) crystal. The surrounding mineral is chalcedony (Ch). B) Monazite (Mnz) crystal in iron oxide matrix with smaller monazite crystals. Barite (Brt) as vug-filling phase

SESSION 2 - GEOMORPHOLOGY, EARTH SURFACE PROCESSES, KARST AND GEOHAZARDS

Conveners

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The evolution of the Earth surface is shaped by physical, chemical and biological processes at a range of temporal and spatial scales. These processes dynamically interact and respond to external tectonic and climatic forcings, leading to a variety of landforms. Calcareous environments are characterized by specific evolution associated with surface and sub-surface karstic processes. Geohazards are processes associated with sudden geological or geomorphological changes, that represent a threat to human communities. These processes can be studied, among others, through field work, lab experiments, remote sensing, or analogue or numerical modelling. This session welcomes contribution in the broad fields of geomorphology and geohazards.

Specific topics include (not exclusive): fluvial, aeolian and coastal sediment transport; hillslope mass movements and soil erosion; karst processes and landforms; surface manifestation of volcanisms and tectonism; weathering and pedogenesis modelling; theoretical and quantitative geomorphology; geological records of Earth surface processes in relation to environmental change; impacts of past, current and future environmental change upon Earth surface processes; relationship between Earth surface processes, hazard, risk, and management.

Invited Speaker

Which came first: mountain or landslide?

Benjamin CAMPFORTS

Department of Earth Sciences, VU Amsterdam, The Netherlands

Environmental change is increasingly linked to the occurrence of mass movements worldwide. This talk begins by discussing a 2022 rockslide in Rocky Mountain National Park and evaluates the impact of shifting environmental conditions in triggering it. Limitations of current observational data are identified, and large-scale landscape evolution models are proposed as an additional tool to understand interactions among stochastic mass movements, topography and sediment dynamics. I explore the impact of landslides on shaping terrain through a combination of field-based metrics and large-scale landscape evolution models. Simulating landslides enables us to identify the origins of several common features in mountainous topography. Model results illustrate how repeated landsliding can cause rivers and ridgelines to gradually but continually shift position over time, such that some mountain drainages grow while others shrink. This type of computer model, which describes how topography and landsliding influence one another, can help the scientific community understand the response of steep terrain to environmental changes, such as those related to climate and earthquakes.

Spatio-temporal groundwater recharge estimation of Mount Guna, Northwest Ethiopia

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Spatially distributed water balance model WetSpass was chosen to estimate spatial and temporal recharge and evapotranspiration of Mt. Guna. Field based data and remote sensing data were used to successfully run WetSpass Model. The observed meteorological input data were corrected to minimize topographical effect by developing a regression equation, which is crucial in recharge estimation for such mountain site. The model was calibrated based on observed average discharge data collected at six river gauges. The recharge estimated by Water Table Fluctuation (WTF) and Chloride Mass Balance (CMB) methods was used to validate the model. The comparison of calibrated WetSpass estimated mean monthly runoff and the mean monthly observed runoff shows a strong coefficient of determination (94%). The mean annual recharge estimated by WetSpass is 409 mm in Mt. Guna. The recharge accounts for about 28% of rainfall received in Mt. Guna. On the other hand, the mean annual recharge of Mt. Guna estimated from Water Table Fluctuation and Chloride Mass Balance methods respectively is 357 mm and 417 mm. This confirms that WetSpass is effective to estimate spatial and temporal recharge in mountains. However, the meteorological inputs and water level data should be corrected to minimize topographic effect. Hence, we propose to use the methods we applied in our study to correct meteorological input data in similar mountains.

Exploring Tectonic Controls on Hydrogeological Dynamics and Geochemical Signatures in Siliciclastic Sub-Basins in a climate change hotspot area - A Case Study of the Tunisian Oriental Atlas

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Tectonic processes sculpt the subterranean landscape, shaping distinct basins and fault systems. In turn, these geological formations exert a profound influence on hydrodynamics, water flow patterns, and geochemical compositions within their confines. Our research delves into this intricate relationship, focusing on the siliciclastic sub-basins of the Tunisian Oriental Atlas, a region situated in a climate change hotspot area.

Through a comprehensive multidisciplinary methodology integrating geological mapping, geophysical modeling, and geochemical analysis, we aim to elucidate how tectonic structures orchestrate hydrogeological dynamics and geochemical signatures across the study area. By discerning the spatial distribution of geological features such as NE-SW, NW-SE, E-W and N-S faults and sedimentary basins and sub-basins, we unravel their impacts on groundwater flow paths, aquifer recharge mechanisms, and solute transport processes.

Water flow dynamics are significantly influenced by the lithological characteristics of the geological layers. This interplay between faulting and lithology plays a crucial role in shaping aquifer properties and groundwater chemistry.

Our research underscores a notable deterioration in water quality, high values of Cl-, Na+, Ca2+, SO42- accentuated by a variety of factors exacerbated by the distinctive climatic conditions of the region. Additionally, the existence of sebkhas, or salt flats, introduces another facet to the hydrogeochemical dynamics of the area. These revelations offer valuable insights for policymakers and stakeholders, guiding the development of effective strategies to safeguard water quality and ensure water security in analogous geological and climatic settings.

Comparing modern remote sensing data to aerial photography for geomorphological mapping of the Virunga volcanoes

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The Virunga volcanoes, situated along the border of DR Congo, Rwanda, and Uganda, are renowned as the habitat of mountain gorillas. In the 1960s, Degroote (1962) studied the geomorphology of these volcanoes using panchromatic aerial photographs. Subsequent research focussed on specific aspects of the geology, geomorphology, and soils of the volcanoes (e.g. Albino et al., 2015; Barette et al., 2017; De Mulder, 1984; Dondeyne et al., 1993). However, an updated synthesis of the geomorphology of the Virunga volcanoes is lacking. We aimed to compare insights derived from digital elevation models and satellite imagery with those from the study by Degroote that was based on aerial photographs. Additionally, integrating this knowledge with current geological, geomorphological, and soil studies, our objective was to produce an updated geomorphological map.

Initially, terrain units were identified using geomorphometric characteristics extracted from a digital elevation model with a 12.5 m spatial resolution based on ALOS PALSAR data. Subsequently, recent lava flows were mapped using satellite images (Harmonized Sentinel-2 MSI). Combining the terrain and landform units with geological information, we generated a comprehensive geomorphological map. Finally, we compared the findings of Degroote with insights we obtained from the remote sensing data.

Applying the Iwahashi and Pike method enabled us to identify 16 broad terrain classes, that we further subdivided based on smaller features identified through a landform classification using the Topographic Position Index. Satellite imagery facilitated the mapping of recent lava flows. The resulting geomorphological map shows the geomorphic structures and landforms of the Virunga volcanoes.

Comparing our results based on remote sensing data, with those of Degroote based on aerial photographs, highlighted differences in resolution, accuracy, and temporal aspects. While aerial photographs provided fine spatial details, the modern remote sensing data and GIS software enabled more accurate mapping over the whole area. Additionally, multitemporal satellite imagery facilitated tracking recent changes such as lava flows. By incorporating these insights, we were able to draft an updated geomorphological map of the Virunga volcanoes.

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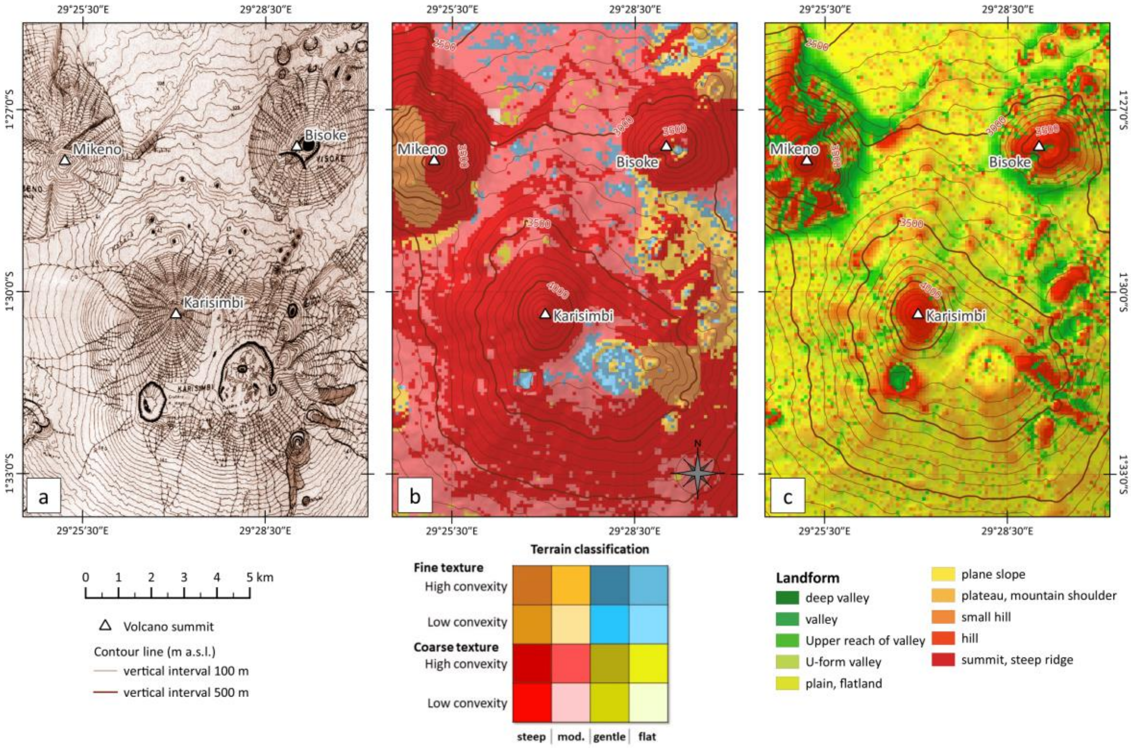

Geomorphologic units of the Karisimbi, Mikeno and Bisoke volcano, the central group of the Virunga volcanoes. (a) Excerpt of the 1962 geomorphologic map based on aerial photographs (Degroote, 1962); (b) Iwahashi and Pike terrain classification, and (c) TP

A novel workflow to detect landslides and flash floods in large unexplored regions

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Landslides and flash floods are geomorphic hazards (GH) that often co-occur and interact and frequently lead to societal and environmental impact. The compilation of detailed multi-temporal inventories of GH events over a variety of contrasting natural as well as human-influenced landscapes is essential to understanding their behavior in both space and time. It allows to unravel the human drivers from the natural baselines and cand be a valuable tool to develop early warning and disaster risk reduction strategies. Yet, creating multi-temporal inventories of these GH events, remains difficult and costly in terms of human labor, especially when relatively large regions are investigated. Current generation (machine learning-based) methodologies generally rely on accurate information on either the GH location (training samples) or the GH timing (pre- and post-event imagery), making them unfit in unexplored regions without a priori information on GH occurrences. We present two detection methodologies that we combined as part of our workflow to accurately detect both location and timing of landslide and flashflood events in previously unexplored areas without a prior information. The methodologies rely on change detection in the pixel time series and are aimed to perform in large and complex regions such as the tropics where data-scarcity is prevalent, landscape is contrasting and alternates between pristine forests and highly cultivated terrain, and where cloud cover is significant. We combine the advantages of both radar SAR and optical imagery from the publicly available, high spatial and temporal resolution (10-20m; 5-12 days) Sentinel 1 and 2 constellation to achieve high spatio-temporal detection accuracies. We show the applicability of our workflow in the western branch of the East African Rift, where we have been able to detect more than 100 new landslide and flash flood events with a median timing of 6 days between 2017 and 2021.

Source, runout and debris-rich floods: capturing the complete landslide continuum for accurate inventory, susceptibility and exposure mapping following Cyclone Idai

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When intense rainfall hits mountainous regions, it can trigger thousands of landslides within a few hours. The parameters that control the occurrence of these landslides, and the methods for modelling zones susceptible for landslide initiation have been extensively studied. Yet, in many of the most severe landslide disasters, the main impact from landslides on local communities occurred far from the initiation areas. The latter indeed largely depend on the landslide mobility (i.e. speed and travel distance). Sediments eroded high on slopes by shallow landslides can be transported kilometres downstream through a cascading chain of hazards – with e.g., debris landslides evolving into debris flows ultimately feeding debris-rich floods – thereby greatly increasing both the landslide destructive potential and its zone of impact. While considering landslide mobility and the potential for cascading hazards is critical for accurate risk mitigation, studies addressing it are remarkably few compared to those that do not. Additionally, existing studies often rely on complex, e.g. physically-based models, limiting their analyses to relatively small spatial scales. With this work, we aim at stressing how capturing the full landslide continuum (landslide initiation, runout and related debris-rich floods) is key for accurate landslide inventory, susceptibility and ultimately exposure mapping alongside some extreme climatic events. We demonstrate the benefits of our approach in terms of hazard and risk mitigation strategies for two districts of eastern Zimbabwe, which were severely affected by Cyclone Idai in March 2019. Using simple, replicable and open access methods, we gained insight into this extreme (in terms of magnitude and impact) event through accurate mapping of the impacts, and the production of comprehensive landslide susceptibility maps and detailed exposure products that account for the complete landslide continuum.

Soil collapses in Wallonia and Hauts-de-France: first insights from accident analysis and perspective in the scope of climate change

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Cellule Risques Sous-sol, Institut Scientifique de Service Public, Belgium

Ground collapses linked to underground cavities are frequent phenomena of varying scale in Wallonia and Hauts-de-France. The two regions share a similar geological context and industrial history. As a result, the underground objects (natural and man-made cavities) and the potential threats they represent are similar. The aim of the RISSC project (Interreg Programme 2018-2022) was to improve practices for managing the risk of ground movement (ground collapse, in the broadest sense) linked to the presence of underground cavities, by local stakeholders (public authorities, local authorities, emergency services, experts, etc.).

One of the project's achievements was to carry out an accident analysis of past events. A simple statistical approach was applied to the existing databases for the two areas. This analysis, which was made difficult and limited due to gaps in the available databases, was nevertheless able to show at first glance the frequent involvement of water in the dynamics of collapses (Figure 1). The massive infiltration of water into the ground can be linked to specific, unforeseeable anthropogenic events (burst pipes, open sprinkler pipes, cisterns, etc.) but also to natural contexts (exceptional rainfall) which, combined with other parameters (local geology, topography, alternating drought and rainfall, etc.), can lead to the occurrence of collapses. However, the link between collapse and climatic conditions remains poorly understood and little studied. In the context of climate change, where extreme events are set to multiply, it seems essential to increase our knowledge of the context in which hydrological factors can lead to collapse.

In a future project, currently being set up, the link between collapses and hydrological factors will be put under the microscope and contextualised in the light of climate change. The project will tackle this issue from two angles: firstly, through a global approach, on the scale of the areas concerned and based on statistical tools; and secondly, through a conceptual approach, on a more local scale, which will include an understanding of the mechanisms leading to collapse with regard to the influence of water infiltration (hydrogeology) on the stability of the soil and subsoil in a sub-cavity context (geomechanics).

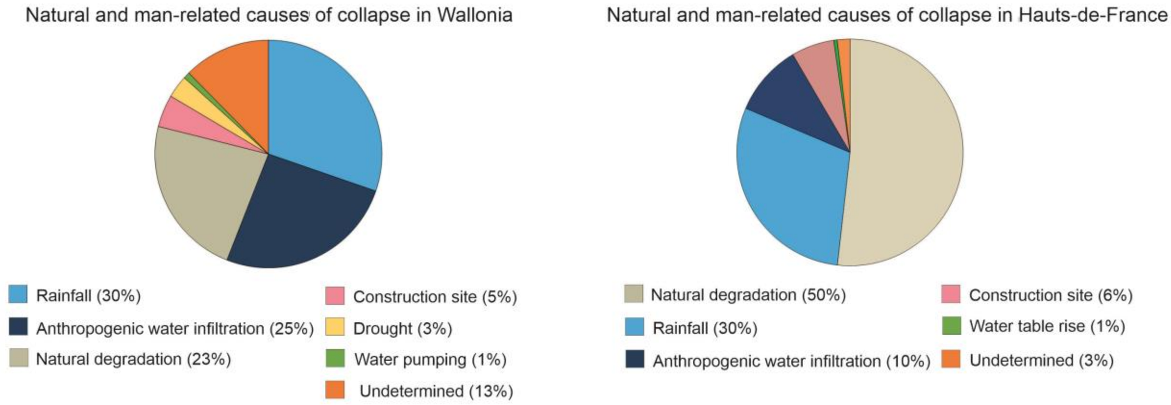

Figure 1: Identified causes linked to collapses recorded in the Walloon and French databases (Source: BRGM, SPW).

Assessment of the groundwater recharge processes of the Mio-Plio-Quaternary aquifer in the Bou-Omrane Bou-Saad Taleh region (Tunisian Southern Atlas) a hydrogeochemical and isotopic approach

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This study focuses on the impact of salinity, arid climatic conditions, and pollution on groundwater quality in the Bou-Omrane Bou-Saad Taleh plain, located in the Tunisian Southern Atlas. We investigate various sources of water salinization in our study area and examine the effect of arid climatic conditions. A thorough understanding of these factors is essential for effective water resource management and promoting sustainable use in the region.

The aim of this research is to characterize the hydrogeochemical and isotopic properties of groundwater, while assessing the recharge mechanisms in the region. Our methodological approach combines thorough investigation with multivariate statistical analysis, integrating hydrogeological, hydrogeochemical, and isotopic data.

Groundwater salinity and composition are primarily determined by the interaction between water and rocks. This process involves the dissolution of evaporite minerals and ion exchange. Additionally, salinity is influenced by the return of irrigation water and the use of agricultural fertilizers.

The results of hydrochemical analysis highlight a predominance of Na-Cl and Ca-Mg-SO4 hydrochemical facies. Overall, groundwater shows significant degradation and high mineralization, as evidenced by elevated concentrations of ions (Cl^-, $SO4^{2-}$, Na+, Ca^{2+}, and Mg^{2+}). Isotopic data from groundwater samples reveal average values of oxygen-18 (δ18O) of -6.75‰ and deuterium (δ2H) of -41.98‰, suggesting evaporation during recharge.

Collapse of the Schieburg tunnel (Luxembourg), geological causes and emergency safety work

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On 27 August 2022, a collapse occurred in the Schieburg tunnel in Luxembourg (built in the 19th century) during repairs to the vault, after a particularly dry period. Around 400 m3 of debris flowed out in a matter of seconds, completely blocking the tunnel and the only railway line serving the north of Luxembourg towards Belgium. The landslide occurred 60 m from the southern entrance, at a point where the overburden above the tunnel is 31 m, and under forest cover.

The geological and geotechnical studies carried out by our office included reconnaissance drilling with parameter recording to a depth of 80 m, geophysical prospecting using electrical resistivity tomography and seismic refraction surveying, and a structural study of all outcrops in the vicinity of the tunnel.

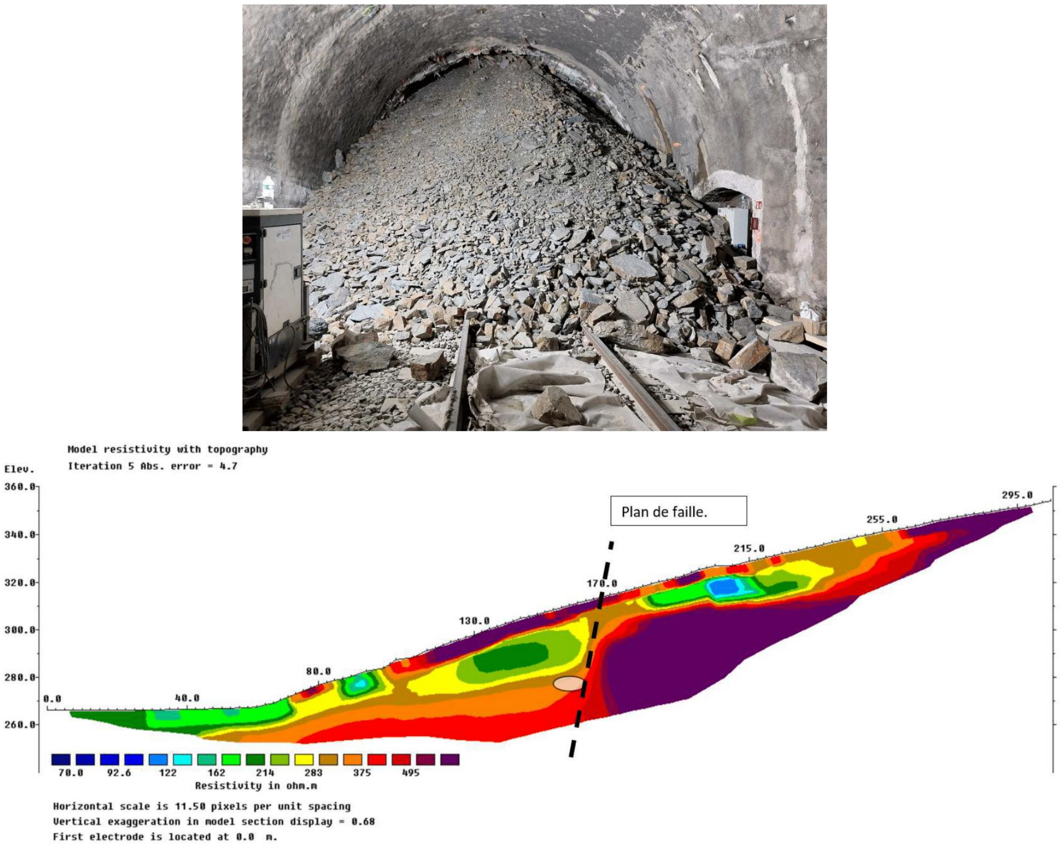
These investigations revealed a highly complex geological and hydrogeological situation, with the landslide zone located at the intersection of a system of conjugate faults not recorded on the geological maps. The results made it possible to estimate the volume and shape of the deconsolidated zone above the landslide, and to propose safety measures to reinforce this zone, safely remove the pile of scree and repair the damaged vault.

Safety measures consisted of injections and anchoring from the vault and from the surface. The final support system consisted of a metal T-beam and steel cleats. To comply with the CFL templates, the vault had to be partially sawn to accommodate the profiles.

In addition to the electrical and seismic surveys carried out during the study phase, electrical resistivity tomography was also used throughout the grouting phase to monitor the filling of the deconsolidated zone and assess the effectiveness of the reinforcement measures. The results also were used to refine the initial geological and hydrogeological model.

Geotechnical monitoring of the safety works was carried out from start to finish, enabling the tunnel to be reopened less than a year after the collapse, despite very difficult access conditions both for reconnaissance drilling and for carrying out the works.

In particular, this monitoring revealed significant water ingress during the works, which complicated the stability of the face and was one of the main causes of the rock deterioration.



Cone of scree just after collapse and electrical resistivity tomography showing the presence of a fault in the area of the collapse

Contribution to the study of the Ngovo endokarst network, Kongo Central, DRC

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Ngovo cave is located 8 km south-west of the town of Mbanza-Ngungu (Kongo Central, DR Congo), to the east of the ridge separating the Kwilu and Inkisi river basins. Most of the known caves in the region are located in the Kwilu basin, Ngovo, the largest cave known, being in the Inkisi basin. The cave is relatively sparse in speleothems, but is remarkable for its large chambers and a 25m-high waterfall. It also has an underground river whose source and outlet are still unknown.

Since 2019, a team of geologists from the GeoRes4Dev project of UNIKIN, UMNG and the RMCA, as well as independent speleologists, have been studying the cave in order to understand the evolution of its network.

Although a schema, probably drawn in the 1950s, was found in the collections of the Royal Museum for Central Africa (Belgium), its accuracy was not sufficient for our scientific purposes. A new map of the Ngovo network was produced during 4 field missions between 2021 and 2024.

This map highlights new connections with other caves in the area. It also makes Ngovo the longest known cave with the longest underground river in Central Africa. The study has also updated knowledge of the hydrographic network by establishing connections between the Kwilu and Inkisi basins, with implications for endemic fauna.

Ngovo Cave Waterfall. © H. Nkodia

Karst evolution in porous environments: evolution of the drainage network in the Boukadir carbonate platform, Algeria

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Porous carbonate soils give rise to unconventional karstic landscapes. The related diffuse infiltration is expected to impede karstification and the establishment of dense drainage networks. In such terrain, the effect of tectonics and climate on drainage development and evolution remains poorly understood. To illustrate this topic we focus on the Messinian tuffaceous carbonate platform of Boukadir, that present karstic feature and a dendritic network, located in the Chélif basin in Algeria, a zone of transpressive deformation linked to the Afro-Eurasian collision. By integrating geomorphological observations with morphometric analyses of the drainage network, we assess the impact of tectonics and climate on the evolution of drainage. Our study reveals variable tectonic deformation and morphological anomalies within the drainage system, characterised by a variable platform tilt and pronounced anomalies to the west. The genesis of these features may be due to factors such as differential compaction and remobilisation of the marlstones, in parallel with the recent propagation of the Boukadir fault beneath the platform.

Land Resilience after the shock of the Tigray war (northern Ethiopia)

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The Tigray war in northern Ethiopia has had significant environmental effects on the land, after two years of fighting, blockade and power outage (2020-2022). This study contrasts post-war observations at 56 sites in Tigray's Dogu'a Tembien district with 26-year legacy data on land degradation, a rare study conducted by the same research team before and after a war. Unlike the war and environmental catastrophe of the 1980s in Tigray, unsophisticated soil conservation interventions such as stone bunds, check dams and forest conservation have now acted as a vital buffer against the repercussions of the armed conflict. However, there have been significant geomorphic changes on battlefields and along the downriver banks. A durable community sense, strong land management ancestry and self-reliance, in combination with the absence of large influxes of internally displaced people as recorded elsewhere in Tigray, all have contributed to the observed land resilience.

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Detecting ground displacements by remote sensing within the possible future area of an Einstein Telescope near the eastern Belgian and southern Dutch border

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The Euregio Meuse-Rhine border region between Belgium (BE), the Netherlands (NL) & Germany (DE) is being considered as a possible location for the Einstein Telescope, which will become an advanced gravitational wave observatory. In the frame of the Interreg Einstein Telescope EMR Site & Technology (E-TEST) project, the complex and poorly known geological context of the BE-NL-DE transborder area of interest (AOI) was studied by numerous Belgian, Dutch and German project partners to demonstrate the feasibility of installation of such an infrastructure. In connection with the E-Test activities, the GERMANE project (Ground Deformation from Meteorological, Seismic and Anthropogenic Changes Analyzed by Remote Sensing, Geomatic Experiments and Extended Reality) was launched independently to study possible climatically and seismotectonically influenced ground deformation hazards impacting the AOI. This research focused on the detection of fine changes of displacement rates in space and time with the use of InSAR measurements near faults and on landslides located in the vicinity of the possible Einstein Telescope location. This study was combined with regional ground deformation measurements, especially applying the Persistent Scatterer Interferometry (PSI), Small Baseline Subset (SBAS) and Parallel Small BAseline Subset (P-SBAS) methods. Through these remote sensing analyses, slope deformation induced by seismotectonic activities and meteorological conditions were characterized, also using a data cube, from the ESA Climate Change Initiative (land surface temperature-LST) and scientists' researches (soil moisture-SM and precipitation-PR). The modelling part was combined with seismological and remote sensing results in an integrated model, which can now be visualised in Virtual Reality.

Concluding, very small mean ground deformation velocities of approximately 2 mm/year were observed within the Einstein Telescope prospection area during the study period (2016-2022). The main area of interest thus revealed to be relatively stable over the last decade. In addition, an insignificant impact of weather conditions on ground deformations was determined. The InSAR results and geological data were placed in the virtual environment to enhance the understanding of the three-dimensional deformation pattern, which may appear to be very complex due to the locally changing geological conditions. This research adds new information to the just completed Interreg E-TEST project and may be of use when the final location of the Einstein Telescope should be determined.

Inventory of Glacial Lakes and Susceptibility Assessment to Outburst Floods in the Kyrgyz Tien Shan Mountains

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In this project, we investigate the dynamics of high-mountain lakes and glacial lake outburst floods (GLOFs) in the northern Tien Shan region of Kyrgyzstan, Central Asia. The study is contextualized within the global phenomenon of glacier retreat, which leads to the formation and expansion of glacial lakes as glaciers lose mass. This phenomenon is a crucial indicator of climate change impacts on glacierized landscapes. The Kyrgyz Tien Shan is a hotspot for high-mountain risks despite its arid climate. GLOFs are common due to the extensive mountainous coverage and substantial glacial ice reserves. The study area, spanning over 280 km and encompassing 7520 km^2, is strategically selected for its proximity to the capital, Bishkek, and the renowned Ala-Archa National Park. This closeness amplifies the potential impact of GLOFs on urban and recreational areas, highlighting the necessity for thorough hazard assessment and proactive mitigation strategies.

To address the challenges posed by the large-scale coverage, the remoteness, and inaccessibility of glacial lakes, we employ an image segmentation method based on high-resolution optical satellite images, such as those from Landsat (Google Earth® imagery) and Sentinel-2. With this approach, we divide the images into distinct regions (water bodies vs. non-water areas) based on pixel intensity values derived from the Normalized Difference Water Index (NDWI). The integration of NDWI calculation based on spectral combination, thresholding, and validation in the mapping process provides a semi-automatic way to detect water bodies, including glacial lakes. Although this automatic classification method can expedite the detection of glacial lakes, it cannot be applied to the entire region due to uncertainties created by atmospheric and physical processes. In such cases, a manual delineation method has been applied for mapping lakes. A morphological classification of the glacial lakes was performed by manually overlaying high-resolution lake images with Advanced Land Observing Satellite (ALOS) terrain data. The lakes were categorized as moraine-dammed, ice-dammed, landslide-dammed, bedrock-dammed, or combined-dammed. Potentially hazardous glacial lakes were identified, and their levels of risk were assessed based on their physical attributes, the morphology of the dams, the characteristics of the source glaciers, and the surrounding environment. This method enabled the creation of a new inventory, including 960 glacial lakes with detailed quantitative information about their locations, geomorphic parameters, and spatial distribution. It aims to understand the physical properties and spatial distribution of glacial lakes, identifying those with the highest potential for GLOFs. Ultimately, this research refines existing knowledge regarding Kyrgyzstan's glacial lakes, enriching our overall comprehension of the impact of glacier retreat on vulnerable mountainous regions and guiding future monitoring and risk management efforts.

Characterisation of a landslide in the Flemish Ardennes, Belgium, using geophysical and geotechnical modelling

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UMons, Fundamental and Applied Geology, Civil engineering

In the Flemish Ardennes (Belgium), the occurrence of massive landslides has been known for a long time, mostly associated with the presence of clay belonging to the Aalbeke Member (Eocene). A recent collaboration between the Faculty of Engineering of the University of Mons (FPMs) and the Service Public de Wallonie (SPW) has focused on the characterisation of one of these landslides. The site is located along the N520 between the towns of Flobecq, Renaix and Brakel. The road is affected by the landslide and needs frequent repairs.

A geotechnical survey focused on the affected road section has been conducted by SPW. It included cone penetration tests, inclinometric measures and drillings. The results have revealed the location of the slip surface. However, the geometry of the landslide and its position relative to the geological units remained unclear.

A geophysical survey was conducted to provide observations over a broader area and try to better understand the context of the landslide. The geophysical acquisitions were made along two profiles. The first one is 232.5 metres long and the second one is 177.5 metres long. Both electrical resistivity tomography (ERT) and seismic refraction tomography (SRT) were conducted along these profiles. The acquisition geometries of ERT and SRT were designed in a way to facilitate combined processing and interpretation.

Open-source tools and in-house code were used to process and to invert electrical and seismic data independently. Discontinuities derived from the SRT inversion were then used to constrain a second inversion of the ERT datasets. The geophysical models were interpreted in the light of the geotechnical survey and regional geological, geophysical, and geotechnical data. The first aims were to try to identify the various lithologies and to locate the position of interfaces between lithological units. The location of the water table is also of interest. Based on this information, hypothesis about the landslide structure, including the position of the Aalbeke Clay were built and discussed.

Subsequently, slope stability modelling was carried out on the landslide model using Geo5 software. Information from the geophysical survey and geotechnical characterisation helped to implement the failure model. The simulations of several cases helped to better understand the mechanisms that can lead to failure.

Late Cenozoic evolution of the Variscan Rhenish/Ardenne Massif: from spatio-temporal patterns of river incision rates to Quaternary uplift history

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The Rhenish/Ardenne Massif (RAM) spreads across parts of Belgium, France, Germany and Luxemburg; it is one of the largest (>40,000 km^2) and most “emblematic” Variscan structures located north of the Alps (think of the “Romantic Rhine”). Intraplate uplift affected the RAM during the Plio-Quaternary along with other Palaeozoic massifs located in the alpine foreland. However, its cause(s), shape and rates are still poorly understood and therefore remain debated (e.g., Demoulin & Hallot, 2009). This was, until recently, mainly due to a lack of reliable ages for uplift markers, such as the Quaternary terrace staircases along deeply incised valleys of the Rhine, Moselle and Meuse as well as their main intra-massif tributaries. Several studies based on numerical dating methods (i.e., in situ cosmogenic nuclides, electron spin resonance, luminescence...) have shed new light on these questions by assigning numerical age estimates on key levels of fluvial terraces (e.g., the so-called main terraces; Rixhon et al., 2011; Cordier et al., 2012) or cave levels related to phases of regional base-level stability (Rixhon et al., 2020).

This contribution first compiles all chronological data produced over the last twenty years and critically assesses their reliability to infer massif-scale spatio-temporal patterns of river incision. Plio-Quaternary incision rates are accordingly reconstructed. A similar trend of increase is reported throughout the RAM with a peak of incision occurring during the Early or Middle Pleistocene and matching the massif-wide geomorphological marker materialised by the main terraces (and associated cave levels if any). However – and importantly – age control reveals a significant time lag (>250 ka) between the south-eastern and north-western RAM margins. The high incision rates onset is consistently older along the Rhine/Moselle and tributaries (e.g., the Sarre) than along the Meuse and tributaries (e.g., Ourthe). This key finding is well in line with Demoulin and Hallot’s (2009) hypothesis arguing for a wave of uplift migrating northward throughout the RAM. It also supports regional tectonic causes for uplift (i.e., late, upper-crustal stress transfer from the Alps to their foreland) rather than more local ones (i.e., mantle plume below the Eifel Massif). Age constraints along the river valleys draining the easternmost part of the RAM – so far absent – along with a global geodynamic modelling will represent further steps to better understand the evolution of the uplift history.

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Remote sensing of geohazards and geo-hydrological hazards in context of data scarcity: from local to regional assessments

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Earth Observation through space- and airborne imagery has become a common approach to detect, map, and measure surface changes or ground movements associated with geohazards and geo-hydrological hazards, such as, landslides, flash floods, earthquakes, and volcanic eruptions. In the context of data scarcity, remote sensing is an unvaluable approach to collect information about these hazards. However, research on such processes in such context remains overlooked and commonly challenging. In the present work, we show through examples how the use of imaging remote sensing allowed us to study geohazards and geo-hydrological hazards in poorly documented areas of tropical Africa, from individual features to regional distribution of hazard events.

With high to very high spatial resolution imagery coming from UAV surveys, collections of historical aerial photographs, and satellite acquisitions, we characterised site-specific topographic changes and ground deformation patterns associated with landslides and volcanic processes. SAR (i.e. radar) interferometry remote sensing was particularly useful for centimetre-scale deformation, while digital image correlation was used on both radar and optical data to characterise larger deformations. These multi-sensor time series allowed tracking magmatic intrusions, volcanic eruptions and lava accumulation in active volcanic zones. They also allowed deciphering the role of climate and urbanisation on ground deformation associated with large slow-mowing landslides.

At a regional scale, mixing both SAR and multispectral approaches allowed studying landslide-flash flood compound events to understand their spatial and temporal distribution with respect to climate and (human-induced) landscape drivers. Moreover, regional-scale historical photograph analysis allowed the reconstruction of multi-decadal forest cover changes and their impact on landslide risk.

The scarcity of data does not only affect the hazard processes, but also the elements exposed. The absence of a recent population census, for example, means that remote sensing can also be used to estimate the population and its distribution. However, all these remote sensing approaches come with limitations associated with the spatial, temporal and spectral resolutions of the imagery used, potential atmospheric disturbance, and the lack of complementary field observations in difficult-to-access areas. We circumvent some of these limitations with the use of a digital article analysis tool and citizen science to answer at best the need for data and scientific information in these regions of Africa, where populations are increasingly impacted by natural hazards.

Impact of hillslope thermokarst development on mineral-OC interactions: case study in Cape Bounty, Canadian High Arctic

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In the Arctic, recent studies show that air temperatures are rising up to 4 times faster than the global average. This polar amplification exposes permafrost – soil, sediment or rock frozen for at least two years – to thawing. This phenomenon could induce a permafrost-carbon-climate feedback, since it contains roughly half the soil carbon present in all other terrestrial biomes (0 - 3 m) and three times more than the carbon currently stored in the atmospheric pool. It is estimated that CO_2 and CH_4 emissions from the Arctic could add 55 - 230 Pg of carbon (in CO_2 equivalent) to the atmosphere, and must therefore be considered in climate models. These estimates are based on simulated volumes of organic carbon (OC) that will be exposed by the increase in thickness of the seasonally thawing active layer, through a process commonly referred to as gradual thawing. In order to refine these estimates, rapid thawing processes such as thermokarst, thermo-denudation and thermo-erosion – which could represent an additional release of greenhouse gases – should benefit from further studies. Here, we study two different types of hillslope thermokarst landforms: an Active Layer Detachment (ALD) which is a one-time event, and a Retrogressive Thaw Slumps (RTS) which repeats annually during summer months. In the Cape Bounty Arctic Watershed Observatory (Canada), we analyzed the total element concentrations, mineralogy, total OC and mineral-OC interactions within the headwalls of two disturbances, as well as within corresponding undisturbed zones. Our results show that 64 ± 10% of total OC is mineral-bound either as organometallic complexes, associated with mineral surfaces or physically protected in aggregates. In addition, there was a lower proportion of mineral-bound OC in the deeper layers exposed by the retrogressive thaw slump. These results therefore suggest that the OC exposed by thermokarst disturbances at Cape Bounty is largely protected by interactions with minerals, but that deep thaw features could expose OC more readily accessible to microbial degradation.

Regional environmental information, inferred from the Hotton Cave – Famenne-Ardenne UNESCO Global Geopark – Belgium

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The Hotton Cave, located in the UNESCO Global Geopark Famenne-Ardenne (Belgium) is a so-called swallow-hole-resurgence cave with an underground river, tributary of the Ourthe river. It develops in Givetian limestone (Calestienne limestone-belt). The cave consists of up to 5 levels of galleries in ~60 meters of limestone. A particularity of the cave is the 30 meters high underground canyon (Galerie du SCB) related to the vertical layering and multi-level karstogenesis favorizing collapses and leading to important voids. The cave is approximately 5 km long, including the ~1 km long touristic part.

Former studies lead by Yves Quinif dated speleothems and underlying river deposits of potentially MIS 15 to 11 in the upper levels, giving a minimal age for the nearby Ourthe river incision (Quinif, 1999). Current base-level, some 30 meters deeper is characterized by a ~20 cm-thick layer of decametric pebbles covered by sand and fine layered clay interpreted as the consequence of regular flooding during the Last Glacial period (Bessems, 1999).

New investigations in the cave, (LEAP project - Learning from the past - Impact of abrupt climate changes on society and environment in Belgium), focusses on environmental changes of specific periods (9.3 ka; 4.2 ka and 3.5ka). A flowstone located in a dry gallery, bypassing sump 2 in the Hotton cave is studied. The gallery is regularly flooded up to a certain level during rainy periods. During the exceptional 2021 rainy summer, even the pristine flowstone in the higher levels of the gallery, was covered by clay. A core taken in the flowstone displays several older clay layers. U/Th dating of the flowstone indicates older flood periods at ~1.5 ~ 2.0 ka; ~3.0 to ~3.5 ka; ~ 4.2 ka; and ~ 4.5 ka. A former studied stalagmite from the same gallery indicated regular flooding between 9 and 7.6 ka and at ~5.8 ka (Verheyden, 2012). Further work will extend the record to pre-anthropogenic times to investigate the anthropogenic impact on the sediment load of flood water related to soil erosion. Does the speleothem record all floods or only those where humans (over-)used the soil?

Studies in the Hotton cave demonstrate the long history of the cave, the important potential for the study of regional environmental and landscape evolution from MIS15 or beyond up to recent times.

°LEAP Project Members : K. Deforce & P. Pincé (RBINS), M. Boudin & M. Wojcieszak (KIK-IRPA), G. Capuzzo, P. Claeys, H. Leonard & C. Snoeck (VUB), P. Crombé, I. De Groote, G. De Mulder (U-Ghent).

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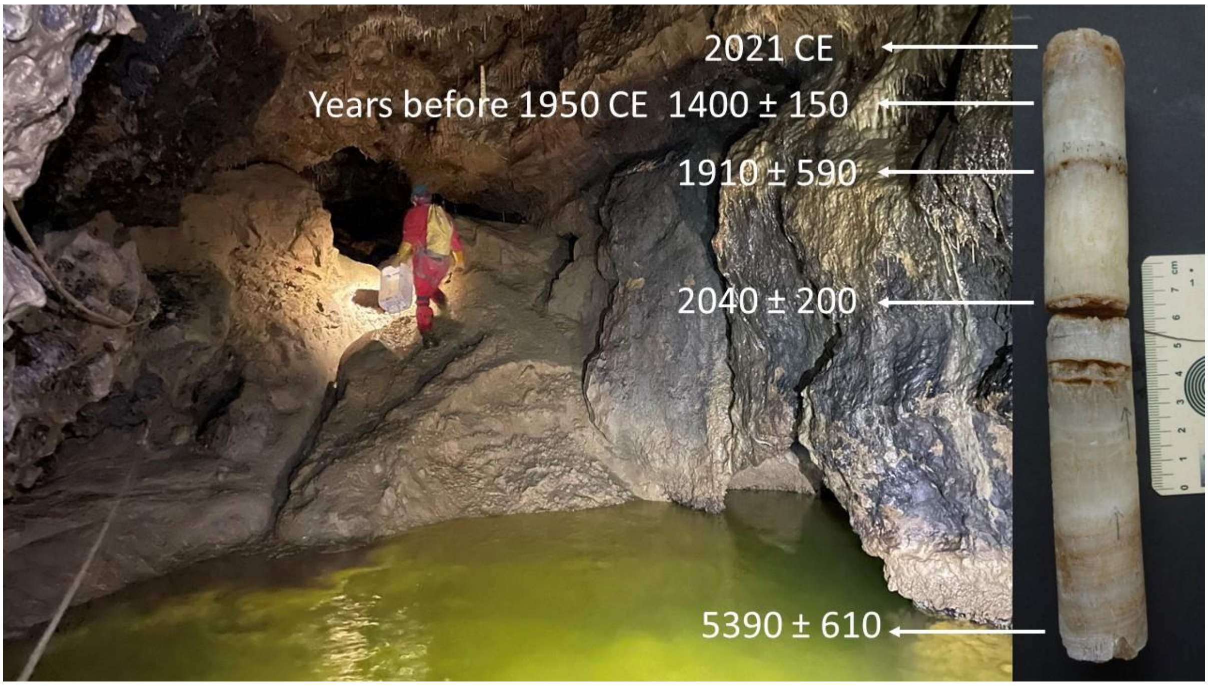

Figure: Hotton cave, Belgium. Profile of the core sample taken in the flowstone covering the sediments in the gallery above sump 2 with ages of the clay layers incorporated in the flowstone and related to successive floods.

Green color of speleothems explained by the presence of Ni-rich serpentinite

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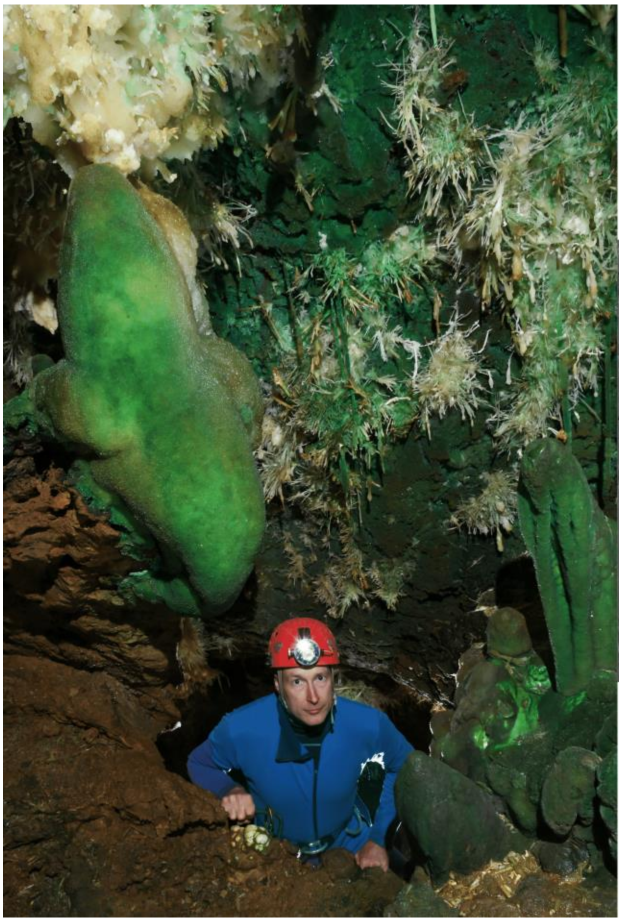
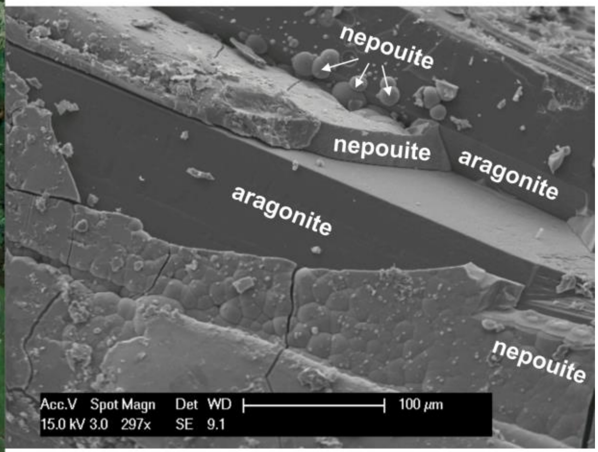
Speleothems, commonly called stalactites and stalagmites, are secondary mineral deposits usually composed of calcite or aragonite and typically found in karstic caves. Despite being naturally white when pure, some might exhibit unusual colors, such as red, black, blue, yellow, purple or green. The causes of these exceptional colorations are various and can be due to the presence of metals substituting for Ca in the aragonite, the presence of foreign mineral phases and/or organic matter, or light wave interferences due to the mineral structure. Among colored speleothems, the green ones are especially poorly understood, because they are extremely rare, hard to reach and barely reported in the literature. For the first time, we describe Ni-bearing nepouite in green aragonite and calcite speleothems, in the Aven du Mont Marcou (Hérault, France). Nepouite is mainly found as flat green lamellar crystals in the outer rim of green speleothems and crystallized alongside radially grown aragonite crystals. Our observation shows that nepouite began to crystallize near the end of the speleothems' growth, due to a change in the chemical composition of the water leaching in the cave. The nepouite from the Aven du Mont Marcou also exhibits extensive substitution between Ni, Mg and Zn. The chalcophile elements responsible for nepouite precipitation (i.e. Ni and Zn) are thought to come from the weathering of pyrite crystals in the overlying rocks, which is consistent with the pH conditions of the cave and the Al-free composition of nepouite. This work will be followed by other studies on colored speleothems, such as blue stalactites from Malaval Cave (France) which seem to be linked to the presence of Zn and Pb-bearing minerals, or red and yellow-colored concretions from Belgian caves that might be caused by the presence of organic matter. These hypotheses will be further investigated.





Left: The Green Room in the Aven du Mont Marcou. Right: Secondary electrons view of nepouite crystals deposited on aragonite crystals.

Correlation between ground surface subsidence and groundwater level trends in the deep aquifer system in western Flanders

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During the last three decades, land subsidence has been affecting several towns of the Belgian Provinces. Groundwater over-exploitation and recharge may have caused subsidence and uplifting of the ground surface. In the western part of Flanders, long and intensive exploitation of the deep aquifer systems (DAS) in the Paleozoic basement, Cretaceous and Landenian aquifers has led to very low piezometric levels and the development of regional-scale deep depression cones. The groundwater over-exploitation due to the economic boom of the 1960s has generally been thought to cause land subsidence. Lowering of the piezometric levels by more than 100 m must have caused compaction of the pumped layers and possibly also the overlying thick aquitard. The combined effect of the compaction in all the affected layers results in land subsidence on a regional scale, considering the spatial extension of the enormous depression cones. In this study, a correlation between INSAR image-derived land subsidence rates and piezometric level trends is established. The land subsidence is quantified using a 3D-groundwater flow model of the DAS and a module for simulating layer compaction and land subsidence for the aquifers, and a 1D column model for assessing compaction of the Tertiary clay. The model results show that the high subsidence rates in the NW part of this region are likely related to the intense groundwater exploitation in the Landenian aquifer. However, the high subsidence rate in the SE zone is not correlated to the Landenian aquifer exploitation, which may be related to an underestimation of the extension of the Landenian depression cone in the DAS model by local non-licensed groundwater exploitations. No spatial correlation with the deep regional piezometric depression cone in the Paleozoic basement aquifer is observed, despite the large drawdowns (> 100 m). The hard rigid rocks in the basement must have a very low elasticity and thus very limited compaction. The result of the 1D column model shows possible compaction of the Tertiary clay by pumping from the underlying Landenian aquifer. It shows that compaction can continue even when groundwater levels in the Landenian are rising again or have stabilized. The 3D groundwater flow model for DAS does not reproduce the piezometric depression cone in the Cretaceous aquifer as it is observed in the monitoring network. This could likely be due to the presence of an important data gap in the pumping rates that were used in the model.

Groundwater flow modeling and surface-groundwater interaction of Lake Tana Basin, northwest Ethiopia

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Lake Tana, with its surface area of around 3,077 km2, occupies a significant part of the Lake Tana Basin area (15,089 km2) located in northwest Ethiopia. This account for 20.4% of the areal extent and means that the overall water balance of the catchment strongly depends on the water balance of the lake itself. Therefore, the groundwater balance of the whole catchment cannot be considered independently from the water balance of the lake and an integrated approach is needed, which incorporates exchange fluxes between groundwater and lake system. A conceptual water balance of the basin is constructed which defines the different components. Components that could be quantified based on available field data or derived from them on one side, and on the other side components that could only be obtained only from model calculations as these are not related to physical quantities that can easily be measured. The groundwater flow model, MODFLOW is used to integrate the different components of the groundwater flow system, while the Modflow LAKE module was used to incorporate the Lake Tana water balance. The combination allowed quantifying exchange fluxes between both systems. The WetSpass model was used to calculate groundwater recharge rates and surface runoff from meteorological and land data, and a baseflow/runoff separation program estimated baseflow and runoff rates from streamflow data. These were used to defined the Modflow boundary conditions. The Modflow model used a discretization into an upper and lower aquifer layers. The simulated piezometric levels approach the global piezometric pattern as seen in observation wells. In the water balance it can be seen that the stream inflow is about 62% of the total inflows into the lake. This river inflow consists of 60% baseflow as can be seen in the gauged sub-catchments. The other 40% may be highly variable with time as it is surface runoff depends on rainfall variation. Groundwater inflow is largely by means of baseflow contribution from the streams draining into the lake and not by direct subsurface inflow from the surrounding aquifers. However, as this water balance component is small compared to the other components, a large error may exist on its estimation.

Keywords: Lake Tana Basin; Modflow; GMS; water balance; lake-groundwater interaction; river-groundwater interaction.

Towards quantitative evaluation of the spatiotemporal rupture variability of megathrust earthquakes in south-central Chile using lacustrine sedimentary records

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In 1960, the Valdivia segment of the Chilean subduction zone hosted the largest earthquake that has so far been instrumentally recorded (Mw 9.5). Paleoseismic studies have revealed that such a ~1,000 km long rupture was not unique in the region and occurs on average once every ~300 years. These so-called full-segment ruptures alternate with more frequent great partial ruptures, which affect only one or few megathrust asperities. Their contribution to the overall stress release and how this affects the recurrence of full ruptures, however, remains unclear. This is mostly because most of these occurred in pre-instrumental times, leaving their along-strike extent and down-dip location poorly constrained. Comprehensive studies evaluating the spatiotemporal rupture variability are thus crucial to validate earthquake cycle models and improve seismic hazard assessment in south-central Chile. In this respect, lakes have been extensively studied in the region, as they provide highly sensitive shaking records by identification of turbidites, mass transport deposits or in-situ soft sediment deformation structures in their sedimentary infill. So far, this allowed for paleoseismic reconstructions covering the last two millennia. A thorough understanding of the relation between the component(s) of earthquake strong ground motion (e.g., PGA, PGV, duration) and their resulting sedimentary signature in lakes is, however, still missing. As a result, characterization of the source parameters of paleo-earthquakes, such as magnitude and rupture extent, up to now relies solely on qualitative or semi-quantitative considerations.

Here, we present some preliminary results from a newly obtained long lacustrine turbidite record from Lago Rupanco. As this record likely covers the last ~6,000-8,000 years, it can significantly extend the existing timeframe for the recurrence of 1960-like earthquakes as well as smaller partial ruptures, while also recording intraplate events. We consider that cumulative turbidite thickness, representing turbidite volume, is a good (relative) measure for the local shaking strength as empirically confirmed by a previous comparative study in several Chilean lakes based on event deposits of different types of earthquakes.

Therefore, it can be used to discern deposits resulting from past strong shaking from those that can be attributed to lower shaking strength, either originating from distant large earthquakes or smaller nearby events. Moreover, we found that the rather subjective macroseismic intensity values that have been considered so far can be approximated by a combination of PGV and shaking duration, opening perspectives towards quantitative characterization of the identified paleo-earthquakes. To strengthen our inferences, we correlate the Lago Rupanco record to other long lacustrine records in the region by matching geochemically identified tephra markers. In this way, we can more confidently distinguish between intraplate and interplate earthquake source mechanisms, allowing us to further constrain the long-term spatiotemporal variability of megathrust earthquakes along the Valdivia segment of the Chilean subduction in a quantitative way.

SESSION 3 - PLANETS, MAGMAS AND VOLCANOLOGY

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Igneous activity has affected all terrestrial planets as well as some satellites of gas giants. On Earth, the compositional variability of magmas is large and depends on the nature of the source, the conditions of partial melting as well as the on the effects of magmatic differentiation processes, such as crystal fractionation, mixing and assimilation in the crust and the mantle. On other planets, magmatic processes are linked to primordial crust formation during magma ocean solidification followed by mantle melting largely driven by cumulate overturn or simpler mantle convection.

In the last decade, abundant rocky exoplanets were discovered in our galaxy. Some of them had or still hold a magma ocean, possibly resulting in the formation of volcanic atmospheres. Recent satellite measurements of super-Earth planets detected a basaltic surface.

This session will highlight research on magma generation and differentiation starting from the formation of the solar system and meteorites, the partial melting of the mantle and crust formation on Earth and other terrestrial planets. We also welcome contributions on exoplanet evolution and magma-atmosphere interaction.

Invited Speaker

The effect of water on alkali trace element diffusion (Li, Rb, Cs) in silicic melts

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Trace element diffusion is a powerful tracer of kinetic magmatic processes such as recharge and fluid exsolution. However, the dependence of diffusivities (D) on melt water contents is poorly quantified, and most trace element diffusivities were determined in water-free melts unrealistic for most natural magmatic systems. Here, we investigate the diffusion of the alkali trace elements Li, Rb, and Cs as a function of water content in rhyodacite, high-silica rhyolite, and peralkaline rhyolite. For the diffusion experiments, homogenous hydrous glass cylinders were produced from trace element-doped and undoped powdered glass with 1–8 wt% H2O. Glass cylinders with the same water content but different trace element concentrations were paired along polished contact surfaces. Diffusion experiments were conducted between 720 and 1100 °C at 100–700 MPa for 5–25 min using gas pressure vessels or a piston cylinder apparatus. Resulting diffusion profiles were analyzed by LA-ICPMS and evaluated by a Monte Carlo iterative fitting procedure for full error propagation. At a given experimental temperature, measured log10D values increase linearly with melt water content, with one order of magnitude increase for Li, two orders for Rb, and three orders for Cs from least hydrous (1 wt%) to wettest (8 wt%) experiment, due to a linear decrease in activation energies. Variations in major element composition only have a minor effect. We illustrate the impact of differential diffusion in hydrous silicic magmas on their trace element budget by coupling our data to a two-phase mechanical model of channelized fluid transport in magmatic systems. Quantifying water-dependent diffusivities provides an important tool to track the exsolution, mass and rate of fluid transport within long-lived shallow mushy magma reservoirs in the Earth’s crust.

Troch J, Huber C, Kueter N, Guillong M, Ackerson MR, Ulmer P, Bachmann O (2024) The effect of water on alkali trace element diffusion (Li, Rb, Cs) in silicic melts. Geochimica et Cosmochimica Acta 365: 101-113.

Residence time of magmas in subduction zones from crystal size distribution: Application to the Chilean volcanoes Osorno, Calbuco, and Villarrica

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Time is a crucial parameter for assessing pre-eruptive dynamics, including the storage of crystals in the magmatic system, the dynamics of ascent, or the cooling of lava flows at the surface. Time has been estimated using different techniques, such as uranium-series disequilibria, diffusion zoning in crystals, or crystal size distribution (CSD) analysis. This latter method was first applied in a geological context by (Marsh, 1984; Cashman & Marsh, 1984). It is based on a steady-state population balance where the crystal population is characterized by the proportion of crystals in each size category. The slope and intercept values of these CSDs provide access to growth and nucleation parameters, respectively. When the growth rate parameter is known, CSD plots can also be used to constrain various magmatic processes, such as magma ascent or the residence time of crystals in the system.

If the data necessary for the development of CSDs are easily accessible by scanning thin sections, the results will strongly depend on various parameters: (1) the quality of segmentation (separation of syneusis/agglomeration textures), (2) the various magmatic processes involved in the nucleation and growth of crystals, and (3) the growth rate considered. Some experimental studies, such as those by (Billon et al., in preparation; Brugger & Hammer, 2010b), have estimated growth rate values that can range between 10-6 to 10-09 cm/s for basaltic/andesitic composition and down to 10-11 for dacitic composition, depending on the composition and calculation method used.

We propose here to estimate the plagioclase residence time in the main magmatic reservoirs of three different volcanoes (Osorno, Calbuco, and Villarrica) from the Central Southern Volcanic Zone of Chile (CSVZ). These three volcanoes, located within the same region, exhibit different eruptive conditions, partly due to variations in their water content. For this study, thin sections of samples ranging from basalt to dacitic compositions have been segmented for each volcano. Particular attention has been paid to the separation of the different crystals, particularly in the syneusis/agglomeration textures. The calculated crystal size distributions (CSDs) have been used with different growth rate values to constrain the residence timescales. Results indicate that the durations obtained with the CSD method (<<10-01-10+02 years) are several orders of magnitude lower than those obtained with the Sr diffusion (10+02-10+03 years) and Uranium series (10+03-10+05 years) methods (Cooper & Kent, 2014). The uranium series provides an overall absolute residence time, while the Sr diffusion and CSD methods measure only the various stages of growth. Additionally, several processes may alter the growth process: (1) a too low temperature (T < Tsolitus), resulting in high viscosity and cessation of growth; (2) too high a temperature (T > Tliquidus), resulting in crystal dissolution; and (3) critical crystallinity achieved.

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Plagioclase growth and nucleation rates in an anhydrous arc basaltic andesite

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Crystallization in magmas, marked by chemical and textural changes, is responsible for the transition from a silicate melt to a completely solidified rock by two main processes: nucleation (J), which corresponds to the formation of initial crystals, and growth (G) of these nuclei that increases the mineral/melt proportion (Cashman, 1990). Numerous experimental studies have been realized to constrain these two processes using different crystallization paths (cooling, decompression, or isothermal crystallization) (Brugger & Hammer, 2010b; Shea & Hammer, 2013), a range of initial compositions (basalt, dacite, trachyte) (Brugger & Hammer, 2010b; Pupier et al., 2008), and focusing on several phases (plagioclase, pyroxene, olivine). However, only a few studies were performed on a basaltic andesite, a common rock in arc volcanic zones.

Here, plagioclase nucleation and growth rates have been experimentally investigated in a basaltic andesite from Osorno volcano (Central Southern Volcanic Zone, Chile). A series of experiments were performed at 1 atm under anhydrous conditions at the Ni-NiO oxygen buffer and with low cooling rates (1°C/h, 3°C/h, 9°C/h). After an initial equilibration at 1190°C (10 °C above the liquidus) for 24 hours, the samples were cooled at different rates and finally quenched at various temperatures from 1165°C to 1000°C. Contrary to many studies, no high-temperature pre-heating was applied in order to preserve some pre-existing plagioclase seeds and to avoid nucleation delay. The main objective was to constrain the plagioclase nucleation and growth rates in these conditions and to compare growth results with literature data to identify the experimental parameters controlling crystal growth. Nucleation and growth rates were calculated considering various methods: Batch (characteristic size obtained as a ratio between the proportion of crystals and their number in the sample), lmax (average size of the 10 biggest crystals), and CSD (proportion of crystals per size ranges) methods.

Despite strong variability of the 2D aspect ratio in the same run, the crystal shape and size are correlated during their growth, with the smallest (< 10 µm) and biggest crystals (> 30 µm) displaying respectively an equant/elongated and tabular/bladed 3D shape. Plagioclase shape varied also with the cooling rate, from 2D tabular/elongated crystals at 1 and 3°C/h to hopper and swallowtail aspect at 9°C/h, suggesting a transition from interface- to diffusion-controlled growth. The nucleation and growth rates respectively comprised between 10+01-10+04 cm-3/s and 10-07-10-09 cm/s, show both a maximum close to the liquidus followed by a general decrease with cooling. This decrease becomes minimal at slow cooling rates, resulting in nearly constant G over time (after about 20 hours of cooling).

The growth rate values estimated in this study are similar to those of (Kohut & Nielsen, 2004; Shea & Hammer, 2013) with basaltic/andesitic composition, but two orders of magnitude higher than data obtained for dacitic composition (e.g. Brugger & Hammer, 2010b). It appears that the growth rate values mainly depend on the crystallization path followed (e.g. cooling/decompression rate, superheating), and the calculation method considered (lmax VS Batch methods).

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What modulates eruptive styles at Villarrica and Osorno volcanoes (Chile)?

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Villarrica and Osorno are two active stratovolcanoes in the Central Southern Volcanic Zone (CSVZ) of the Chilean Andes that share several geochemical characteristics: near-primary, tholeiitic parent magmas (50-53 wt. % SiO2), overlapping major/trace element differentiation trends, and comparable storage conditions [1-4]. Yet, their eruptive styles contrast each other significantly. Villarrica is a steady-state, open-vent stratovolcano with a lava lake since 1985, which produced ~100 low to moderate intensity Strombolian eruptions and lava flows since 1579 CE. Osorno is a closed-vent stratovolcano with 10x less eruptions for the same period. We initially proposed that differences in eruptive style and frequency could be due to a relatively higher degree of crustal permeability under Villarrica than Osorno due to the Liquiñe-Ofqui Fault Zone [5]. Preliminary analyses show that both volcanoes have broadly similar olivine chemistry ranges and multimodal distributions, with minor differences in olivine and melt chemistry/textures between Villarrica (Fo72-87) and Osorno (Fo66-82) [4,5]. Diffusion timescales for both volcanoes are mostly < 150 days, with few crystals recording > 250 days. This suggests the degree of crustal permeability underneath the volcanoes are likely comparable, prompting consideration of other factors. In this contribution, we evaluate the role of magma supply rate, storage conditions, and slab input in modulating eruptive styles at Osorno and Villarrica based on an updated dataset of magma storage conditions, diffusion timescales, geochemical data compilations, and inferences drawn from published literature. We find that magma storage conditions of both volcanoes are similar to each other at T~1100°C, P~200 MPa, along with comparable input of fluids released from the down-going slab. The multimodality in olivine chemistry, diversity in types of olivine growth zones and textures, timescale ranges, coupled with the relatively high magma supply rate estimates for Villarrica from the literature suggest magma supply rate could modulate eruptive style at Villarrica and Osorno. With this contribution, we aim to further current understanding of subduction zone magmatism and geodynamics, with implications on volcanic hazard reduction.

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Trace element partitioning between apatite and silicate melts

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Apatite [$Ca_{10}(PO_4)_6(F, Cl, OH)$] is a ubiquitous mineral in igneous, metamorphic, and sedimentary rocks. Its crystal structure can accommodate a variety of trace elements. As a common accessory phase, apatite is weakly affected by later alteration, preserving information about the parent magma and making it of significant importance in petrology. When tracing magma evolution based on the composition of apatite, it is necessary to elucidate the partitioning behavior and controlling factors (P, T, fO_2, and crystal-melt composition) of various elements between apatite and melt.

To better constrain the trace elements partitioning between apatite and silicate ± carbonatite melts, we conducted experiments at pressures of 5 kbar and temperatures of 960-1100 ℃ in a piston cylinder apparatus, and run products were analyzed for trace elements by laser ablation inductively coupled plasma-mass spectrometry (LA-ICP-MS). We report new experimental apatite/melt partition coefficients for a wide range of trace elements (REEs, Rb, Ba, Y, Sr, Zr, Hf, etc.). Using these measured trace element partition coefficients, we established a lattice strain model formalism for apatite and silicate melts, allowing us the estimate the physical properties of the crystallographic sites hosting the trace elements. Combining our results with previously published data, we propose a general model to predict partition coefficients between apatite and alkaline melts under a wide range of P-T conditions.

Olivine and their Cr-spinel inclusions to determine the liquidus temperatures and mantle source composition: the example of the Southern Volcanic Zone of the Andean arc

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Informations about the mantle sources and their melting conditions can be obtained from the composition of liquidus phases of the mantle melts. In basalts, forsteritic olivine and Cr-spinel usually crystallize first and are stable together on a restricted range of temperatures. Their compositions have thus recorded the geochemical signature of the parent/near primary magmas and of the liquidus temperature. In this study, we have analyzed 150 olivine-Cr spinel couples from pyroclasts collected in four different subduction zone stratovolcanoes (Osorno, La Picada, Villarrica, Mocho Choshuenco) and two of their associated Minor Eruptive Centers (MEC) (Cordón Cenizos, San Jorge) belonging to the Southern Volcanic Zone (SVZ) of the Andean arc (Chile). Temperatures have been calculated with the empirical regression of Coogan et al (2014), which takes into account the Al exchange between the two phases and the spinel Cr# (molar Cr/Cr+Al), and with the three equations recently proposed by Zhang et al. (2023). The first is a thermodynamic formalism comprising spinel compositional parameters (Si, Ti, Fe, Mg, Cr, Al, Mn), the second is a refinement of the Coogan's model based on a more extended experimental database and in the last one, the possible coupled substitution of Al and Cr in olivine is considered. The thermodynamic model includes the Fe-Mg exchange in spinel whereas one of the empirical regressions depends on Cr substitution in olivine. As both are sensitive to re-equilibration, the temperatures are possibly underestimated. When considering the highest temperature obtained in each sample for each equation (Osorno: 1131-1255°C, La Picada: 1060-1280°C, Villarrica: 1102-1197°C, Mocho Choshuenco: 1070-1157°C, Cordón Cenizos: 1031-1133, San Jorge: 1177-1283°C), results from the different geothermometers usually overlap when errors are considered and are close to the temperatures derived from petrological data. The trace element (Ni, Ca, Mn) composition of olivine (Fo90-76) indicates a peridotitic mantle source for the different volcanoes: NiO (0.09 – 0.035 wt.%), MnO (0.15 – 0.36 wt.%) et CaO (0.14 – 0.45 wt.%). Finally, the H_2O content of the parent magma calculated with the Gavrilenko et al. (2016) regression which is based on the partition coefficient of CaO between olivine and melt gives H_2O contents that are usually higher than those derived from petrological data except for Mocho-Choshuenco (2.6-6 wt.% H_2O).

Formation of intermediate to felsic crustal plateaus on Venus: Is water required?

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The observation of low viscosity lava flows and shield volcanoes on radar maps, combined with in-situ X-ray fluorescence analyses performed by three Soviet landers, strongly suggests that Venus' crust is primarily basaltic. Still, some of the most intriguing features of Venus are its crustal plateaus, characterized by heavily deformed terrains, which have long been suggested to bear a superficial resemblance to Earth's continental crust and mountain ranges. Infra-red emissivity spectra from the Galileo and Venus Express missions tend to support the presence of a larger fraction of felsic minerals in the plateaus compared to the surrounding basaltic plains [1-2].

On Earth, flux melting of the mantle wedge at subduction zones, followed by fractional crystallization or partial melting of hydrous basalts, are believed to be the two primary mechanisms generating the large volumes of intermediate to felsic rocks that make up the continental crust. By contrast, igneous differentiation of water-poor basaltic melts typically yields negligible amounts of felsic melts. The possibility that highland plateaus are dominated by intermediate to felsic rocks will be evaluated by the EnVision and Veritas missions, in the hope of providing evidence for the presence of water oceans and, therefore, habitable conditions in Venus' distant past.

In this work, we show, using thermodynamic calculations (Perple_X), that the melting of dry eclogite is another viable mechanism that can produce large volume of intermediate to felsic melts, in the absence of water. An average basaltic crust, of composition identical to the ones analyzed at the Venera 14 and Vega 2 landing sites, would transform to a quartz eclogite at a depth of 50 to 60 km. Partial melting of this material can produce 15-25 % of dacitic melts. The crust of Venus could have reached this depth under crustal plateaus, according to gravity and topography investigations [3]. It has also been suggested that the current young surface of Venus could indicate that abundant basaltic material was recycled to the mantle [4]. Remelting of this material could fuel occasional but large-scale magmatic events and account for the formation of felsic crustal plateaus in the absence of water. Confirmation that crustal plateaus are dominantly felsic by future missions might therefore not necessarily indicate that wetter and more hospitable conditions prevailed on early Venus.

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The conditions of differentiation in the main storage reservoir beneath the Mocho-Choshuenco volcano (Southern Volcanic Zone, Chile)

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Volcanism along the Andes results from the subduction of the Nazca and Antarctic plates under the South American plate. Mocho-Choshuenco is a Chilean volcano located in the Central Southern Volcanic Zone (CSVZ). Formed during the late Pleistocene to early Holocene Period, this volcano has been highly explosive ever since. The combination of this explosivity and the rapidly increasing population in the region makes Mocho-Choshuenco a hazardous volcano. Therefore, tighter constraints on its magmatic system are needed. To achieve this, a selection of tephra from different eruptive events of Mocho-Choshuenco was analyzed to determine the pre-eruptive conditions (P, T, % H_2O and fO_2) of the magma reservoir. Various geothermobarometers based on mineral–liquid equilibria were used to estimate these parameters. Pressure was calculated using different geobarometers (clinopyroxene-liquid, clinopyroxene only and amphibole only) with average values ranging from 1.4 to 2.8 kbar (approximately 7 km depth). Temperatures were estimated to range from 1012°C to 1215°C using models based on clinopyroxene- and olivine-liquid equilibria. Amphibole appears to be a late crystallizing phase, as lower temperatures were deduced from its composition, and the calculated composition of melts in equilibrium with amphibole are SiO_2-rich. The amphibole composition also allowed for the estimation of an oxygen fugacity of about NNO+1.6 and a water content of 5.8 wt. % in the evolved melts. The water content of the parental magma was further calculated with the Rayleigh's distillation law at about 3 wt. %. This water content is higher than those estimated for nearby volcanoes such as Osorno and La Picada but is similar to the value obtained for the parent magma of Calbuco.

Petrography and geochemistry of Martian basaltic impact structures analogues (Vargeão Dome, Vista Alegre, Brazil; Lonar Crater, India)

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Impact cratering is a fundamental process in the Solar System, with collisions strongly influencing both the evolution of planets and the development of life throughout their evolution history. Impact structures and craters resulting from these collisions are preserved on all rocky and icy bodies and represent the most common geological landform at their surfaces. Nevertheless, processes such as erosion, tectonic deformation or burial tend to reduce the number of impact structures on Earth, leaving gaps in the impact cratering record of the terrestrial surface. In contrast, the surface of Mars is covered by 60% of early, ancient Noachian crust and the impact cratering history of Mars is well preserved. The Martian crust is currently the centre of interest of the NASA-ESA Mars Sample Return missions, drilling and collecting samples from Jezero crater. As the majority of the Martian surface is covered in volcanic or volcanically sourced sedimentary units, terrestrial impact craters and structures formed in basaltic target rocks represent excellent analogues to study Martian planetary surface processes and products, although such sites remain relatively rare on Earth.

This work focuses on three basaltic impact structures: Vargeão Dome (Brazil, 12.4km diameter), Vista Alegre (Brazil, 9.5 km diameter, and the Lonar crater (India, 1.88 km, 570 ± 47 kyr3), with the aim to understand impact-related processes affecting basaltic targets based on detailed petrographic, bulk geochemical, and isotopic analyses.

The different types of impactites (monomict and polymict impact breccias, both melt-bearing or not and lithic) have been petrographically studied to trace impact-induced processes such as shock, melting and mixing of the targets to better understand how impact events affect basaltic target rocks and their associated minerals. Bulk geochemical compositions (major and trace elements) have also been determined to trace variations induced by impact processes, but also to evaluate the level of post-impact alteration (impact-induced or not), before applying less conventional stable isotope systems (e.g., Fe, Cu, Zn, Ge) to trace the thermodynamic history of the studied lithologies.

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High CO2 contents in magmas of Mocho-Choshuenco volcano (Chile): insights from melt inclusion analysis of the sub-Plinian Enco eruption

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Mocho-Choshuenco volcano has produced several highly explosive eruptions during over the past 18 ka, which make it one of the most hazardous volcanoes in the southern volcanic zone of Chile. However, this volcano is still relatively little studied to date, and detailed characterizations and trigger mechanisms of its sub-Plinian to Plinian eruptions are needed.

The present work focus on a geochemical study of the products of the sub-Plinian, andesitic, Enco eruption that occurred ca.1600 years ago. Major and trace elements compositions, as well as the volatile (H_2O, CO_2, Cl, and S) contents of melt inclusions (MIs) trapped in minerals (olivine, plagioclase, and pyroxene) were determined using electron microprobe, ion microprobe (SIMS), and 3D confocal Raman mapping.

Though the whole-rock composition of the Enco magma is andesitic (60.2 ± 1.1 wt.% SiO_2), the melt inclusions have SiO_2 contents ranging from 50.3 to 67.3 wt.%, following the magmatic series of Mocho-Choshuenco. Two main "clusters" can be identified: (1) the olivine-hosted MIs with basaltic to basalte-andesitic compositions (50.3–55.9 wt.% SiO_2), and (2) the pyroxene- and plagioclase-hosted MIs with andesitic to dacitic compositions (56.3–67.3 wt.% SiO_2). The compositions of the most mafic MIs are close to those of the most mafic erupted magmas. Geochemical modeling of major and trace element compositions indicates that mixing occurred between a mafic magma and an andesitic-to-dacitic magma.

In melt inclusions, glass analysis revealed typical parental arc magma values for H_2O (2.6–3.8 wt.%), S (116–1936 ppm), and Cl (620–1439 ppm). However, CO_2 contents in the glass are very high in some melt inclusions with concentrations up to 2836 ppm in olivine-hosted MIs and more than 4000 ppm in plagioclase-hosted MIs (4213 and 4430 ppm measured in two MIs). These suggest trapping depths >~ 17–22 km. Presence of solid carbonates inside inclusion-hosted bubbles clearly indicates that the CO_2 contents measured in the glass phase were minimum values. Corrections were applied to take into account the CO_2 trapped in MI bubbles, showing that 41 to 93% of the total CO_2 amount can be trapped in the MI bubbles.

We conclude that a CO_2-rich basaltic magma ascended and mixed with a shallower andesitic magma. The magma cooled and exsolved high amounts of CO_2, which may have dramatically increased the pressure and triggered the highly explosive Enco eruption. Additionally, a CO_2-flushing event cannot be excluded. Questions remain regarding the origin of the CO_2 in the magma (crustal assimilation of carbonate material? from the subducting lithosphere?...) and if other explosive eruptions from Mocho-Choshuenco were also characterized by the emission of CO_2-rich magmas.

Feignon JG, Cluzel N, Schiavi F, Moune S, Roche O, Clavero J, Schiano P, Auxerre M (2022) High CO_2 content in magmas of the explosive andesitic Enco eruption of Mocho-Choshuenco volcano (Chile). Bulletin of Volcanology 84:40, 20 p.

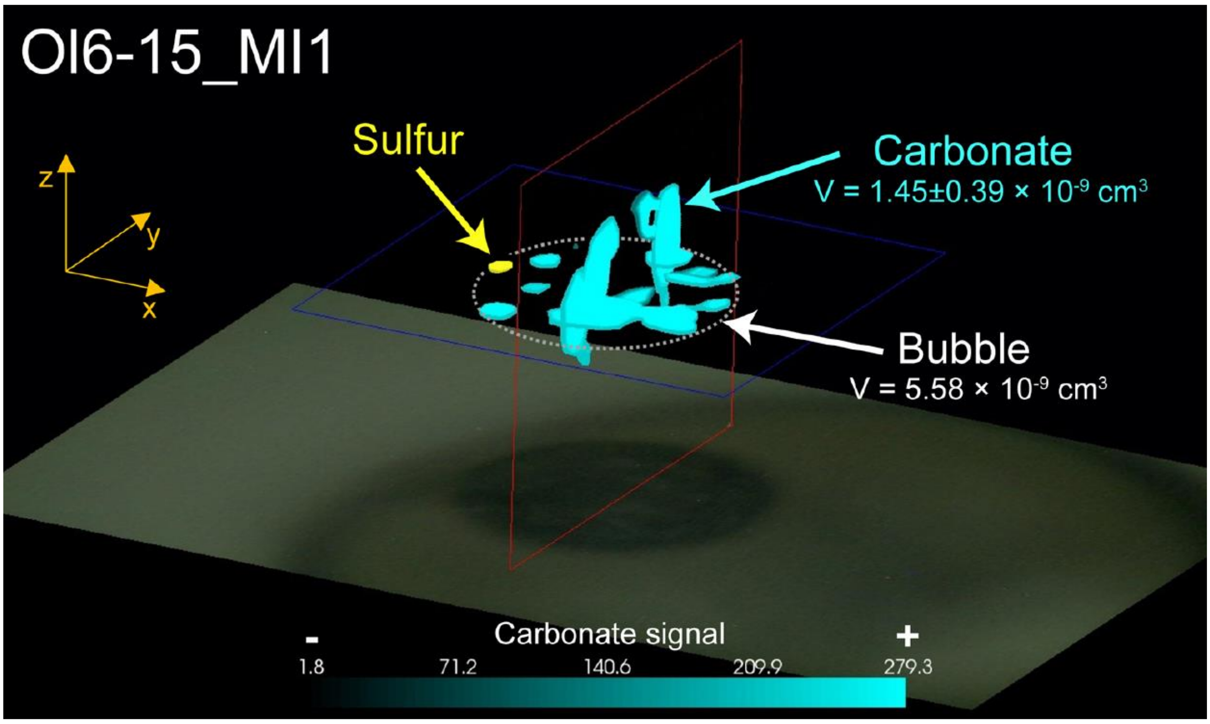

Figure 1. Raman 3D-map of bubble in olivine-hosted melt inclusion (Ol6-15_MI1), showing the distribution of carbonates inside the bubble (represented in light blue). The yellow area corresponds to S, indicating that melt inclusion bubble is also a reservo

Magma-atmosphere coupling of sub-Neptune exoplanets

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Atmospheres of hot sub-Neptunes (equilibrium temperatures > 1000 K) are being characterised by the James Webb Space Telescope (JWST). Recent modelling efforts suggest that the magma-atmosphere coupling of hot sub-Neptunes strongly impacts their atmospheric chemistry, enriching the atmosphere in refractory element-bearing gases, e.g., SiO, SiH4. To determine atmospheric chemistry, we implement a new state-of-the-art code, atmodeller, that models an equilibrium chemistry reaction network. Based on the calculations for atmosphere chemistry in the Si-O-H system with mass conservation for H between the atmosphere and the interior, we can classify sub-Neptune populations into steam worlds, hydrogen worlds, and silicon worlds. We quantify the strong impact of including non-ideal gas behaviour and gas solubility in magma on these populations. These populations should exhibit distinct atmospheric signatures that are detectable with JWST transmission and emission spectroscopy.

Magma chamber processes, differentiation modelling and plumbing system underneath Nyamulagira volcano (East African Rift)

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Magmatic rocks in the East African Rift (EAR) are characterized by a wide compositional heterogeneity associated with different mantle sources and conditions of melting (Rooney, 2019). However, this variability of magma composition remains poorly constrained in some regions of the EAR, as well as differentiation processes.

In this study, we investigate magma chamber processes and reservoir conditions through textural and compositional features in historical lavas of Nyamulagira, an active volcano of the western branch of the EAR, located in the Virunga Volcanic Province, in Eastern D.R. Congo.

Our results indicate evidence for multiple reservoirs beneath Nyamulagira in which magma compositions and textures evolve through magma recharges, mixing and convections. We distinguished three different storage regions beneath Nyamulagira, extended from ~ 30 km to ~ 2 km.

We propose a differentiation model for Nyamulagira that combines fractional crystallization, crystal accumulation as well as magma mixing. These processes take place at the different reservoir levels although our results suggest that crystal accumulation is dominant in the deep region, whereas fractional crystallization and mixing-homogenization are mostly taking place in the upper reservoirs.

Rooney, T. O., (2020) The Cenozoic magmatism of East Africa: Part V – Magma sources and processes in the East African Rift, Lithos, Volumes 360–361, 105296, ISSN 0024-4937.

Late-Devonian Fossil Micrometeorites extracted from Belgian Carbonates

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Introduction: The flux of extraterrestrial (ET) material to the Earth does not appear to have been constant over time, but so far, no consistent reconstructions of the flux through time have been compiled. This results from the conventional proxies used to assess variations in ET input (iridium concentrations, osmium isotope ratios, 3He content and/or ET spinel chromites minerals) coming with inherent biases and stochastic large-scale events documentation of the sedimentary record. Global ET flux estimates vary over 3 orders of magnitude from hundreds to thousands of tons per year [1], but the cause of this variation is likely linked to neither short time scale cosmic events, nor to terrestrial biases [2]. Estimations of the ET flux variation in abundance and composition is limited to data from collections with relatively short accumulation windows (≤50 ka old, up to 1-3 Myr for sedimentary deposits) and based on limited micrometeorites (MMs) populations with large average sizes between 200 and 400 µm [3]. While most of the arriving ET material weathers away quickly under the oxidizing conditions at the Earth surface, MMs and other specific refractory minerals may resist alteration and diagenesis [4]. As such, assessing the complete ET flux is necessary in order to understand the nature and magnitude of changes in the intensity and composition of this ET influx, and recovering full fossil MMs from terrestrial sediments could represent a solution. In addition, assessing periods of higher ET material flux arriving on Earth could provide insights into the past atmospheric composition due to oxidation of the cosmic spherules (CSs) during atmospheric entry [e.g. 5].

Results: In this study, we have extracted MMs from Belgian carbonates, with in total 1222 MMs identified from 26 kg of carbonates. This collection includes well preserved 3 types of CSs, with a large I-types collection, and the oldest confirmed silicate-rich G-types and S-types. We also assess information about their parent body origin and alteration history of the MMs using oxygen isotopic composition. The present study provides the first fossil MMs collection recovered from Late-Devonian samples, dated from over 350 Myr ago, and represent a new proxy to investigate the composition and abundance of the past ET flux to Earth. Their alteration history will allow us to assess the alteration conditions during Late-Devonian, and could represent a new proxy for assessing Earth's atmospheric oxidizing conditions during the Late-Devonian. This study will try to reconstruct a first ET flux at high resolution and identify all potential variations in the ET material across the stratigraphic interval. In addition, by analyzing conventional proxies in the sediments, we plan to identify differences between these various applied techniques and define optimal strategies to trace noticeable variations of the ET flux with time, proposing an effective multiparameter method for future reconstructions.

[1] Prasad et al. (2013). J. Geophys. Res.: Planets 118:2381–2399. [2] Genge et al. (2017). Geology 45:119–122. [3] Suttle & Folco (2020). J. Geophys. Res.: Planets 125(2):e2019JE006241. [4] Meier M.M.M. et al. (2010) Earth Planet Sci Lett 290:54–63. [5] Rudraswami et al. (2022). The Astrophysical Journal 940(1):25.

Preparation of Mercury analogue materials to calibrate instruments onboard the BepiColombo spacecraft

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Understanding the formation and evolution of planet Mercury is crucial to comprehend the processes that have shaped the solar system and other exoplanetary systems. The observational work initiated by NASA's MESSENGER mission will be built upon by the BepiColombo mission (Benkhoff et al., 2021), a joint endeavor of ESA and JAXA. Onboard of the BepiColombo spacecraft, which will enter Mercury's orbit in late 2025, the Mercury Imaging X-ray spectrometer (MIXS, Bunce et al., 2020) will measure the atomic composition of the top 10 to 20 µm of the surface by fluorescence spectroscopy. MIXS will use X-rays emitted from the solar corona as its source. Its primary goal is to generate a global map of Mercury's regolith atomic composition but specific locations will undergo higher-resolution measurements by rotating the device to increase the dwell time.

MIXS's signal calibration relies on numerical modeling of X-ray radiative transfer and laboratory experiments. However, due to the unique composition of Mercury' surface (high sulfur and low iron content), usual reference geochemical standards provide incomplete calibration of the MIXS data. Moreover, the signal will be influenced by factors such as observation geometry and grain size. To address these challenges, a ground facility has been established to simulate space observations on Earth. Various samples will be analyzed to mimic possible regolith compositions (with differing compositions and textures), in order to fine tune data processing protocols and instrument parameters.

We are producing pressed pellets of known chemical compositions for this purpose, chosen to address critical scientific questions regarding Mercury's composition and evolution. The MESSENGER mission has revealed peculiar characteristics of Mercury's surface, showing abundant potassium and sulfur, indicative of high volatile content. Understanding the spatial distribution of these elements is crucial as they are linked to pyroclastic volcanism and the formation of hollows (i.e. depressions believed to form by sublimation). Therefore, we prepared pellets with a range of K_2O and S concentrations relevant to the surface of Mercury (0 – 2 and 0.5 – 10 wt.%, respectively). Calcium is added to the samples containing potassium as the peaks of these elements overlap, complicating potassium detection. Besides these global characteristics, different geochemical provinces, probably formed by partial melting of a heterogeneous mantle, have been identified. Sodium is more abundant in the northern smooth plains, hinting at a mantle source richer in clinopyroxene. Sodium detection is however challenging due to the overlap with the magnesium K emission line. Hence, we also prepared samples with varying Na_2O content (ranging from 0.1 to 8 wt.%) and a fixed MgO concentration. These samples, along with other additional materials produced by other teams, will enable accurate and precise measurement of the surface atomic composition of Mercury.

Benkhoff J, Murakami G, Baumjohann W, Besse S, Bunce E, Casale M, Cremosese G et al. (2021) BepiColombo - Mission Overview and Science Goals. Space Science Reviews 217(8): 90. Bunce E, Martindale A, Lindsay S, Muinonen K, Rothery DA, Pearson J, McDonnell I, et al. (2020) The BepiColombo Mercury Imaging X-Ray Spectrometer: Science Goals, Instrument Performance and Operations. Space Science Reviews 216(8): 126.

Investigating low-pressure magma-atmosphere interactions by experimental petrology: an overview of the evacuated silica tube technique

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Evacuated silica tube experiments are designed to investigate multi-phase interactions within a closed system, operating under low pressure (below 1 bar), high temperatures (up to 1400°C), and controlled oxygen fugacity (ranging from ~IW+2 to IW-6). The experimental setup comprises a crucible containing the sample and a solid buffer within an evacuated silica tube that enables gas-melt interaction under controlled temperature. Complete or partial melting of the sample enhances evaporation of volatile elements and the production of a vapour in thermodynamic equilibrium with the silicate glass. This is particularly valuable for replicating natural systems involving gaseous components (e.g., fluid inclusions, vapor), as well as magmatic melts and crystals, and allows the investigation of a wide range of magmatic processes such as moderately volatile element solubility, crystallization, element partitioning, diffusion, or degassing processes. Various magmatic environments can be reproduced, ranging from the formation of chondrules in the protoplanetary disk to exogenic planetary processes (e.g., volcanism, ore formation, sulfidation). While this technique is highly adaptable and offer versatility, it comes with experimental limitations, including the potential reactivity between the sample and SiO(g) produced from the silica tube, challenges in determining gas speciation and their partial pressures, the impact of partial pressure of volatile species on the C-CO buffer equilibrium if a graphite crucible is used, and temperature limitation due to the softening point of silica (~1400°C). We provide an overview of this technique along with the applications conducted in our laboratory, encompassing the study of metal-silicate equilibria (Cartier et al., 2024), elemental speciation in reduced magmas (Pommier et al., 2023), sulfur isotope fractionation, volatilization, sulfidation processes (Renggli et al., 2021), as well as the development of geochemical standards.

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Is the elliptic geomorphological structure near Berdorf, Luxembourg a maar-diatreme volcano?

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Luxembourg's Land Registry and Topography Administration provides since 2019 an open access high-resolution national LiDAR database (https://lidar.geoportail.lu). During a systematic geomorphological study of the LiDAR data from the UNESCO Global Mëllerdall territory, an exceptional ellipse structure was noticed NW of the village Berdorf. Furthermore, a spatially coherent small circular anomaly can be observed on the 1994 Belgian Geological Survey radiometric airborne measurements. This observation is of utmost importance as the area around the Sauer and Moselle rivers shows in the border region between Luxembourg and Germany multiple signatures of young and ongoing large scale geodynamic processes. Kreemer et al. (2020) report highest ongoing central European uplift rates (1 mm/a) from that region. Meyer et al. (in prep.). mapped new mofettes and naturally CO2-rich hydrogen carbonate water sources are all spatially linked to faults and are located within a radius of 13 km around the elliptic structure. The emitted pristine gas in the area is CO2 dominated (around 97%) and a significant He content of 540-800 ppm. This strong He component of the gas phase is contrary to a shallow crustal gas source due to carbonate dissolution. Finally, Dillman & Negendank (1982) reported the furthest southwestern geologically young "Eifel" volcano at the Petrisberg in Trier - less than 25 km SE of the present study area.

To cast light on the origin of this structure a geophysical survey consisting of two 700 m gravimetric profiles with 74 gravity stations had been measured in December 2023. In addition, gamma spectrometric data (K, U, Th) along two gravity profiles and continuous acquisition magnetic measurements were acquired by the company GexplOre, France. Due to the complex topography the gravimetry survey was far from easy. The residual of the simple Bouguer anomaly suggests a small negative anomaly (≈ -0.15 to -0.35 mGal) in the center of the study area. While positive gravity anomalies (+0.140 up to +0.4 mGal) are observed on the edges of the survey area. The residual of the complete Bouguer anomaly confirms the small negative anomaly in the center of the structure. The residual magnetic field data are mainly increased within the structure boundaries (4 to 8 nT) except for the northern part of the NW line while the data outside the structure are ≤ 0 nT. This distribution agrees with trends observed on other Maar structures. The spectrometry data show all the same element trends. The area outside the structure boundary has higher contents of the radioactive elements in contrast to up to detection limit low concentrations within the structure. However, the maximum concentrations are observed at the SW ridge of the structure. A plausible hypothesis for the studied structure would be that it might be the remanent of a Maar volcano. But further geological and geophysical studies are needed as, despite of a negative gravity anomaly and positive magnetic anomaly within the elliptic structure, the observed anomalies are smaller compared to reported data from other Maars. However, these Maar structures are located within significantly different geological settings, where the density contrast between the maar lake sediments, the diatreme fillings and the surrounding bedrock are much larger.

Dillmann W, Negendank JFW (1982) Ein Lapilli-Tuffschlot südlich Trier, das südlichste Vorkommen kretazisch-känozoischen Vulkanismus in Eifel und Hunsrück. Mainzer Geowiss Mitt (11): 29–32 Kreemer C, Blewitt G, Davis PM, (2020) Geodetic evidence for a buoyant mantle plume beneath the Eifel volcanic area, NW Europe, Geophysical Journal International (222,2), 1316–1332

Mantle sources underlying Nyiragongo as inferred from olivine phenocrysts

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The Nyiragongo volcano, part of the Virunga Volcanic Province (VVP) in the Democratic Republic of Congo is a uniquely silica-undersaturated (32 – 49 wt.% SiO_2) and alkali-rich (7 – 17 wt.% $Na_2O + K_2O$) volcanic system. Through alkaline volcanism in the western branch of the East African Rift System is by no means rare, the compositions erupted by Nyiragongo are extreme even within this context, and the other volcanoes in the VVP predominantly erupt silica-saturated compositions.

In order to address the origin of the geochemical character of Nyiragongo it is imperative that the mantle source feeding the volcanic system is well-understood. We approach this issue through the combined use of primitive whole-rock compositions and detailed geochemical analysis of early-crystallized olivine hosted by these samples.

Major and trace element compositional data of the olivine indicates a Ca-rich, but otherwise conventional geochemical signature indicative of melt derivation from a peridotite restite. However, whole-rock data requires the melting of K-rich phlogopite and/or amphibole in the presence of apatite, garnet, and clinopyroxene since this would produce Si-undersaturated, Ca-, and K- rich melts. Geochemical modelling using recently acquired partition coefficients suggests that such melting must primarily occur at high pressures (3 GPa), outside of the stability field of amphibole, in line with the thick lithosphere bordering the Tanzanian craton.

Combining the peridotite restite-signature from olivine compositions with the phlogopite-pyroxenite melt-source inferred from whole-rock data results in a model of metasomatic vein-melting, wherein veins emplaced in the subcontinental lithospheric mantle during the Pan-African orogeny are preferentially molten through a breakdown reaction of phlogopite at temperatures of 1150 to 1350 °C.

Petrology and evolution of the Sandoa-Kapanga basement across the southern Kasaï craton (Democratic Republic of the Congo)

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The Kasai craton covers the southern part of the Democratic Republic of the Congo and is – like other Archean granitoid-greenstone terranes – composed of a range of felsic igneous to metamorphic rocks, in among mafic-ultramafic rocks (Batumike et al 2009, De Bruyne et al 2019). As a much-needed petrological pilot reconnaissance study, a total of 39 samples of felsic granitoids, banded gneisses and migmatites were collected from across for the southern Sandoa-Kapanga half of this craton, including an alleged Paleoproterozoic meta-sedimentary rock sequence of the Luiza Complex. Texturally, samples can be subdivided into less deformed granitoids, more banded/foliated gneisses, as well as potential 'migmatites' (with distinct biotite-rich 'melanosomes' and felsic 'leucosome' veins). Compositionally, samples are subdivided into a (1) dominant granitic and (2) a less exposed Tonalite-Trondhjemite-Granodiorite (TTG) suite (cf., Fig. a-b). TTGs tend to have relatively low HREE concentrations, together with a lesser depletion in Sr and Eu, consistent with some garnet amphibolite to eclogite crustal source. I-type granitoids are LILE/HFSE-enriched, with distinct Nb-Ta troughs, and most of these are depleted in Sr, Eu and Ti; attributed to both plagioclase and oxide fractionation. Positive Sr and Eu anomalies among other I-type granitoids may be attributed to plagioclase accumulation. Rare A-type granites are more HFSE-enriched (including Nb-Ta and HREEs) yet also relatively low Ti concentrations, suggestive of oxide fractionation. Zircon U-Pb geochronology (Fig. c) identifies one Paleoproterozoic alkali granite sample (~2.11 Ga) and two Neoarchean granitoid samples (~2.85 & ~2.65 Ga), while a gneissic sample from within the Luiza Complex provided the most obvious igneous ~2.76 Ga age and one migmatite sample is dominated by ~2.85 Ga spot analyses. The other gneissic and migmatitic samples provide wider and predominantly Mesoarchean age scatters, including possible 'igneous' peaks at ~3.26 and 3.175 Ga, respectively. Apart from rarer Paleoproterozoic A-type alkali granites and Neoarchean I-type granites, there is no obvious correlation between textural, compositional and geochronological groups, where older migmatites and gneisses tend to be granitic and a younger (but not Paleoproterozoic!) Luiza gneiss is trondhjemitic. Despite such discrepancies, the petrological and geochronological record provided by this pilot study on sampled felsic basement rocks compares overall well with existing sparce results from the southern Sandoa-Kapanga half of the Kasai craton (cf., references in de Wit and Linol 2015), as well as emerging alluvial zircon data from a neighbouring northern half of the Kasai craton (Debruyne et al 2019) and more comprehensive in situ zircon rock age databases from distal Sao Francisco, Angolan, Ntem and Bomu cratons (Teixeira et al 2017, Jelsma et al 2018, Debruyne et al 2019, Turnbull et al 2021, respectively) within a Greater Congo Craton. Further research of a similar kind is required to test if Paleo-Mesoarchean remnants within these Archean blocks amalgamated during a common Neoarchean orogen and/or if younger orogens – like the Umbendian/Kibaran orogen separating a Tanzanian(-Bomu)

block – subsequently added to the growth of a Greater Congo Craton and/or what Archean fragments across the World may have detached from it during intervening supercontinental break-ups.

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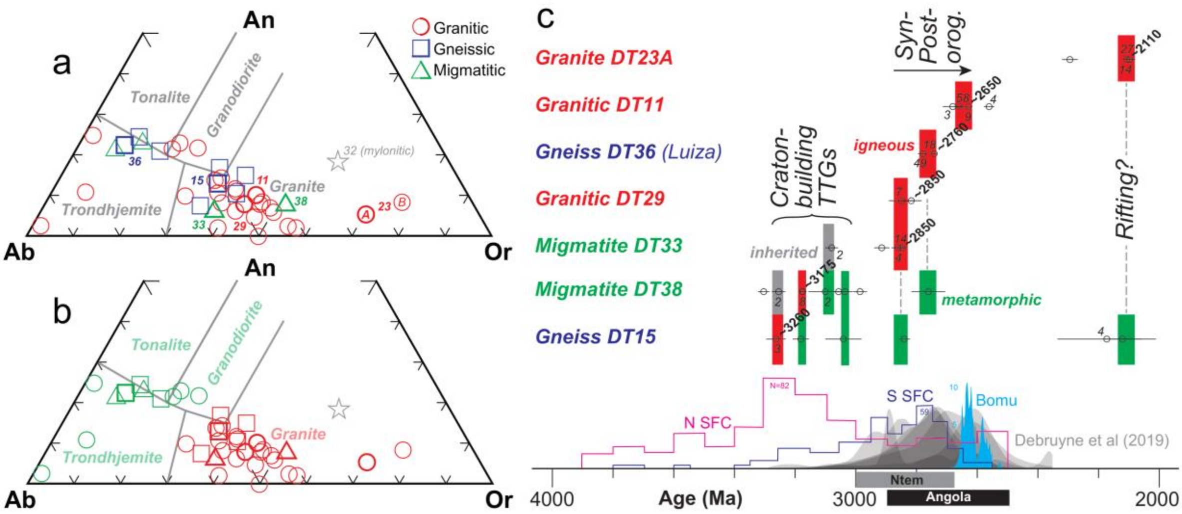

(a-b) Geochemical classification of 39 felsic rock samples and (c) summary of geochronological results for seven selected samples from the southern Sandoa-Kapanga region of the Kasai craton. Preferred igneous ages (in Ma) indicated in bold. Number of U-Pb

Internal structure and K depletion of Mercury inferred from the partitioning of trace elements at highly reduced conditions

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The study of the chemical behavior of elements is a powerful tool to gather insights on the geological evolution of planetary bodies. Here, we investigate the effect of highly reducing conditions on the partitioning of elements between the silicate, metal and sulfide melts under the conditions of Mercury's bulk silicate part during its primordial differentiation (Pirotte et al., 2023). We performed experiments at various temperatures, pressures and oxygen fugacity (1500 – 1700°C, 0.1 – 3 GPa and IW – 8 to IW – 1) on synthetic powders representative of the bulk silicate Mercury, which yield partition coefficients data for more than 30 minor and trace elements. Combined with data from the literature, we model the behavior of U, Th and K during the planet's differentiation and the formation of lavas. We confirm that these elements are strongly lithophile for most conditions, with U becoming chalcophile only at very low oxygen fugacity (<IW – 6). We also show that U is constantly ~20 more chalcophile than Th over the range of oxygen fugacity considered. As such, we find that the formation of an FeS layer at the core – mantle boundary, hypothesized by some author (e.g. Cartier et al., 2020), would fractionate U and Th as the former is more chalcophile than the latter under reducing conditions. Such a fractionation is inconsistent with the surface Th/U data obtained by MESSENGER. We suggest that an FeS layer should not have formed on Mercury under reducing conditions (<IW – 4), or that the bulk Th/U of Mercury was sub-chondritic. If an FeS did not form on Mercury, it implies that heat-producing elements (U, Th and K) are concentrated into the thin silicate part. Our model also show that the surface K/Th and K/U ratios are respectively 2 – 4 times and 3 – 6 times lower than expected if the planet formed from chondritic material. These findings imply that the planet may have lost a significant amount of K, via mechanisms that are yet to be identified.

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The Crystallization of the Magma Ocean of Mercury: An experimental study on the early evolution of the innermost terrestrial planet

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Planet Mercury has unique chemical characteristics and physical properties among the terrestrial bodies1. In particular, Mercury is the smallest terrestrial planet of our Solar System and is characterized by a large metallic core. It is now widely accepted that during accretion, the heat liberated from radiogenic decay and early large accretional impacts was sufficient to completely melt Mercury. This early stage, referred to as "Magma Ocean", has been first invoked for the Moon and is thought to have affected most terrestrial planets. As the silicate and metal portions separate, the progressive crystallization of the silicate part results in the formation of the primordial solid mantle. What occurs during this critical period of differentiation sets the stage for all subsequent events that shaped Mercury as we see it today. This includes mantle remelting and the production of a secondary magmatic crust, as well as the stability and storage of heat-producing and volatile elements that are crucial for planetary dynamics and potential building of an atmosphere. The geochemical data returned by NASA's MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft revealed an unusually high concentration of sulfur of surface volcanic units coupled with the paucity of iron. This pointed to highly reduced conditions (low oxygen availability) of formation of surface lavas. Sulfur is therefore thought to be a major mantle volatile, with profound implications for melt temperatures, phase equilibria and, as a consequence, the vertical structure of the mantle2. The central objective of this project is to investigate the structure of the primordial mantle of Mercury as a direct result of the crystallization of its magma ocean, thus providing a revised standard model for the evolution of the planet in its early history. To tackle these issues, laboratory experiments are now being performed on Mercury-like mantle compositions, at high temperature and different pressures, in conditions of low oxygen fugacity and sulfur saturation. Experimental results (phase equilibria, major element distribution) are then combined with thermodynamical modelling (inspired by the studies on the lunar magma ocean3) to simulate the fractional crystallization of Mercury's magma ocean, in order to reconstruct the stratigraphic sequence of Mercury's primordial mantle. Preliminary results show that orthopyroxene and olivine are the main silicate minerals making up the primordial mantle of Mercury, and that the presence of sulfur in the MMO stabilizes orthopyroxene over olivine. Our final outcomes will therefore help understand not only the early evolution of Mercury, the structure and heterogeneities of its mantle, and the formation of its crust, but also the evolution of Mercury-like terrestrial exoplanets.

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[2] Namur, O, Charlier, B, Holtz, F, Cartier C, McCammon, C, (2016) Sulfur solubility in reduced mafic silicate melts: Implications for the speciation and distribution of sulfur on Mercury. Earth and Planetary Science Letters 448, 102-114

[3] Charlier, B, Grove, TL, Namur, O, Holtz, F, (2018) Crystallization of the lunar magma ocean and the primordial mantle-crust differentiation of the Moon. Geochimica et Cosmochimica Acta 234, 50-69.

Experimental constraints on the low-pressure phase equilibria and liquid lines of descent of mafic, alkaline magmas

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Alkaline magmas, characterized by high K2O and Na2O, occur at a variety of settings worldwide, including continental rifts, ocean-islands and arc-settings. They encompass a wide range of compositional and mineralogical diversity, and include both silica-saturated and undersaturated compositions. The crystallization of feldspathoids, a family of aluminosilicate minerals formed when too little silica is available to form feldspars, is one of the most obvious mineralogical features of silica-undersaturated alkaline magmas. However the boundary between the stability fields of plagioclase feldspar and the feldspathoids in the compositional space of alkali basalts, and the effects P, T, volatiles and fO2 on the evolution of residual liquids during progressive cooling and crystallization are poorly defined. Oxygen fugacity in particular, which affects the stability of Fe-bearing phases through control of melt Fe2+/Fe3+ ratios, has the potential to influence the path of alkaline melt differentiation significantly, and warrants closer study.

This study examines the dry phase equilibria and liquid lines of descent (LLDs) in mafic alkaline magmas, with the aim of understanding differentiation processes in shallow crustal storage regions. Five primitive (9.3-11.1 wt.% MgO) and four evolved (5.0-5.6 wt.% MgO) alkaline samples, from Fogo (Cape Verde), Terceira (Azores), Tristan da Cunha, Nyamulagira (Democratic Republic of the Congo; DRC) and Nyiragongo (DRC) were used as starting compositions. Equilibrium crystallization experiments were performed in a gas mixing furnace at 1 atm, between 1220-1100°C and 1170-1050°C for experiments using primitive and evolved compositions respectively. Oxygen fugacities corresponding to the fayalite-magnetite-quartz (FMQ) buffer, FMQ-1, FMQ+1.5 and FMQ+3 were chosen to reflect natural variability.

Saturated phases in primitive samples include olivine ± spinel ± clinopyroxene ± plagioclase ± pseudobrookite. Evolved samples saturate spinel ± olivine ± clinopyroxene ± plagioclase ± nepheline ± ilmenite ± pseudobrookite ± whitlockite ± rhönite. Nepheline is the only feldspathoid to saturate in these experiments, and is restricted to the evolved starting composition from Nyiragongo, the most silica under-saturated, at 1050°C. Experiments at higher fO2 produce LLDs that evolve towards increasing silica-saturation due to crystallization of phases poor in silica relative to the melt. This effect predominantly results from enhanced stability of spinel under oxidising conditions, alongside clinopyroxene and Fe-Ti oxides. Melt FeO content also reflects the crystallization of spinel and Fe-Ti oxides, the latter controlling melt TiO2 in addition. Melt CaO content however, is largely controlled by the volume of clinopyroxene, which is further reflected in the composition of other CaO bearing phases, such a plagioclase. Finally, the absence of highly alkaline phases, this increased crystallization at high fO2 enriches the melt in alkalis, while melt fractions fall.

These experiments demonstrate that redox conditions exert a strong control on mineral assemblages, and the degree of melt evolution, with oxidising conditions producing smaller volume, silica-enriched residual liquids at a given temperature. Additionally they show the limited stability of feldspathoids under the conditions investigated. Subsequent work will explore the effect of pressure and volatiles on feldspar and feldspathoid stability, and the evolution of alkaline magmas.

An improved model for post-entrapment crystallisation of olivine-hosted melt inclusions: constraining complex uncertainties

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While compositions of glassy olivine-hosted melt inclusions provide unique information about deep magmatic plumbing systems, magma storage depths and the early differentiation of primary mantle melts, they are almost always altered by post-entrapment crystallisation (PEC) processes (van Gerve et al., 2024). Various algorithms exist to calculate PEC extents and the composition of the melt inclusions prior to partial crystallization (e.g. Danyushevsky and Plechov, 2011; Rasmussen et al., 2020; Brahm et al., 2021). These algorithms depend on calculated parameters such as melt iron speciation, olivine-melt Fe-Mg partition coefficients [Kd(Fe-Mg)] and crystallisation temperature. These parameters can be modelled in various ways and as such the model choice potentially significantly influences calculated PEC extents and corrected melt compositions. However, currently available PEC correction algorithms are either static and only implement a single model for each parameter or rely on dated models.

We provide an improved PEC correction Python code that includes a wide selection of up-to-date models for each parameter (fig. 1). Moreover, the code is flexible and can be extended with additional models by the user if needed. Our results show that calculated crystallisation extents can vary by more than a factor of two by changing a single model, highlighting the importance of their careful selection. This is especially important for melt iron speciation models, as they significantly impact equilibrium olivine compositions though the calculated Fe-Mg partition coefficients. Moreover, many iron speciation models are only applicable at 1 bar, while crystallisation of melt inclusions can take place at greater pressure, potentially up to 20 kbar.

Errors on each model are included in the PEC correction code and can be propagated to the calculated PEC extents in a Monte-Carlo simulation. Additionally, analytical errors on melt and olivine compositions can be included in the error propagation, constraining all potential sources of error. Using melt inclusion data from the Azores (van Gerve et al., 2024), we show that typical errors on PEC extents are below 50% of their calculated values. These errors are small compared to the range in PEC extents calculated with different model settings and selecting appropriate models is therefore crucial for calculating accurate PEC extents. Our PEC correction code provides the flexibility needed to do this and as such presents a significant improvement over existing algorithms.

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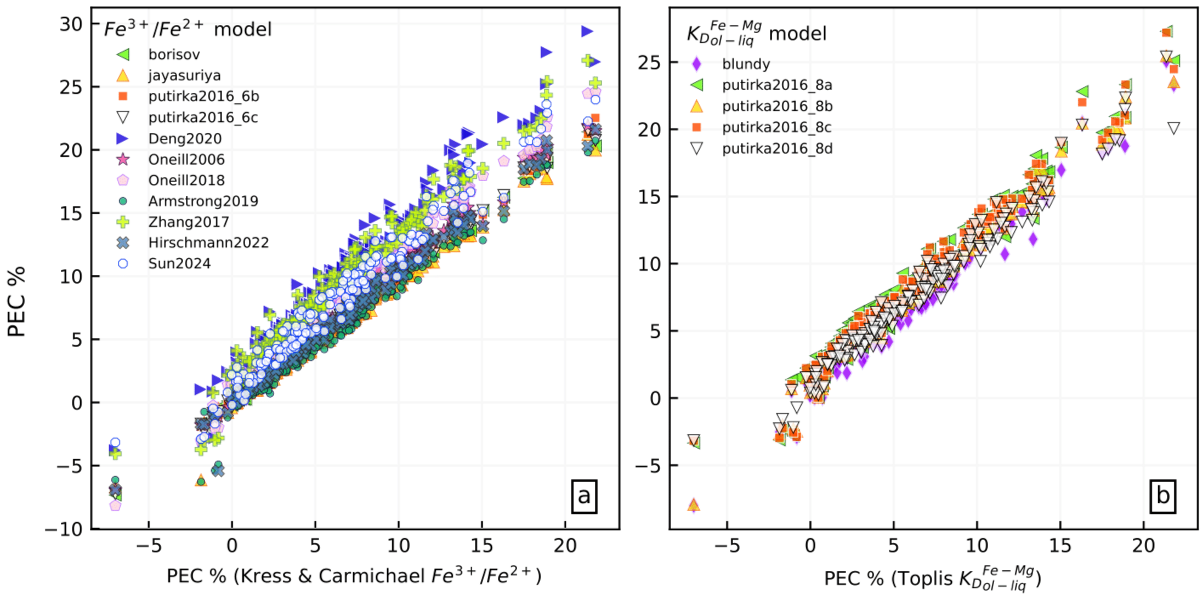

Figure 1. PEC extents of Azorean melt inclusions (van Gerve et al., 2024) calculated with various [a] melt Fe3+/Fe2+ and [b] Kd(Fe-Mg) models. Results between individual models can vary by more than a factor of two.

Phase one of the ERupT project: geo-electric monitoring of the Reykjanes geothermal field during the recent volcanic unrest in Iceland

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Geo-electric methods such as Electrical Resistivity Tomography (ERT) and Induced Polarization (IP) have become increasingly important in the characterization of volcanic and geothermal systems. The methods rely on the electrical properties of the subsurface. In volcanic settings, the main influences are temperature, gas content, mineral precipitation, and the presence of alteration clays.

The ERupT project aims to assess the suitability of ERT to visualize the dynamics in volcanic hydrothermal systems. With the long-term aim of improving hazard assessment associated with phreatic/hydrothermal eruptions. The Reykjanes Geothermal field was chosen for the experiment, in September 2022 the field was characterized using geo-electric methods allowing us to identify zones of high and low activity and areas where new surface manifestations are likely to occur.

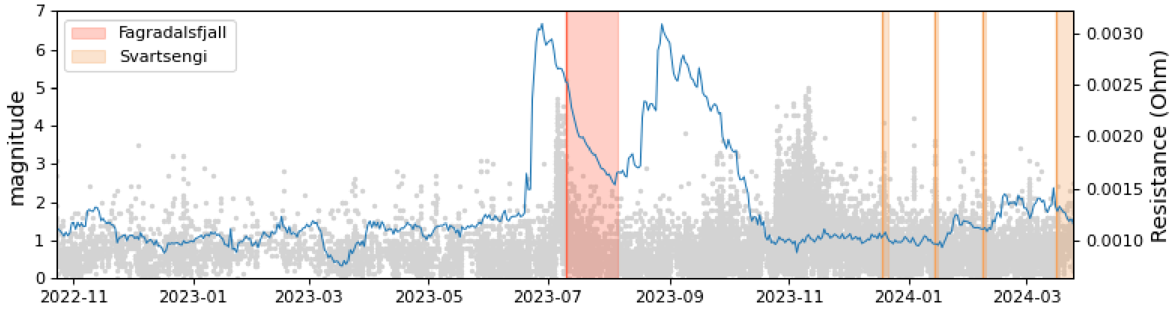
The monitoring profile is situated in an area where we expect the most changes to occur, it was installed in October 2022 and automatically measures one profile per day with currently 19 months of almost uninterrupted data. The profile Is 355 meters long and has a depth of investigation of 30 to 50 meters.

The 2021 eruption at Fagradalsfjall marked a new age of volcanism in the Reykjanes peninsula, since the start of the ERT monitoring 5 occurred. The first eruption happened in the Fagradalsfjall system on July 10th 2023, after that activity moved towards the Svartsengi system, which has been periodically erupting since December 18th 2023. The eruptions are located at respectively 10 and 25 km from the field site.

Although the ERT system is located at a considerable distance from the eruption sites and the investigation depth is shallow, we observed signals possibly related to both eruptions and accompanying unrest, manifesting as a significant increase in resistance (figure1). When visualizing this with the earthquake magnitude on the peninsula, a pattern can be observed. An increase in resistance is followed by an earthquake swarm and later a volcanic eruption. In the case of Fagradalsfjall these events follow each other quickly, i.e. a few days, whilst for the Svartsengi case it's months. In this context, an increase in resistance is likely caused by a drop in saturation due to high gas levels, which can be caused by magma degassing during the uprise. This raises the question of the time difference, possible factors are the difference in morphological context and preferential flow paths relative to our monitoring site.

It should also be noted that this behavior is not observed in all data points, hence advanced processing is needed combined with interpretation using data from other methods. Tremor and soil temperature data are available along the ERT profile, together with one CO_2 sensor.

To our knowledge, this is the first time that ERT has been used for daily monitoring of a volcanic system. With joint interpretation to deduce the signal origin, we believe that ERT can be a valuable addition to volcanic monitoring networks.



Evolution of the Resistance in one pseudo-point, with an indication of the earthquake magnitude on the peninsula and volcanic eruptions.

Mantle melting behaviour in low-Mg exoplanets

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As the search for habitable exoplanets becomes more prominent, plenty of exoplanetary research is needed to deepen our understanding of the formation and evolution of all types of exoplanets. Although, as surface and interior compositions of rocky exoplanets still cannot be directly determined, rocky exoplanets are assumed to have similar refractory element ratios, e.g. low Mg/Si vs. high Mg/Si, as their stars considering they have formed from the same cloud of gas and dust. This assumption allows to examine different compositions and their effect on the interior of a planet with that composition. The aims of this MSc research are (1) to determine the melting behaviour of non-peridotitic mantles of low-Mg planets, and (2) to determine the composition of melts produced in a non-peridotitic mantle and the formation of a secondary volcanic crust, and (3) to get first order constraints on the atmospheric composition.

The selected compositions are based on the EH composition of Berthet et al. (2009), as enstatite chondrites are assumed to be one of the potential building blocks of reduced planetary bodies. From the three selected compositions, with a varying molar Ca/Al ratio (0.76, 0.85, and 0.95), synthetic samples are prepared using the following pure oxide powders: SiO_2, Al_2O_3, Fe_2O_3, MgO, $CaSiO_3$, and Na_2SiO_3. High temperature experiments are run with the samples in a vertical tube gas-mixing furnace at five different temperatures (1300°C, 1325°C, 1350°C, 1375°C, and 1400°C), at an fO_2 of FMQ-2 for 50 to 100 hours. Afterwards, the samples are chemically analysed by the Scanning Election Microscope, developing a thermodynamic model of mantle melting for various lithological sources. The SEM is also used to attain BSE images to determine the distribution of melt and crystals in the samples. Electron Dispersive X-ray Spectroscopy is used to chemically analyse the experimental products.

The main crystallising phases present in the experimental products are orthopyroxene and quartz. They both occur as anhedral to euhedral crystals within the melt, with quartz occasionally being trapped in Opx crystals at lower temperatures. The composition of the melt has decreasing amounts of Si and Al, and increasing amounts of Mg with increasing temperatures, i.e. degree of partial melting. The melt composition is also slightly influenced by the increasing Ca/Al ratio in the starting composition, where an increase of Mg and Ca is visible and a decrease of the amounts of Na and Si. However, these are not highly significant differences as they only vary up to 2 oxide% with increasing Ca/Al ratio. Further, the estimated fraction of melt in the samples range from 25% to 55%. This wide range is mostly due to the occurrence of melt blobs in certain samples, greatly affecting the estimations. An increasing Ca/Al ratio also increased the melt fraction present in the experiments, although only at higher temperatures. At lower temperatures a more dubious trend is visible. In general only a minimal influence of the Ca/Al ratio is visible within the samples of this research, causing more CaO and slighly less Al_2O_3 to be present in the melt at higher Ca/Al ratios. Lastly, predictions for volatile saturation in the produced melts show the following general evolution in dominant volatile species: H_2-CH_4 -> H_2 -> CO -> CO-CO_2. An increasing H as H_2O concentration shift the atmospheres with reduced oxygen fugacities (IW-3 to IW-6) from a CO-rich to H_2 and CH_4 rich atmospheres. At more oxidized conditions (IW to IW+3) the atmospheres are always CO-CO_2 rich.

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Forming Mercury-analog planets in the solar neighborhood

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Rocky exoplanets with high core mass fraction (CMF) are broadly defined as Mercury-analog planets due to their high bulk densities. Mercury, in our solar system, serves as a benchmark due to its exceptionally high CMF of 0.7 [1]. Mercury also has distinctive chemical attributes, with a mantle nearly free of Fe (0.17 wt.% [1]) and differentiated under an extremely reduced conditions (oxygen fugacity, fO_2: IW-3 to IW-6 with IW referring to iron-wüstite equilibrium; [2-3]), which results in a significant amount of light elements partitioning into its core [2]. In this study, we are interested in asking: what are the compositions and interior structures of Mercury-analog planets, how do they form, are they rare or common, are there multiple pathways to forming a Mercury-analog planet?

We consider the elemental abundances of key rock forming elements (O, S, Na, Si, Mg, Fe, Ca and Al) from the host star in the solar neighborhood (< 200 parsec). We employ a devolatilization model based on elemental condensation in a steady protoplanetary disk that considers size and temperature distribution of the star to predict the compositions of hypothetical Mercury-analog planets. Crucially, the extent to which oxygen can condense into solid silicates during planetary formation significantly influences their core size, and compositions of both core and mantle. We found that only 5-7% of the stars may form Mercury-analog planets. Mercury-analog planets can have CMF spanning from 0.3 to 0.6, with bulk planet fO_2 varies between IW-2.5 to IW<-7. Their mantle typically has low Fe/Si ratio (< 0.1), while the core can be Si dominated (50 wt.% Si + ~ 50 wt.% Fe). These distinct compositions imply that Mercury-analog planets likely have different interior structures and may preserve unique atmospheric compositions. Our models are then used to classify whether the identified exoplanets may resemble Mercury-analog or not. Additionally, we highlight the uniqueness of Mercury within our solar system, suggesting a lateral event such as a giant impact or mantle evaporation may have stripped its mantle, contributing to its unusually high CMF.

[1] McDonough & Yoshizaki 2021 [2] Namur et al., 2016 [3] Cartier & Wood 2019

SESSION 4 - EXPLOITATION, GEOHERITAGE, ORNEMENTAL STONES, INDUSTRIAL MINERALS

Conveners

Capucine Bertola, Pierres et Marbres de Wallonie (capucine.bertola@pierresetmarbres.be)

Jan Elsen, KU Leuven (jan.elsen@kuleuven.be)

In this section Belgium's rich geological heritage is depicted in its impact on landscapes and its provision of the mineral base of the built environment, past and present. The link between the geological substrate and cultural heritage were created and maintained by many generations of inhabitants with profound knowledge of their environment, but this link seems to be broken today. Much of the traditional knowledge has been lost on where to find and how to use local mineral resources or on the hazards related to former exploitations or land use. Geoscientists have become essential partners to archeologists, historians, architects, city planners, tourist agencies … in reconstructing these links, but also to quarry operators, construction companies for providing sound bases for efficient and ecological extraction and use of the subsurface materials. The geological diversity of Belgium's landscapes is gradually becoming acknowledged as a valuable resource for education and tourism and integrated into global protection and management schemes.

Invited Speaker

Role of Microbial Carbonates in CO2 Storage

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In recent decades, the increased consumption of fossil fuels has led to a dramatic rise in atmospheric CO2 levels. To mitigate this increase, measures to limit greenhouse gas emissions and other pollutants have been implemented in recent years. The possibility of carbon capture and storage (CCS), as well as the capture of other pollutants, offers new perspectives in regulating these parameters, which are primarily responsible for current and future climate changes. Among the processes for capturing and storing CO2, approaches focusing on the ability of organisms to induce carbonate precipitation seem particularly promising through the accumulation of carbonate deposits in rivers. Long considered to result from abiotic processes attributed to chemical precipitations, carbonate concretions contain a significant microbial component, suggesting an active role in the formation of these carbonate deposits. Therefore, carbonate concretions result from a balance between abiotic and biotic processes. While the functioning of microbial systems and their role in carbonate precipitation are relatively well understood, significant gaps remain in quantifying the volumes of carbon that can be stored and the kinetics of mineralization. By defining optimal bio-physico-chemical conditions and constraining mineralization kinetics, it becomes possible to predict the volumes of CO2 and pollutants captured and stored in the form of carbonates induced by microbial community activity. One potential use for the resulting carbonated products could be in construction materials or bioremediation through pollutant mineralization.

Fifty shades of black – nondestructive methods for the identification of Belgian black marbles

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The world-famous black marbles of Belgium are not marbles in the petrographic sense. Rather, they consist of fine-grained, well-cemented Paleozoic limestones devoid of veins or fossils. Consequently, they exhibit a uniform pure black color, and can be finely polished. Several detailed studies have been dedicated to these ornamental stones, including those focused on Basècles (Overlau, 1966) and Dinant (Mottequin, 2004) (see also Dusar et al., 2009).

Five varieties of Belgian black marbles were recently investigated for discrimination purposes (Boulvain et al., 2020). They span in age from Frasnian (Golzinne) to Visean (Dinant, Theux, Basècle, Lives). Three methods were employed: petrography, magnetic susceptibility (MS), and geochemical analysis of major elements and REE.

The MS results clearly differentiate the Frasnian black marble from its Visean counterparts. However, MS fails to distinguish between the various Visean black marbles. Petrographic analysis revealed various microfacies reflecting predominantly quiet environments, occasionally interrupted by more energetic phenomena such as turbidites or storms. These microfacies were integrated into two depositional models: a calm offshore setting, situated below or in close proximity to the storm wave base (Salet, Basècles), and a shallow yet highly sheltered zone protected from waves and currents (Lives and Golzinne).

Nevertheless, all these techniques are destructive and require sampling, with sample sizes ranging from approximately 1 g for geochemical analyses, around 10 g for MS, to the preparation of thin sections for petrography.

The aim of the present study is to evaluate spectrophotometry, a non-destructive method, for identifying black marbles. This method may be complemented by portable MS, eliminating the need for sampling.

Spectrophotometric analysis of 170 samples was conducted using a CM-700d/600d spectrophotometer from Konica Minolta. This device features openings with diameters ranging from 3 to 8 mm, allowing for averaging over a relatively large surface area. The parameters provided by this instrument include: L* for luminance, a* representing the position of the sample color on the red-green axis, and b* representing the position of the sample color on the yellow-blue axis. The device employs a pulsed xenon lamp as its light source and covers a spectral range from 400 to 700 nm. Specular reflection can be either included or excluded.

Comprehensive tests were conducted using various parameters and capabilities of the device, with the best discrimination achieved through the L* and a* values. Experiments were also carried out to assess the effect of surface treatment on marble samples, revealing that the most favorable results were obtained from acid-etched or polished surfaces.

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550 Million years of Geology of Wallonia through the building stones of historical buildings in Liege – a popular science project

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Through the main historical building of Liege Medival city center, we have designed a stroll allowing to go through 550 Million years of the geological history of Wallonia. This tour combines information on the Geology of Wallonia and on the history of extractive activities in Belgium.

Our tour starts Place Saint Lambert. We can see Cambrian or Ordovician slates on top of some historical buildings. Then the Pavés de Quenast (Silurian magmatic rocks) are the testimony of a subduction phase. The Society of Quenast porphyr was one of the most active producing cobbles in the 19th century, with those cobbles in the Grand Place de Bruxelles, Champs Elysées and Place Rouge.

After the building of the Caldeonian mountain belt, the following sediments are the preliminary result of the erosion of this mountain belt, with conglomerate, sandstones and slates (on top of the Palais des Princes Evèque). When the mountain belt is partially eroded and provides less detrital material, carbonates starts to develop and we can observe the beautiful “Marbre Rouge” mud mound place Saint Lambert, as well as on the emblematic Perron. The Quarries of “Marbre Rouge” have been very active from the 16th century and the Marbre Rouge has been used among other in the Versaille Chateau. We continue our tour to the Saint George area, at the rue sur les Foulons and we observe the Rhisnes Formation, lateral equivalent of the mud mound, with bioturbated limestones. In the place Saint Barthelemy, we can see the Lustin Formation “reefal deposits”, as well as the Famennian sandstones as cobbles.

In the court Saint Antoine, we have the transition to the Carboniferous with the famous “Petit Granit” full of crinoids. The “Petit Granit” quarries are active since the 17th century, however, in Liege, the material is used mostly after the 19th century. Then we reach the court of the Musée de la Vie Wallonne, with the “Pierre de Longpré”, rich in ooids and crinoids and the “Pierre de Vinalmont” rich in ooids (with beautiful cross and herringbone stratifications). We can also see the “Pierre de Meuse” displaying dark limestones with corals, or stromatolites.

The Namurian “Grès d’Andenne” can be seen in the rue Pierreuse. It is noticiable that this stone is actually a very sturdy quartzite, and has been used in most of the numerous steep streets of Liege. We reach the Terrasse des Minimes, with the Westphalian sandstone. This stone was easily extracted in and around Liege and so, has been largely used, but it is easily altered.

The Bajocian “Pierre de Longwy” is exposed in the court des Minimes and is also strongly altered. We go back to the Palais des Prince Evèque to see the “Maastrichtian chalk” and to revise the multiple occurrence of Lower Carboniferous stones in the court of the Palace. We finish with the place Saint Lambert and with the Paleogene “Pierre de Gobertange” full of large bioturbations.

One geological site of the Geopark Famenne Ardenne on the list of the second 100 IUGS geological sites

DELABY S., HALLET V., QUINIF Y., VERHEYDEN S.

UGGp Famenne Ardenne

Since 2024, there have been two UNESCO Global Geoparks (UGGps) in Belgium, Schelde Delta a new geopark labelled this year and Famenne Ardenne labelled in 2018 (Verheyden, 2024). A UNESCO Global Geopark are single, unified geographical areas where sites and landscapes of international geological significance are managed with a holistic concept of protection, education and sustainable development. The purpose of a UGGp is not exclusively on geology but to explore, develop and celebrate the links between that geological heritage and all other aspects of the area's natural, cultural and intangible heritages. (https://www.unesco.org/en/iggp/geoparks/about).

The Famenne Ardenne UNESCO Global Geopark has highlighted the Devonian stratigraphy and its emblematic karst. This karst, mainly swallow holes resurgence systems and underground meander cutt-offs type due to the underground pathways of rivers, in Appalachian relief, is developed mainly in a Givetian limestone band known locally as the Calestienne. The Calestienne is characterised by a high density of karst phenomena with a particularly high population and anthropization.

The designation is not permanent but for a period of four years after which the functioning and quality of each UNESCO Global Geopark is thoroughly re-examined during a revalidation process.

In 2023, our geopark successfully received a revalidation mission extending our recognition until 2027. To achieve this, we focused on our actions. The Starting point, the identification, characterization, digitalization, study, and management of geoheritage and geological sites. The establishment of the geopark has had a profoundly positive impact by raising awareness among the public, including policymakers, about the significance of geology. While there is still progress to be made, these initiatives have fostered a greater appreciation for geoheritage and its role in enhancing our understanding of Earth processes through research. The public, whether residents or tourists, has shown keen interest and curiosity in exploring these territories in novel ways. Geo-heritage is now also taken into account in the development of nature parks.

The Durbuy Anticline stands as an easily accessible and captivating geological feature, drawing in a diverse audience. Its significance is deeply ingrained in the local culture and heritage, actively embraced and promoted by the medieval town of Durbuy.

This site represents an archetype anticline and as such it is a classical site used for the education of geology and geoscience for students from Belgium and neighboring countries.

In 2023, with the help of the NCGS (National Committee for Geological Sciences, Belgium), the Durbuy Anticline was proposed as a candidate geosite to feature in the esteemed Second 100 IUGS Geological Heritage Sites in the History of geosciences (Verheyden, 2024).

An IUGS Geological Heritage Site is a key place with geological elements and/or processes of international scientific relevance, used as a reference, and/or with a substantial contribution to the development of geological sciences through history (https://iugs-geoheritage.org/).

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The wonderfully exposed Durbuy Anticline in the medieval town of Durbuy taken by drone was first described in 1807 by the famous Belgian geologist Jean-Baptiste-Julien d'Omalius d'Halloy. (photography Christian Burlet).

Geodiversity of a stone deposit in the old city centre of Antwerp: source of information on Roman and medieval trade and use

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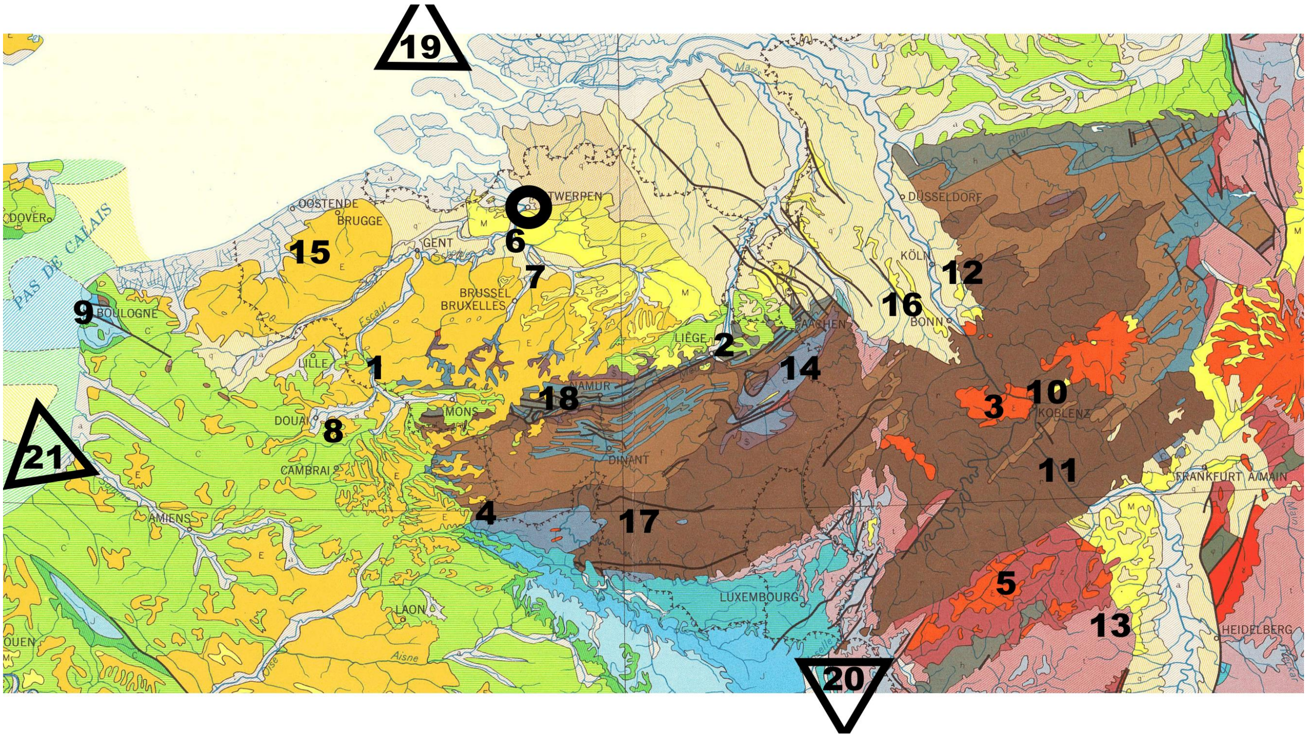
Archaeological excavations in the medieval city centre of Antwerp, due to the renovation of the Scheldt quays, uncovered under the Noorderterras a stone deposit, which was studied for its lithological content. In total more than 7.5 tons of stone were excavated, cleaned and classified into >17% of Tournaisian stone from on-site or nearby demolished buildings, unexpectedly <20% of septaria from clay pits along the Scheldt and Rupel rivers, 58% of ship ballast stone, the remainder composed of other building stones, utensils and artificial stone. Among the ballast stones, 15% was composed of flint, probably deriving from the coastline in actual northern France. 43% of ballast stone material was composed of mostly siliciclastic rocks, mainly vein quartz, veined quartzite and quartzite. Among these, Lower Devonian Taunus and Koblenz quartzites were predominant, deriving from the southern edge of the Rhenish Massif but likely collected from downstream river Rhine terraces. Building stones and utensils allowed even more precise provenance determination. Basaltic millstones from the East Eifel used to be recycled as building stone; more special were occasional finds of pestles in garnet-amphibolite from the Caledonides of middle Norway and the Eidborg whetstone from southern Norway. Lede stone was obtained from the nearest-by occurrences in the area between Brussels and Mechelen (Malines), due south of Antwerp. Glauconiferous sandstone from local Neogene sands found its way into the stone deposit, although not known as a building stone. Calcareous tufa and Carboniferous sandstones, probably both from the Liège basin, are similar to nearby finds in gallo-roman context, hence are likely recycled. Calcareous sandstone of Boulogne, Connincthun calcareous sandstone – the first record in Belgium – and Marquise oolite of Jurassic age, together with the Cretaceous flints point to coastal trade in direction of Boulogne-sur-Mer. Building stones composed of volcanic tuff of the Römer Tuff type and Triassic Bunter Sandstone suggest a Rhenish origin, no longer persisting in the existing historical buildings. This Rhenish origin is further supported by unique rock types such as Reimerath Trachyte, Palagonite Tuff, Nahe Red Porphyry, Oligocene Hydrobienkalk from the Neuwied Basin. It can be concluded that the area of Cologne to Mainz along the river Rhine was the major trade destiny for Antwerp harbour, serving as a port of transshipment for coastal trade along the southern North Sea shore, in the period from the 9th to the 14th century.



Provenance map of natural stones recognised in the Noorderterras stone deposit, assumed or proven depending on the stone type: O: local glauconiferous sandstones, lithified Quaternary sand; 1: Tournai limestone; 2: calcareous tufa, Carboniferous sandstones; 3: volcanic tuff, basalt(lava), scoria, Reimerath trachyte; 4: Macquenoise arkose; 5: melaphyre, Nahe-porphyry; 6: septaria; 7: Lede stone; 8: Artois sandstone; 9: flint, chalk, Boulogne calcareous sandstone, Connincthun sandstone, Moulin-Wibert limestone, Marquise oolite; 10: Hydrobia limestone; 11: Taunus quartzite, Koblenz quartzite, vein quartzite, vein quartz; 12: Paleozoic sandstones; 13: Bunter sandstone; 14: chloritoid-vein quartz, Revinian quartzite; 15: Ypresian sandstone (veldsteen); 16: Aquaduct-Marmor; 17: Haybes arkose; 18: speleothem; 19: garnet-amphibolite, Eidborg whetstone (Norway); 20: granite, lydite, metaquartzite (Vosges); 21: granite (Channel Islands) (Atlas of Belgium, Plate 2).

The Boulogne calcareous sandstone and coquina, important historical building stones in the Counties of Artois and Flanders

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Whereas historical building stones from the Boulonnais area, such as the Marquise Limestone and the Boulonnais marbles are better-known, the historical importance of the Boulogne calcareous sandstone and coquina has only recently been elucidated. The latter rock types represent particular beds within a 120 m thick sequence of Late Jurassic mixed siliciclastic-carbonate marine deposits, superbly exposed along a 30 km long coastal cliff section north of Boulogne-sur-Mer (Pas-de-Calais department, France). The exposed rocks belong to the Middle-Late Kimmeridgian and (Early) Tithonian stages and consist of grey to beige calcareous sandstones, siltstones and limestones alternating with dark-grey to black organic-rich shales, marls and mudstones, deposited in a storm-dominated, nearshore marine environment. Sandstones form the real backbone of the Boulonnais cliffs and correspond to the succeeding formations of the Grès de Connincthun, the Grès de Châtillon and the Grès de la Crèche. Sandstone beds from the lower Grès de la Crèche unit used to be quarried for building and pavement stones near Boulogne-sur-Mer. Moreover, most of the heterogenous calcareous sandstones and thick-shelled coquina beds occurring in the coastal cliffs and on the beaches between Boulogne and Cap Gris Nez, have been used as ballast and building stones, at least since the twelfth century. Besides local use (e.g., in and around Boulogne-sur-Mer) they have been exported to many coastal settlements of the Flanders County and as far as the Antwerp area (Dreesen et al, 2024). Medieval building stones have been identified for the first time in the Bruges area by Debonne and Dreesen (2015). In modern times the above sandstones were extracted from different quarries on the mainland ("Pierre de Baincthun"). However, after inspection of medieval buildings in the Artois and Flanders Counties, we found a much broader lithological spectrum corresponding to various lithofacies of the Crèche and Châtillon Formations. Moreover, thin shelly tempestites and thick sandy coquinas, lithostratigraphically belonging to the intermediate Argiles de Châtillon, have been used as well. Therefore, two new building stone names are proposed (Dreesen et al., 2024): the Boulogne Calcareous Sandstone grouping all late Kimmeridgian to early Tithonian calcareous silt- and sandstones and the Boulogne coquina corresponding to the sandy shelly limestones occurring within the Late Kimmeridgian and Early Tithonian.

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17th century Fort Mahon or Fort d’Ambleteuse standing on the Grès de la Crèche Formation and built with the same material (© R.Dreesen)

Effect of water saturation on the mechanical properties of various chalks characteristic of the Northwest European geoheritage

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Chalk rock holds significant socio-economic value in Northwestern Europe, primarily because it serves as an important groundwater aquifer. It supplies about half of England's groundwater and up to a quarter in southern Belgium. Beyond its geological significance, chalk also has a deep cultural impact. It plays a substantial role in shaping landscapes, especially in coastal regions, such as the iconic Etretat cliffs. Chalk has also been used in construction, as is the case in the Beauvais Cathedral (France) built in the 13th century. Underground chalk quarries have historically provided lime for agriculture and building material. Some, like the "Crayères", have been converted into Champagne cellars of which some are included in the UNESCO World Heritage list. Underground chalk quarries frequently face collapses, leading to engineering issues. The formation of sinkholes in northern France is becoming a recurring problem, and the spectacular landslides of chalk cliffs in Normandy and Boulonnais are also dependent on weather variations and chalk's water saturation.

Our study investigates the impact of water on the mechanical behaviour of different chalk lithotypes. We sampled five chalk lithotypes, namely white micritic, calcarenite, argillaceous, cemented and cemented phosphatic chalk (Faÿ-Gomord et al., 2016). A thorough petrographic characterization was performed, including NMR analysis, MICP, optical microscopy, and SEM observations. The cemented phosphatic chalk displays a unique bimodal T2 distribution, reflecting two major pore size populations. Microscopy allowed to determine that the first peak corresponds to the microporosity of the matrix, while the second corresponds to large pores. The latter may be associated with intense burrowing during eogenesis, within the early stages of hardground formation.

The mechanical properties of the chalk were characterized by performing uniaxial compressive tests on dry and 100% water-saturated samples. As reported in literature (Georgieva et al., 2021; Geremia et al., 2021, Pajiep et al., 2024), saturated samples display a lower strength than dry samples. The sensitivity to water is often expressed by the wet-to-dry (WDR) ratio. Strength in most samples drops by 60%, meaning a WDR of 0.6. However, the WDR of argillaceous chalk equals 0.8. On the other hand, the WDR of the phosphatic sample is only 0.23. This is likely due to the early cement consolidating the framework of the microtexture and the grain-to-grain contact not being easily affected by fluid-rock interactions.

Additionally, the water-saturation of large pores - unlike micropores - may not significantly impact the strength of the rock. Similarly, the Young's modulus WDR equals 0.16 for the argillaceous chalk and ranges from 0.2 to 0.36 for most other chalks. However, for the cemented phosphatic chalk, the WDR equals 1, indicating that the elasticity of the sample is not altered by water saturation.

These preliminary results already highlight the influence of the chalk microtexture, its depositional setting, and diagenetic history on the mechanical properties of the samples when facing water-saturation. Given the expected increase in water infiltration due to climate change, water saturation could pose a significant threat. Therefore, additional analyses are being conducted to better understand and forecast its impact on chalk.

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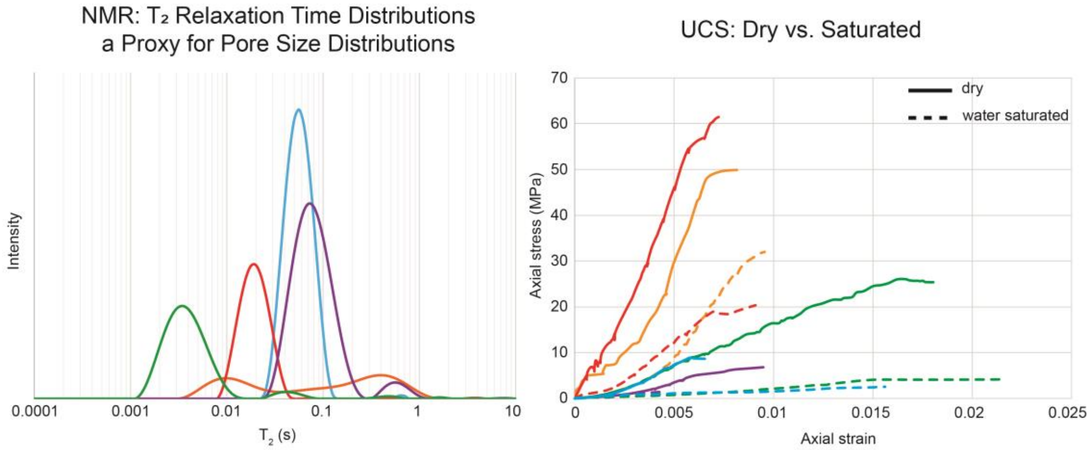

	Sampling location	He-Porosity (%)	Gas Permeability (mD)	Average Pore throat diameter (nm)	Tortuosity	Average dry UCS (MPa)	Average saturated UCS (MPa)	Average dry Young Modulus (MPa)	Average saturated Young Modulus (MPa)
White - micritic	Obourg quarry, BE	43,4	5,3	278	6,2	7,0	2,4	1904	384
Cemented	Flamborough cliffs, UK	21,5	0,4	168	4,2	58,1	24,1	9892	3606
Calcarenitic	Normandy cliffs, FR	44,1	15,4	670	6,6	5,0	1,9	1072	396
Argillaceous	Cap-Blanc Nez cliffs, FR	20,0	0,2	103	8,3	20,5	3,2	1536	255
Cemented phosphatic	La Malogne quarry, BE	17,2	4,3	463	7,2	41,4	31,9	6539	6567

(1) Representative NMR T2 analysis reflecting pore size distribution (2) Characteristic Strain versus Stress curves from the uniaxial compressive tests (3) Main results and characterization of five chalk lithotypes. Colours in the table correspond to the

A historical perspective on underground limestone quarrying in Limburg, Belgium: the archives of the former Department of Mines

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Since the Late Middle Ages Maastricht Stone has been excavated in underground quarries leading to extensive underground gallery networks (Lahaye et al., 2022). It is often assumed that since the end of the 19th century underground exploitation was of little importance. However, Nijland et al. (2017) showed the annual production rates for limestone building blocks in the 20th century for Limburg (NL) having clear revivals since the start of the First World War into the 1930's and after the Second World War till 1960 after which a gradual decrease follows. Besides the use as building material, it is also used for various industrial processes of which the cement industry is the most known. The underground limestone quarries in the province of Limburg (BE) have remained largely unexplored compared to the Dutch province of Limburg, where more historical interest was developed for quarries such as the Sint Pietersberg in Maastricht and the region of Valkenburg.

This research aims to investigate the evolution of limestone production in underground quarries in Limburg (BE) and to identify the active underground quarries since 1850. Additionally production statistics of limestone from Limburg are put in perspective by making a comparison with national production statistics of various other natural building materials. Also the relevance of limestone production for industrial processes such as the cement industry and the use of soil conditioner is explored.

The archives of the former Department of Mines, dating back to 1852, provide a detailed insight in the statistics of limestone exploitation of underground quarries in the Belgian province of Limburg. Reporting on the quarry process and conducting safety supervisions, these documents provide a reliable historical dataset. In addition to from annual statistics such as production values, number of workers, number of active work fronts, detailed information from individual underground quarries are obtained by studying archives such as inspection reports from mining engineers.

The results show strongly varying production values for building blocks from 1873 up to 1900. From 1901 till the start of the First World War production peaked, superseded by similar values as in Dutch Limburg after this period. The excavation of limestone for other purposes than building material has always been present on a small scale but production strongly increased after the First World War. After a strong diminishment and even a total decline during the recession years of the 1930's, a strong expansion set in and this industry soon became dominant over building block production. After the Second World War, block production increased again to a high around 1950 followed by a gradual decrease into the 1960's. These results suggest that the assumption that the underground production of limestone was of little importance since the 19th century, can be disputed.

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Impacts of the mining operations on the biodiversity in the Katanga Copper belt

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The Katanga Copperbelt that crosses the southeast part of the Democratic Republic of Congo (DRC) is home to the world-richest Cu-Co deposits (Mambwe et al 2023; Liu et al 2024). To make the best of mineral exploitation so that it partakes to trigger of the country socio-economic development, several reforms were undertaken by DRC government to improve the mining sector governance. In this gait, the Law N° 81- 013 from 02 April 1981 had been amended and supplemented by the law n°82-039 from 05 November 1982, which in its turn had been amended and supplemented by law n° 007/2002 from 11 July 2002 known today as the DRC's ancient mining code. The latter consecrated the DRC's mining sector liberalization with the aim to attract more foreign direct investments towards the Large-Scale Mining (LSM). The same law established conditions to enable Congolese to practice the Artisanal and Small-scale Mining (ASM) of mineral resources. In 2018, the new Law no. 18/001 of 09 March 2018 was promulgated to address the weaknesses shown by the 2002 mining code. These different reforms undertaken in the mining sector resulted in a significant increase in the mining output enabling the DRC to rank itself as the African leading producer of copper and the world first producer of cobalt. However, this growth in the mining output was accompanied by the generation of huge amounts of mineral wastes and mine tailings together with metal-laden that polluted the environment (Shengo et al 2020).

Indeed, their management had not been conducted environmentally friendly to safeguard the environment and this makes them to threaten human health, wildlife and biodiversity. Thus, some mining effluents are discharged into rivers without prior treatment, causing river pollution which leads to the death of fish and other aquatic organisms, contamination of the drinking water of the population. The stock of the waste and tailings in the area causes soil and air pollution through wind erosion during the dry season and is an additional source of water pollution during the wet season through water erosion. Soil denudation by open-cast mining causes deforestation, actually certain plant species endemic to the copper-bearing hills of Katanga are threatened with extinction. There is also another need to banish all bad practices in artisanal mines such as the enrichment of useful minerals through the washing of ores in watercourses to rid them of the gangue minerals. A new look on the ecology within the climate change must be the first priority and the respect to the environment regulations must be reinforced. Any mining activity should make the conservation and protection of flora and fauna one of its priorities. There is a need to maintain the best environmental practices throughout the life of the mines so that to minimize releases of toxic pollutants.

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Scientific, Educational and Tourism Potential of the Mbanza-Ngungu caves in DR Congo

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In Central Africa, the geology of caves remains little known. The study of the cavities in this region mainly focused on archaeology and biology. However, geological knowledge is essential for the preservation of these sites. The studies, carried out as part of the GeoRes4Dev project led to the RMCA, has been funding geological studies on karst in the DRC since 2019, in the Mbanza-Ngungu region which has numberous caves. The work began with the inventory of known caves in the region. They also allowed the discovery of new cavities, a certain number of which have been topographed. Lithological, sedimentological and hydrological studies are underway in different caves.

Among these, Ngovo and Ndimba were the subject of studies which provided archaeological materials of significant importance, which enabled them to appear since 1997 on the provisional list of possible UNESCO world heritage sites. Some caves, including Ngovo, are home to an endemic fish species Caecobarbus geertsii.

Caves are preserved areas containing valuable archives of Earth's history, recording thousands, even millions of years of geological evolution. Speleothems, sediments, and the orientation of caves provide essential clues about past environmental conditions, tectonic movements, climate change, and the evolution of the Earth. By studying, understanding and preserving this region, we can better understand the challenges our planet faces today, including climate change, biodiversity loss and ecosystem degradation. The caves also provide a unique context for studying underground biodiversity and human history through archaeological remains.

In addition to their scientific value, the caves have educational importance. Educational programs and awareness activities are increasingly being promoted in schools, higher education institutes in the region, and among the general public who visit the caves to observe geological processes, endemic species, discovering the richness and diversity of this unique heritage.

On the tourist level, the Ngovo and Ndimba caves have been attracting visitors since colonial times. Recent years, we have observed an increase in local tourism. However, there is lack of raising awareness among visitors regarding the caves vulnerability and the importance of their conservation.

The creation of a UNESCO Global Geopark (UGGp) around the Mbanza-Ngungu caves would preserve a unique geological and biological heritage, while offering sustainable development opportunities for local communities. Encompassing the Mbanza-Ngungu area within an UGGp could elevate the region into a leading destination for education and tourist, thereby contributing to the conservation and enhancement of its natural and cultural resources.

Splendid speleothems in Ndimba cave. P. Lahogue©MRAC.

Tufa deposits at the eastern edge of the Hesbaye Plateau (Vottem and Hollogne-aux-Pierres, Belgium)

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This presentation discusses the little-known deposits of calcareous tuff in obsequent rivulets draining the eastern edge of the Hesbaye Plateau. Hollogne-aux-Pierres has been known for its remarkable tufa deposits. Nowadays, the tufa (located in the municipal park) is inactive. Before the stream (the Mahai) was buried in a culvert, there were active deposits of this rock. In 1832, several encrusting springs heavily laden with calcareous tuff were described. Blocks of limestone tuff can be found in various buildings in the village, including the Lucas Farm and the church tower, as well as under the lime tree in the Place de l'Eglise. The source of the Rida in Vottem produces very clear water, as evidenced by a large deposit of active tufa. There are also gours. Such petrifying springs are quite rare north of the Meuse. There is an extremely rare moss, Campylium stellatum. Further upstream, the sources of the Rida have been drained over time. Towards the middle of the 20th century, there was an ancient quarry "Trô à'l Tonîre" as a scar in the landscape, which was then filled in by municipal waste. It is more than likely a limestone tuff quarry. The old Roman road Tongeren-Trier "Lî Tchaussèye" runs alongside this old quarry. It is just a short step to think that Vottem was one of the sources for the limestone tuff used in Roman constructions in Tongeren, located 15 km away.

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Partial view of the 6-metre high abandoned tufa quarry in Hollogne-aux-Pierres

Embodied carbon of construction products: A calculation tool. Application to natural stone and its relevance to low-carbon strategies

Tristan PESTRE, Olivier CHÈZE

Technical Center for Natural Building Materials (CTMNC), Natural Stone Department, Paris

With the increasing focus on sustainable construction and stringent climate regulations like France's RE2020, there is a pressing need for accurate environmental data to guide low-carbon building strategies. Traditionally grouped with other geosourced materials, the natural stone industry faces unique challenges in quantifying and reducing its carbon footprint. The carbon footprint of natural stone varies, considering its role as long-term carbon storage within the lithosphere and, in less favorable scenarios, as materials extracted and minimally transformed with the potential for extended use [1].

To address these needs, CTMNC's Natural Stone Department has developed a reproducible tool for calculating the climate change impact of natural stone construction solutions [2]. This tool not only aids the natural stone industry but could also become applicable to other construction products, fostering comprehensive eco-design strategies.

The tool employs an inverse analysis of verified Environmental Product Declarations (EPDs) from the INIES database and other trusted Life Cycle Assessments (LCAs), adhering to EN 15804 standards. It calculates the carbon footprint from 'cradle to grave', considering product thickness and density, transportation modes, and distances. Users can adjust these parameters through an Excel-based interface to generate printable tables and graphs.

The study highlights that the climate change impact per unit area of natural stone is proportional to the product's thickness and density. However, on a mass basis, the impact is inversely proportional to thickness – 'When more is better' [3]. Transportation significantly influences the overall carbon footprint, with local sourcing demonstrating markedly lower impacts. For example, natural stone walls have a median impact of 40 kgCO2eq/ton and are less impactful than cross-laminated timber (CLT) and low-carbon slag concrete [4].

The findings underscore natural stone's viability as a low-carbon construction material, especially for local applications. The tool's adaptability to other products and integration into LCA software positions it as a critical resource for stakeholders aiming to meet climate targets. If natural stone were chosen over concrete for 30% of new French collective housing projects from 2025 to 2050, it could reduce embodied emissions by 2.8 Mt CO2e, compared to 0.4 Mt for slag concrete and 1.2 Mt for CLT [4].

The tool will soon incorporate additional environmental indicators (like water needs, energy consumption, etc.) and expand its scope to include a collective EPD configurator for the natural stone sector. A new version is anticipated by the end of 2024.

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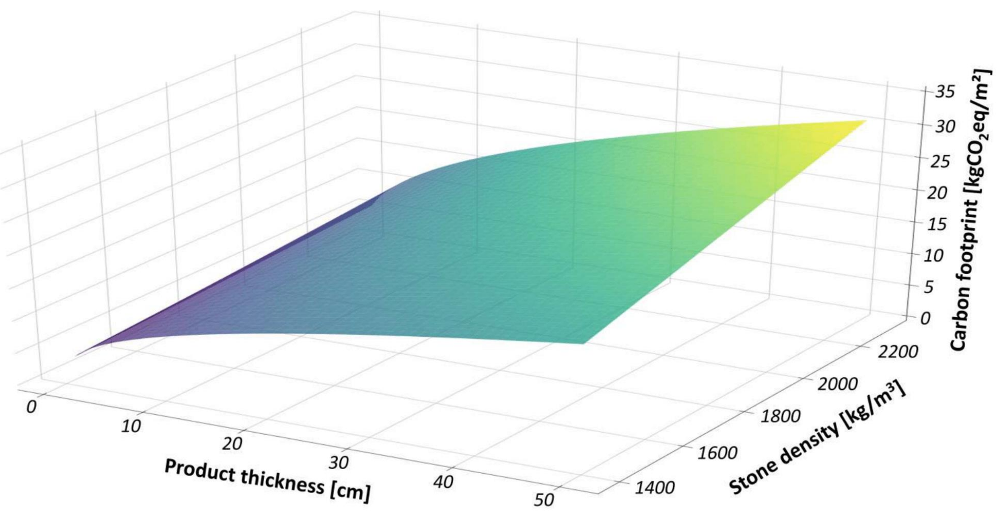

CTMNC poster natural stone carbon calculation tool

Heritage Stones in Belgium, particularly in Wallonia

Francis TOURNEUR

SPW / ARNE, Service géologique de Wallonie

The concept of geoheritage has been introduced a long time ago but it took some time to be used in our country. Among different actions, the project of designation of 'Global Heritage Stone Resource' was elaborated more than 10 years ago and two publications in 'Episodes' proposed two historical stones from Belgium, the 'Lede Stone' from the Lutetian (Tertiary of Flander) (T. de Kock et al., 2015) and the 'Belgian Bluestone' called 'Petit Granit' from the Tournaisian (Lower Carboniferous, Paleozoic of Wallonia) (D. Pereira et al., 2015). The last one was nominated in 2017 and the first one, in 2019. In 2016, at the Congress of the EGU in Wien, F. Tourneur & D. Pereira proposed the two most classical Belgian 'marbles' (indeed compact limestones), the 'Belgian red marbles' and the 'Belgian black marbles'. A detailed publication on the last ones (F. Tourneur, 2018/2020) allowed to introduce a candidature in 2019, following a new protocol established for 'Heritage Stones'. The recognition of the 'Belgian black marbles' was granted in February 2024 and the case of the 'Belgian red marbles', as evident as the 'black' ones, is in construction to be submit as soon as possible, to achieve the global recognition of the Belgian marble production – the other varieties, grey, black and white, breccias… are of more limited diffusion. In the meantime, R. Dreesen et al. (2021) published a detailed paper on the 'Pierre de Meuse' ('Meuse Limestone') as historical heritage stone, but until now, it was not followed by the introduction of an official proposition to the Commission.

The HERitage STONES ('HerSTONES') designated lithic materials with historic use for more than 50 years, wide-ranging geographic applications. They have to be commonly recognized as a cultural icon, including association with national identity and/or significant contribution to architecture, sculpture and decoration. But they are supposed to be available for quarrying, for new realizations and correct restoration of cultural heritage. The designation, purely academic, brings potential benefits in cultural, scientific, architectural, touristic, environmental and/or commercial.

The International Commission of Geoheritage [https://iugs-geoheritage.org] was created at the IGC in Cape Town in 2016, with three different subcommissions, on sites, heritage stones and geocollections – the second one is here concerned, with the International Geoscience Programme 637, titled 'Heritage Stones Recognition'. A general public book, richly illustrated, is in press about the first 50 designated heritage stones, in parallel with the web site, frequently updated. The first subcommission already published a book on the first 100 geosites around the world. Strangely enough, nothing from Belgium, particularly from Wallonia, yet one of the cradles of modern geology. The intention is to propose in the following years the most iconic places, like the cliffs of Dinant, Waulsort and Visé, or the region around Couvin, Frasnes and perhaps Givet – if an agreement can be found with the French comities. The last subcommission, on geocollections, created later, is only beginning its program, but some paleontological collections in Belgium are évident, like the world-famous Iguanodons from Bernissart in Brussels or the renowned fossils of the black marble of Denée, preserved at Maredsous abbey – this last ones already recognized as treasures ('trésors') of the Fédération Wallonie-Bruxelles.

SESSION 5 - SEDIMENTOLOGY, STRATIGRAPHY AND DIAGENESIS

Conveners

Anne-Christine Da Silva, ULiege (ac.dasilva@uliege.be)

Marc De Batist, UGent (Marc.DeBatist@UGent.be)

This session supports any submission related to basin research and sedimentology and stratigraphy. This includes all types of sedimentary settings (marine, continental, deep, shallow, clastics, carbonate), oriented towards basin scale or more local studies. We also welcome research associated with techniques and technologies in sedimentary and stratigraphy research.

Invited Speaker

Sedimentology at the heart of interdisciplinary research for society

Hannes CLAES

Department of Earth and Environmental Sciences, KU Leuven, Belgium

What is the latest big revolution in the field of Sedimentology? It seems that, for at least half a century, we are carrying out sedimentological research in a very similar, consistent way. Are we at a standstill?

Sedimentology as a term was born in 1925 (A.C. Trowbridge) or formally in 1933 (H.A. Wadell). After a focus on heavy metals, provenancing and thin-section petrography, the hydrocarbon industry caused a huge boost from the 1950s. Differences in sediments and sedimentary rocks were appreciated because of their different application (e.g. source vs reservoir vs cap rocks). And by considering sediments and sedimentary rocks as products of processes related to depositional conditions and environments, the concept of facies gained a central role in sedimentology-driven science. In addition, sedimentologists started looking at modern analogues to understand depositional processes. In the 1960s and 70s, sedimentology like the rest of geology was strongly influenced by the concept of plate tectonics and also the biotic contribution in the rock cycle gained appreciation. The introduction of sequence stratigraphy and the concept-boost of outcrop analogues in the 1980s seem to be the last big revolutionary changes in sedimentology.

Since then sedimentologists use a consistent approach, where basin-scale seismics, outcrop (analogue) studies, (thin-section) petrography completed with chemical laboratory analyses are positioned centrally. This approach has proven its value time and time again, and continues to do so. The standard set of techniques got of course a significant upgrade (e.g. resolution) and are complemented with state of the art imaging and analysis techniques. Lidar, Photogrammetry and (X-ray) Computed Tomography help to make the transition from 2 to 3 dimensions. With image analysis at their center, they are also particularly suited for including AI applications, the latest cool kid on the block.

Where we know that, in the past, industry acted as the main engine behind the change in approach (1950s), modern enigmas related to geothermal energy, gas or nuclear waste storage, wind energy, potentially toxic chemicals and even the building stone industry would be expected to drive new approaches. Sedimentologists are challenged to think differently and across disciplines. And indeed, where once sedimentologists adopted a multimethodological approach to study sediments and sedimentary rocks as the products of processes, we now can use sedimentary insights to optimize sedimentary processes for industrial applications. For example, precipitation of calcite ($CaCO_3$), is a fundamental process studied by many sedimentologist since years. The same process of cementation traps CO_2 over time spans of >1000 years and is highly desirable for underground CO_2 storage (CCS). From a whole other point of view, the same process can be used to cure CO_2-negative bricks and pavers (CCUS). And from again another point of view, cementation of sediments around windmill monopiles strongly influences stability during operation but also decommissioning after operation. With just one process as an example, sedimentological insights seem to be more relevant than ever. Perhaps as modern sedimentologists we started to change our way of thinking already and unknowingly are part of the next revolution?

Seismic and sedimentological characterization of the post-eruption infill of the Laacher See caldera lake in Germany

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The East Eifel Volcanic Field (EEVF) in the west of Germany has received increased scientific attention in recent years due to new findings on ongoing deep magma-related seismicity and regional uplift. The most recent volcanic event in the EEVF was the eruption of the Laacher See Volcano around 13 ka BP, which is well-studied in central Europe due to the Laacher See Tephra frequently being used as a regional chronostratigraphic marker. This eruption event featured several phreatomagmatic and Plinian phases, as well as vent migration and magma chamber collapse, resulting in the formation of a caldera which subsequently filled with groundwater to form a lake. Present-day activity of the Laacher See system is evidenced by degassing vents in the lake and along its shores, emitting CO2 of magmatic origin. Although the Laacher See Eruption has been the topic of many studies in the past, the structure and infill of the caldera has not been fully documented. During two surveys at Laacher See in 2019 and 2021, several types of geophysical data were collected to investigate the lake floor and subsurface. High-resolution seismic reflection profiles were acquired with different acoustic sources, using different frequencies. These profiles were used to construct a seismic stratigraphy of the lake sedimentary infill. Additionally, a multibeam echosounder was used to construct a high-resolution bathymetric map of the lake floor. Our results show two vent-shaped subbasins within the caldera depression that are mostly filled with acoustically laminated sediment, reaching depths of at least 50 m below the lake floor in the northernmost subbasin. Several stratigraphic units can be identified, which are not always evenly spread across the different subbasins, pointing at different phases of basin infill. In the central part of the lake, we identify a large gas accumulation zone through enhanced reflections and acoustic blanking, preventing visualization of the basin infill and structure underneath. Along the slopes of the lake, the laminated lake sediments often contain mass-transport deposits, occurring along at least 9 different stratigraphic horizons in the lake infill. The lake bathymetry also shows the presence of multiple block-shaped morphological features and sediment creep structures. In order to reconstruct the sedimentation history of the lake since the 13 ka BP eruption, a total of 4 sediment cores were taken during coring surveys in 2019 and 2023, with recoveries between ~3.5 and ~8.5 meter below the lake floor. These sediment cores will be integrated with the reflection seismic data to further characterize different phases of sedimentation in the lake. The acquired data shows promising results that will help to reconstruct the sedimentary evolution of Laacher See since its eruption and aid in a better understanding of the caldera formation and structure, and its sedimentary infill history.

Lithofacies/Microfacies analysis and depositional environments of Ypresian- Lutetian carbonate platform in the Tellian zone, Northwestern Tunisia

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Ypresian to Late Lutetian carbonate platform analysis in northwestern Tunisia were conducted in order to investigate the controls of the facies distribution, particularly in terms of petroleum exploration. This organic matter-rich limestones were deposited within the paleo-depressions in the studied area, characterized by the proliferation of radiolarian and planktonic foraminifera (Bou Dabbous Formation – source rock). Simultaneously, benthic foraminifera-rich limestones were deposited on the flanks and tops of the higher zones (El Garia Formation - reservoir), where nummulites are the most common fossils, like all around the Mediterranean basin during the Eocene period (Belayouni et al., 2011). The globigerina-rich layers could be considered as unconventional reservoir rock. Microfacies analysis and detailed sedimentological observations show Fourteen lithofacies and nine microfacies, distributed in a platform system. The distal ones correspond to globigerina/radiolarian-rich mudstones and wack-to-packstones recognised in the Ragoubet Tassera (TS) and Oued Kasseb (OK) sections. Locally, organic matter filled stylolites/ fissures and oil seeps were observed in the field (in OK section) during the sampling process. The uppermost part of El Garia Formation in Ain El Goussa (AG) section, shows shallower microfacies, characterized by nummulites-rich pack- to grainstones with the presence of annelids and Ostrea.

The lithological description of the studied succession shows an alternation of massive limestones and marly beds. Based on lithology, thickness variation of the beds' doublets, their facies and fabrics, and sequence stratigraphy, five lithostratigraphic units were defined. According to previous studies (Rachdi M., 2022, Vennin et al., 2014; Berrocoso et al., 2013), to the lithofacies' distribution and third-order depositional sequences, nine sequence boundaries were located. The sequence boundaries are commonly characterized by a major facies variation with some subaerial exposure features that were mainly observed in OK section. The correlation of relative sea-level changes derived from the vertical stacking pattern of facies with the global sea-level curve of Sneeden (2010), and coeval successions worldwide, suggests that eustatic sea-level fluctuations played a role in the evolution of this carbonate platform during the Lower Eocene. Meanwhile, regional/local tectonic subsidence within the different tectonic units: the Kasseb and the Adissa tectonic Units (e.g. paleo-highs and paleo-depressions) present the overriding factor controlling the depositional processes of the Bou Dabbous and El Garia formations in NW Tunisia.

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The chemostratigraphic record of the earliest Silurian at Huy, Belgium

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The earliest Silurian is marked by adverse conditions following the termination of the Hirnantian glaciation. The deglaciation was accompanied by the spread of anoxia a major extinction pulse and the widespread deposition of transgressive anoxic black shales. From these black shale records it has been inferred that the climatic conditions remained invariantly adverse during the earliest Silurian. Whether a similar conclusion can be drawn from earliest Silurian non-black shale records remains underexplored. As such an integrated (chemo)stratigraphic study was conducted on a pale earliest Silurian shale succession from a section in Tihange (rue de Bonne Esperance), Belgium, with the intent to constrain paleoclimatic conditions during the earliest Silurian in a non-black shale succession. The combined observation from the XRF, magnetic-susceptibility, spectral gamma-ray, (rock-eval pyrolysis) TOC, IMCP-MS and biostratigraphy records indicate that the earliest Silurian is marked by increasingly humid conditions, increasing weathering rates and a trend towards more reducing conditions. Furthermore, a mercury anomaly (persistent irrespective of normalisation) is observed, which might indicate that LIP activity during the earliest Silurian, could have driven some of the paleoclimatic changes observed in the proxy records.

Impact of orbital forcing on sedimentary records, transition to glacial state and on anoxia expansion through the lower Carboniferous

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The lower Carboniferous marks the onset of the Late Paleozoic Ice Age (LPIA) [1], characterized by bursts of anoxia of different magnitudes through the Tournaisian and Visean stages (in the lower Carboniferous). These anoxic events are the Lower Alum Shale (LASE [2]) at the base of the middle Tournaisian, The Tournaisian Carbon Isotope Excursion (TICE, also called KOBE [3]) in the middle Tournaisian, and the Visean Carbon Isotope Excursion (VICE [4]). Clues have been accumulated pointing to the possibility that anoxia and glaciation may have been paced by changes in Earth's orbit parameters through the Phanerozoic ([5]). These changes are the astronomical (Milankovitch) cycles (Eccentricity, Obliquity and Precession) with specific durations. They impact the incoming solar radiation and seasonal contrasts, hence global climate. In this project, we intend to use cyclostratigraphy (the identification of astronomical cycles in the geological record) as a tool to establish a chronological framework of the lower Carboniferous to reach precise estimates of the durations of these anoxic events and to understand their connection with climate dynamics and orbital forcing. We also intend to delve into Milankovitch forcing related to ice age evolution through the lower Carboniferous. Therefore, five geologic sections have been selected in Namur-Dinant basin in Belgium and one section in Germany. Sections will undergo a high-resolution sampling then multiple analyses will be applied (major and trace elements, total organic carbon and stable carbon isotopes). Preliminary study of the Salet Road Section shows promising results through the time series analysis of the bed hardness, revealing both short and long eccentricity cycles. Overall, this research aims to deepen our understanding of the Carboniferous ice age, its triggers, and the complex climatic mechanisms of Earth during this period.

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Meandering alluvial systems in the Lower Devonian, La Roche-en-Ardenne area (Saint-Hubert Formation)

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The study focuses on the base and top of the Lochkovian Saint-Hubert Formation near La Roche-en-Ardenne, utilizing quarries and boreholes. The primary aim is to understand the nature of rivers in the Ardenne region during the Lower Devonian.

The predominant lithologies in the studied sections are medium- and fine-grained overbank deposits (60%), representing levees and lowlands of the alluvial plain. Carbonate nodules and rhizomorphs are present, but no persistent crusts were observed. Coarser deposits (40%) correspond to fluvial channels, with quartz-dominated sandstones indicating relatively high sediment maturity. The main sedimentary structures observed include planar and trough lamination. Lateral accretion forms associated with point bar development are primarily restricted to the smallest channels. Main channel bodies, reaching up to 6 meters in thickness, often lack lateral accretion sets, indicating relatively low-sinuosity river deposits.

Microfacies analysis reveals seven types, quartzites being less abundant than mudshale and quartzwackes, depicting a landscape characterized by low slope, large alluvial plains, and meandering smaller distributaries. Pedogenetic glaebules are usually associated with roots and may be reworked and incorporated into sandstones (channels, crevasse splay) or mudshales during erosion episodes of the alluvial floodplain.

The vegetation consisted of small, short plants adapted to a climate with alternating wet and dry seasons. The architecture of deposits in the Saint-Hubert Formation is influenced by the response of fluvial systems to marine base-level changes. The ideal short-scale deposition cycle involves channel sands grading into fine sands, mudshale with bioturbation and pedogenesis, and topped by siltstones with channelized crevasse splays. On a larger scale, there is evidence of long-term accommodation increase, leading to thickening upward cycles and a higher proportion of alluvial plain deposits. This trend aligns with the onset of a future marine transgression depositing marine facies in the Mirwart Formation. Overall, the study provides valuable insights into the Devonian alluvial systems, including sediment characteristics, depositional environments, and landscape evolution.

Detection of quasi-periodic recurrences in sediment logs

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Cyclostratigraphy relies on the detection of Milankovitch cycles in sedimentary sequences. In practice, investigators use information from various sources. Among them, the sedimentary log, which details a succession of discrete units, is often the starting point that leads cyclostratigraphers to suspect that Milankovitch cycles may be preserved in the record and used for estimating the duration of the record.

Formally, the sedimentary log can be considered a digital signal, consisting of units of varying lengths, each characterized by one of a discrete set of possible facies.

To our knowledge, there is no algorithmic method to detect (or at least suggest) the existence of quasi-periodic patterns in a digital signal that would be robust against the specific challenges of cyclostratigraphy: multiple periodicities, amplitude modulation of the pattern (e.g., by eccentricity), and varying sedimentation rates.

The purpose of this contribution is to propose an inventory of possibilities, with comments on their strengths and weaknesses.

The WarmAnoxia project : current status

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The Devonian period (419 to 359 million years ago) stands as a critical epoch in Earth's geological history, marked by significant climatic and environmental transformations. During this era, 29 instances of ocean anoxic or hypoxic conditions have been identified and documented.

The dynamics of these Ocean Anoxic Events (OAEs) and their underlying mechanisms have been investigated over the last decades. It has been hypothesized that the cyclical nature of anoxia in geological records can be attributed to astronomical cycles. These cycles involve changes in the rotation of the Earth's axis and the geometry of its orbit, impacting seasonal variations and the level of incoming solar radiation, thereby affecting the global climate on geological timescales.

In the WarmAnoxia Research project (funded by the FNRS), we have initiated an investigation that relies on:

1. Cyclostratigraphic analysis of outcrops and cores covering periods from the Emsian to the Famenian, including Oued Fercla (Morocco), Lansing Core (USA), AKZO core (USA), and West Valley core.

2. Modelling of deep-ocean dynamics and biogeochemical responses to changes in continental configuration and orbital forcing throughout the Devonian using the cGENIE modelling framework.

3. Numerical simulation of regolith dynamics and nutrient flows to the ocean using a realistic climate model (HadSM3) coupled with a model of the regolith (GEOCLIM).

The purpose of combining modelling and cyclostratigraphy is to provide constraints on the timing and duration of anoxia with respect to astronomical forcing (specifically, the timing of so-called "nodes" of eccentricity) and to investigate possible physical and biogeochemical mechanisms that would explain this link.

The poster showcases mid-term results associated with this project.

Characterization and correlation of the Miocene successions in the Schoten borehole, northern Belgium

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The integration of geotechnical and geophysical well-logs, sediment and biostratigraphic analyses of borehole Schoten (northern Belgium) provides a better characterisation of the glauconite-rich sandy Miocene successions near their type sections. It also provides a means for correlation of the type sections towards with more distal areas along the contemporaneous southern North Sea Basin. The Rupelian Boom Formation in the Schoten area is unconformably overlain by the Lower to Middle Miocene Berchem Formation. The Berchem Formation is formally subdivided into the Edegem, Kiel and Antwerpen members which can be identified on the gamma-ray log of borehole Schoten. Sediment analyses show that the glauconite content is the main factor contributing to the changes of the gamma-ray values, while some gamma-ray spikes might be related to the presence of phosphatic nodules. We were able to correlate the geophysical log signature of the members of the Berchem Formation across large areas and tectonic structures, which shows the regional significance of the boundary between these members. Indeed, the boundary between the shell-bearing Edegem Member and the partly decalcified (dissolution of the aragonite) glauconitic sands of the Kiel Member corresponds with the boundary between the Dutch Veldhoven and Groote Heide formations. The shelly Antwerpen Member corresponds with the upper part of the Dutch Groote Heide Formation. The overall higher gamma-ray values for the middle Miocene Antwerpen Member are likely related to the eustatic sea-level high during the Mid-Miocene Climatic Optimum. Maximum sea-levels within the Antwerpen Member correspond to shell beds with phosphatic nodules. In the Schoten borehole, the Berchem Formation is unconformably overlain by the upper Tortonian Borsbeek Member of the Diest Formation, making this the northernmost observation of the latter member.

Exploring Silurian Unconventional Hydrocarbon Resources in North Africa: An In-Depth Case Study

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North Africa, the Arabian Peninsula, and adjoining regions are anticipated to play a pivotal role as global energy hubs in the 21st Century. This transition is supported by the abundant unconventional shale oil and gas reserves, the development of carbon capture and storage (CCS), and advancements in new renewable energies such as geothermal, hydrogen/helium, and associated critical resources. However, realizing this potential necessitates a comprehensive understanding of the geology, requiring progress across various scales, ranging from regional basin models to focused studies.

The remarkably well-preserved Lower Paleozoic strata in North Africa are integral to the globally widespread occurrence of graptolite-bearing marine sediments in the expansive Gondwana shelf area. The Early Silurian Oued Imihrou black 'hot' shales represent a primary hydrocarbon source-rock, contributing to significant oil and gas fields in Paleozoic deposits in many North African intracratonic basins and globally. Despite this, crucial information for basin analysis remains inadequately understood, even in Algeria's largest hydrocarbon-producing province.

The present study is focused on the southern margin of the prolific Berkine – Ghadames and Illizi (BGI) basins, specifically the Tassili n'Ajjer area. The picturesque Lower Paleozoic outcrops of the Tassili n'Ajjer plateau offer invaluable insights into understanding and characterizing the sedimentology of the Silurian deposits, as well as reconstructing the diagenesis- and thermal maturity-evolution of the entire region. A variety of techniques and independent approaches, including X-ray diffraction, electron microscopy, organic petrography, programmed Rock-Eval pyrolysis, Raman spectroscopy, and illite K–Ar geochronology, are employed.

The 400 m-thick clastic strata of the Silurian succession on the Tassili n'Ajjer plateau exhibit a general trend of thickening- and coarsening-upward (shallowing-upward), with notable variability in depositional environments, as evidenced by numerous sedimentological and ichnological characteristics.

X-ray analysis and field emission scanning electron microscopy reveal kaolinite, illite, and iron-rich chlorite as the main authigenic mineral phases. K–Ar data indicate episodic in situ illite crystallization at different times, with the oldest illite at about 335 Ma and the youngest between 238 and 179 Ma, under diagenetic-to-hydrothermal conditions.

Paleotemperature estimates determined by Raman spectroscopy (~130–232°C), illite crystallinity (0.37–1.58 $\Delta°2\theta$), and graptolite reflectance (VReqv, 1.09–1.84%) suggest deep diagenetic-low anchizone boundary conditions. This broadly indicates late oil-to-dry gas zones of hydrocarbon generation and destruction, particularly in the westernmost part of the Tassili n'Ajjer plateau.

At least two heating events and diagenetic fluid flow processes are identified, primarily in response to various tectonic events, including fault reactivations and the migration of hot, potassium-rich fluids throughout the Phanerozoic. These events and processes significantly influenced hydrocarbon maturation, migration, and/or entrapment, especially along inherited N-S lineaments and Hoggar Massif mega-shear zones.

In conclusion, the most promising regions for future unconventional hydrocarbon resource exploration are those adjacent to major lineaments. These areas, characterized by subsequent igneous activity and frequent occurrences of unrestricted hydrothermal fluids, exhibit significantly advanced maturation processes, positioning them as prime targets for exploration.

First evidence of Triassic above the lower Devonian of the Oesling (Luxembourg)?

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As part of the Hosingen bypass project, located in the Oesling region (a region of northern Luxembourg whose Devonian bedrock is equivalent to that of the Belgian Ardenne), the boreholes drilled for the geotechnical study revealed a sedimentary fill up to 20 m thick in places where the lower Devonian rocks of the Clervaux and Wiltz formations were expected at shallow depths.

This sedimentary fill was found in 12 exploration boreholes, covering a total surface area of almost 10,000 m2, in 2 different locations more than a kilometer apart, indicating that this layer could be found in several locations and would not be linked to an isolated event. It is a conglomerate containing rounded pebbles of sandstone, quartzite and shale, varying in size from a few centimeters to more than ten centimeters, with a reddish clayey cement. All the pebbles are aligned parallel to the horizontal, indicating that the fill post-dates the deformation of the underlying Devonian shale and sandstone.

Geophysical investigation using electrical tomography have revealed the presence of several faults of different orientations in the area where the fill is thickest. These faults appear to have formed a tectonic sedimentary basin, creating favourable conditions for a fluvial fill, and also preserving part of it from erosion.

In the absence of fossils, the age of this horizon has not yet been established, but the similarity of facies, composition and colour with the Triassic layers known in Belgian Lorraine, Germany and Luxembourg, as well as the geological history of Luxembourg, suggest that these layers may also be Triassic in age. Indeed, they bear a striking resemblance to the Buntsandstein conglomerate that outcrops in the Folschette quarry some thirty kilometers to the south-west. This would be the first time that layers of this age have been found in the Oesling region, much further north than the outcrops already known in Luxembourg and Belgium. Further studies and analyses are nevertheless needed to estimate the age of this geological horizon and attempt to map its extension more precisely.

Zoom in on the conglomerate overlying the Lower Devonian sandstone

Astronomical calibration of the Kellwasser Crisis and Frasnian-Famennian boundary in the West Valley core (Appalachian Basin, New York State, USA)

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The Devonian Kellwasser Crisis near the Frasnian-Famennian boundary (~372 Ma, Da Silva et al., 2020) is linked to one of the biggest Phanerozoic biodiversity crises and had an especially large impact on contemporaneous marine ecosystems. Even though the crisis has a widely variable expression in the geological record, it is classically associated with carbon-cycle perturbations and pulsed ocean anoxia that led to the deposition of black shale couplets characterized by a positive carbon isotope excursion, akin to the Lower and Upper Kellwasser Event Horizons in Germany (Carmichael et al., 2019). To date, no consensus has been reached on the exact trigger mechanism(s) for either Lower and Upper Kellwasser Event. Regardless, growing evidence points towards the influence of astronomically forced climatic stresses on Devonian marine systems. Most notably, absence of extreme seasonality during a 2.4 Myr eccentricity node prior to the Upper Kellwasser Event has been suggested as the determining factor for the timing of its onset (De Vleeschouwer et al., 2017; Da Silva et al., 2020). Yet, this hypothesis still remains open to debate as only a limited number of astrochronologies have been proposed for the Kellwasser Crisis interval.

The West Valley (WV) core comprises middle Frasnian to lower Famennian distal foreland basin strata and its geochemistry (Sageman et al., 2003) and sequence stratigraphy (Ver Straeten et al., 2011) have been thoroughly studied. The Pipe Creek and Hanover Formations recorded the Lower and Upper Kellwasser Events respectively, both of which are characterized by black shales, elevated total organic carbon (TOC) content and a positive δ13Corg carbon isotope excursion. In order to constrain the duration of the WV Kellwasser Crisis interval and, to explore the phase relationship between the Lower and Upper Kellwasser Events and astronomically forced paleoclimate changes, the WV core was subjected to cyclostratigraphic investigation. A strong astronomical imprint in the TOC was identified, revealing amplitude modulation of the 100-kyr short-eccentricity cycle by the 405-kyr long-eccentricity cycle. The WV core TOC-signal was tuned using the stable 405-kyr eccentricity period, yielding a floating astrochronology. Subsequent time-domain time series and spectral analyses revealed an equally strong imprint of eccentricity on titanium content, anti-phased to the TOC signal – strongly implying a link between organic matter preservation, terrigenous sediment supply and astronomically forced changes of the paleoenvironment. Furthermore, the astronomically calibrated WV core provides durations for the Lower and Upper Kellwasser Events as well as the Kellwasser Crisis interval, consistent with previous reports (e.g. Da Silva et al., 2020). Finally, new insights obtained on the phase relationship between the onset of the WV Kellwasser Events and nodes in the 2.4-Myr eccentricity cycle are globally contextualized.

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An integrated micro-CT and thin-section method for quantitative 3D analysis of unconsolidated sediments

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High-resolution imaging of unconsolidated sediment at the grain level is increasingly required for the accurate reconstruction of past climate and environment. The primary tool to investigate the arrangement of particles and matrix of unconsolidated sediments from different depositional environments is thin-section micromorphology. It allows the detailed characterisation of sedimentary facies on a microscopic scale (i.e. microstratigraphy), providing depositional and post-depositional process information. However, thin-section preparation poses a potential risk to the integrity of the sediment (micro)fabric, and thin-section analysis is spatially limited to 2D representation of 3D samples, which can lead to incorrect classification of sedimentary features and structures. A promising technique to overcome the limitations of thin-section micromorphology is X-ray computed microtomography (μCT), as it allows visualisation of internal 3D sediment composition, texture and fabric at high resolution. We created an integrated method of μCT and thin-section analysis by developing a 3D-printed subsampler that can effectively (1) extract areas of interest from soft sediment cores, (2) stabilise the unconsolidated "wet" sediment during μCT scanning and (3) allow dehydration and impregnation to be carried out while the sample is in the subsampler, which ensures an undisturbed sample for thin-section preparation. Here we apply our new methodological approach on sediment cores from Alaskan and Chilean lakes. Subsamples (8.0x1.5x1.5 cm) of different depositional environments (turbidites and glacial varves) were extracted from the sediment cores, scanned with μCT at a resolution of 5 and 20 μm at the Centre for X-ray Tomography of Ghent University (www.ugct.ugent.be) and thin sections were prepared. The μCT scanning of subsamples enabled the systematic and quantitative 3D analysis of sedimentary microfacies and proved to be a valuable integration tool for the conventional (qualitative) descriptions of thin sections, improving the paleoenvironmental reconstructions in the study areas.

Millennial scale marl-limestone rhythmites in the Middle Cambrian (500 My) Marjum Formation (Utah, USA) and their modulation by Milankovitch cycles

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Middle Cambrian offshore deposits of the Marjum Formation, Utah, USA are characterized by four scales of superimposed cyclicity defined by variable abundances of fine siliciclastics versus limestone; these include the limestone-marl couplets (or rhythmites; 5-10 cm) which are bundled into parasequences (1-2 m), and small-scale (5-10 m) and large-scale (20-40 m) sequences. Time series analysis of SiO_2 and lithologic rank stratigraphic series reveals cycles consistent with Milankovitch cycles with periods corresponding to Cambrian orbital eccentricity (20 m, 405 ky; 6 m, 110 ky), obliquity (1.8 m, 30 ky), and climatic precession (1.15 m, 18 ky). Astronomical calibration of the lithologic rank series indicates that the main sub-Milankovitch cycle at 0.065 m has a period of approximately 1 ky and corresponds to the basic rhythmite couplet. All scales of cyclicity are interpreted to be the result of wet vs. dry monsoonal climate oscillations controlling the abundance of fine terrigenous sediment influx to the basin. A plausible millennial-scale climate driver is solar activity. These results provide one of the oldest known geological candidates for solar-influenced climate change modulated by Milankovitch forcing.

Towards a Lithotectonic Framework for Belgium

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Nearly every geological subdiscipline relies to some degree on regional geological knowledge. In the introductory section of most geological papers it is standard practice to provide regional geological background information. Stratigraphic terminology is often well defined while other disciplinary concepts rely, at least to some degree, on generally agreed definitions or hierarchical schemes, such as paleontological, structural or magmatic terminology. This, however, is much less the case for the regional geological building blocks. Their names are usually composed of a combination of a geographical locality and a geological term. A few examples from Belgium are Brabant Massif, Campine Basin, Stavelot-Venn Inlier, and Malmedy Graben. Most of these have in common that, although their importance is well recognised, their definitions are vague and sometimes even conflicting, in that their meaning may differ between contexts and authors. Even if their meaning has drifted or become less exact, as a result of their frequent historical use, they commonly remain in use today.

This issue is not exclusive to Belgium, but seems to be an altogether historic and worldwide phenomenon. Recently within Europe there is a growing awareness of this issue, resulting in important but rather isolated efforts to better structure and define regional information (Hintersberger et al. 2017; Németh 2021; Le Bayon et al. 2022) which have been brought together through pan-European cooperation (GSEU – Horizon Europe 101075609). The central element that seems to encompass most geologic features, is the lithotectonic unit (a distinct unit based on its partly separate geological history; URI: http://inspire.ec.europa.eu/codelist/GeologicUnitTypeValue/lithotectonicUnit). Grabens, basins and inliers are examples of lithotectonic units. In order to define and describe these units more accurately, lithotectonic limits are introduced. These are planar features, such as faults and unconformities, that correspond to the geologic events that formed the lithotectonic unit (Piessens et al. 2024). All information is organised and linked in vocabularies (thesauri) that together not only adequately define each concept, but also determine the relations between them, placing them in space and geological time (Plašienka 1999). This outlines the core methodology, around which 2D and 3D multi-scale visualisations are built, annotations can be added, existing ontologies can be linked (such as the ICS Geological Time Scale Ontology; Cox and Richard, 2005) and newly developed extensions such as the Modified Wilson Cycle (Németh 2021). As such, the work at Belgian level is closely linked to the ongoing international developments.

Making use of the ongoing developments at European level, Belgium was the first country to set up a lithotectonic working group that became operational in 2023. Its first goal is to provide a lithotectonic framework that describes a starting set of main geological units and limits in Belgium, according to emerging European standards (the work at European level is linked to the implementation of INSPIRE and is in communication with the GeoSciML community), by the end of 2024. The working group meets approximately every 2 months, and organisationally resides under the National Commission for Stratigraphy in Belgium. The working group will soon be looking for additional experts (junior and senior) in its continuing effort to identify and define broad superstructures, detail the regional geology to the more local level, to tackle new types of lithotectonic elements, or better address parts of geological history. Potential candidates are encouraged to contact one of the authors or the NCS secretariat.

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Development and decease of the Frasnian buildups of Belgium

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The development of the middle and late Frasnian buildups is well correlated with eustatic third-order sequences. During the middle Frasnian, the onset and growth of the three levels of reefal members (« Arche », « Boverie » and « Lion ») correspond to the transgressive system tract (TST) of three recognized sequences. During the high-stand (HST) and the falling-stage system tracts (FSST), their vertical growth decreased, and they evolved to large progradant carbonate platforms, 1 – 3 km wide and up to 140 m high (including the relatively small original biohermal core), in which boundstone are replaced by beds of packstone – grainstone, then by shallow-water and interdital mudstone (FSST). As a result, most of the volume of the so-called reefs is not actually built and there is no evidence for the development of atolls rimmed by stromatoporoid-coral barreers, as it was usually suggested (among others, Boulvain et al., 2005), because no such structure has been observed in sections currently showing the total extent of these formations.

The emersion of these limestone platforms during the regression phases stopped the carbonate production until the next transgression, during which limestone production resumes.

At the start of the transgression of the first sequence ("Aisemont sequence", Mottequin & Poty, 2016) recognized in the upper Frasnian on the top of the Lion Member (and laterally on the top of the Neuville Formation), clayey limestone rich in Disphyllidae and Pachyporidae developed, heralding a new buildup, as had previously been the case at the base of each of the three middle Frasnian reefal members, but were rapidly halted by the first Frasnian crisis affecting corals and stromatoporoids.

Thereafter, carbonate production never recovered as before. Reddish microbial mudmounds rich in Phillipsastreidae (Petit-Mont-type mudmound), or smaller greenish mudmounds rich in stromatactys but devoid of macrofauna, developed during the TST and HST of this first late Frasnian sequence. Their growth was mainly vertical and there was no marked progradation during the HST. During the FSST of the Aisemont sequence, mudstones and shallow-water stromatolites developed on the top of the Petit-Mont-type mudmounds, then emersion stopped their development. During the last sequence of the upper Frasnian ("Lambermont sequence" of Mottequin & Poty, 2016), the extension of anoxic-dysoxic facies prevented the development of large buildups, and only micro-mounds, 1 to 2 m wide, have been recorded to date.

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Study of the sedimentological characteristics of the Belgica mound province contourite drift in the Porcupine Seabight, offshore Ireland

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The Belgica mound province, offshore west Ireland, hosts a small (~30 km^2) contourite drift confined between the Irish Shelf in the east and numerous cold-water coral mounds in the west. These contourite deposits are the result of the interplay between the Atlantic Mediterranean Water and the complex seabed morphology. The identification of contourites in the sedimentary record is still subject to ongoing marine research. The small size of this drift makes it the ideal location to study the internal sedimentological variation within a contourite drift, which is currently poorly understood.

During RV Belgica campaigns in 2022 and 2023, several sediment cores were taken at the crest and the sides of the mound of the contourite drift. Here, we present the preliminary results of the sedimentological and compositional analyses of these cores. Medical CT scans and line scan images were used to visualize the sediment cores. The sedimentological analysis involved grain size, density and magnetic susceptibility measurements. The composition of the cores was determined using an Itrax XRF scanner. Based on the sedimentary characteristics, there is no difference between the cores from the crest or the side of the mound. Cores from both locations can be subdivided into two major units. A medium sandy top layer and a clayey silt to sandy silt unit. The lower unit is heavily bioturbated, masking many of the primary sedimentary structures.

Integrated bio-chemostratigraphical correlations across Paleocene: Accuracy and Biases of carbon-isotopes on organics (δ13Corg), from marine to continental sections

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Over the past thirty years, a large number of studies dealing with Paleocene carbon isotope chemostratigraphy has been performed by several authors. The objective of these studies was to elucidate the underlying mechanisms of the significant perturbation in the Earth's carbon cycle that occurred during the Paleocene. Additionally, the studies aimed to decipher the marine and terrestrial biotic turnovers, the evolution of mammals, the changing environmental ecology, and finally, to refine the stratigraphy of this epoch. The Paleocene Eocene Thermal Maximum (PETM) was the first "hyperthermal" event recognized by Kennett and Stott (1991). It represents a major part of the studies performed for this epoch. Up to now, a small number of transient events are well known and recognized, mainly during the Eocene Series. However, numbers of these studies were focused only on one precise (high- frequency) carbon perturbation event (e.g. PETM, Latest Danian Event (LDE), Early Late Paleocene Event (ELPE)), instead of the whole Paleocene carbon cycle evolution (low-frequency), often because of the lack of well exposed, "complete" and biostratigraphically well-constrained sections. Moreover, the carbon isotope studies which take into account the whole Paleocene sediments are mainly generated from benthic foraminifera or on bulk carbonate with some potential biases. The isotopic analysis of δ13Ccarb is of course dependent on carbonate availability and may be perturbed by carbonaceous fluids when sediments are affected by diagenesis leading to less reliable isotopic signal.

This study reconstructs a complete organic carbon isotope (δ13Corg) framework of the reference marine Zumaia section (Spain) where the GSSP of the Danian/Selandian boundary (DSB) and the Selandian/Thanetian Boundary (STB) are defined, the well expanded marine Sidi Nasseur section (Tunisia) and the well expanded continental Albas section (France).

It further suggests tentative correlations of these three sections to refine the carbon isotope stratigraphy of the Paleocene with a bio- stratigraphic support if available.

Then it compares this organic carbon isotope signal with other complete carbon isotope record of the Paleocene and finally it criticizes the "limits" and potential biases of the $\delta 13C_{org}$ long-term chemostratigraphy.

Stylolites in Chalk in the Mons Basin: Evidence of Pressure Dissolution Related to Regional Tectonics

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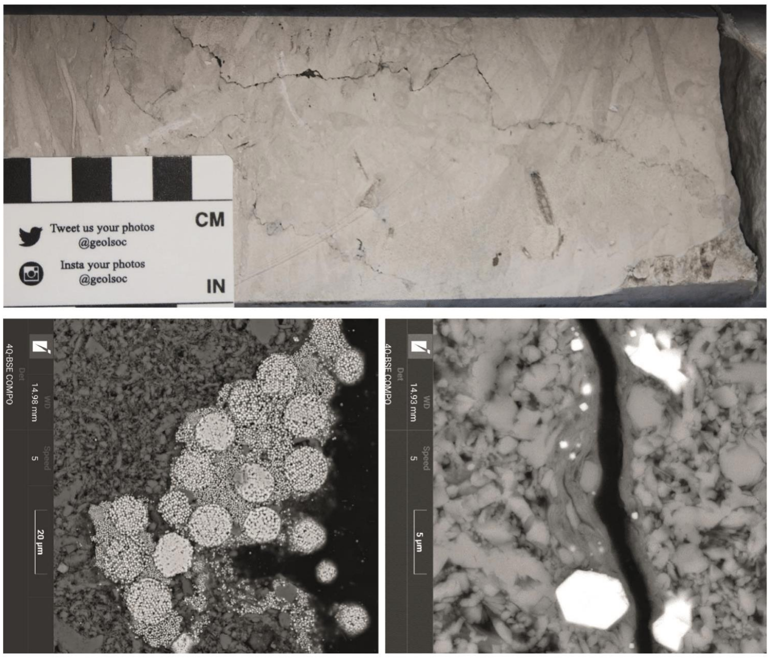
Stylolites are common pressure dissolution features observed in calcareous rocks. They are mostly associated with burial diagenesis or potential tectonic compression events. In chalk formations, stylolites are common at depths higher than 800m in the North Sea and Northern UK (Fabricius et al., 2007). Strong evidences of local compression tectonics have been reported in areas such as Flamborough Head and Southern England. They resulted from inversion tectonics along major crustal structures like those in the Isle of Wight and Selwicks Bay. However, in the Paris Basin and the adjoining Mons Basin, stylolites in chalk have not been previously reported. In these regions, where burial diagenesis of chalk does not exceed 400m, chalk is believed to be only mildly impacted by stylolites features.

Earlier studies (Vandycke et al., 1991;, Vandycke, 2007) indicated that the Mons Basin was affected by an E-W trending right lateral strike-slip fault system during the Early Maastrichtian. This led to the development of a stress field characterized by NE-SW extension and NW-SE compression. Detailed studies of the faulting of white chalk revealed evidence of dissolution along major fault planes (Angelier et al., 2006; Gaviglio et al., 2009). The current study involved detailed logging of three chalk boreholes from the Saint-Vaast and Trivières Formations, which are Upper Cretaceous in age (Descamps et al., 2020). A total of 300m of Campanian-Santonian chalk was logged, revealing evidence of vertical tectonic stylolites,. which are considered to be caused by horizontal compression, with the largest principal compressive stress being horizontal. Several strike-slip faults are also observed nearby the stylolites. SEM-Back scattered electron and EDX analysis allowed to study the insoluble residue and the oriented clay concentration along the stylolitic planes. Pyrite was observed in various forms within the stylolites, with the presence of largely developed framboidal pyrite, suggesting the activity of sulphate-reducing bacteria. The different generations of pyrite, and the various phases of oxidation, indicate different episodes of fluid flow along the stylolites at different stages of the diagenetic history. The clay-rich nature of the Saint Vaast chalk, with an average insoluble residue content of 5%, allowed for a better development of the stylolites. This unique observation attests of the existence of significant phases of a compressive regime in the Mons Basin, either related to the Maastrichtian strike-slip event or a record of the Oligocene inversion orogenesis well known in the north of Europe.



Stylolites in Mons Basin Chalk. Observation under SEM-Back scattered electrons. Top : Clays resulting from pressure dissolution within a stylolite. Flakes parallel to the stylolitic plane. Bottom: Concentration of pyrite within a stylolite.

Pore System Evolution in Olenekian Buntsandstein Formations: Implications for Reservoir Quality

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Buntsandstein sandstones known as important sources of building stone, major groundwater aquifer, hydrocarbon reservoir, and increasingly being considered for geothermal and gas storage applications in the Europe. This study examines the depositional and diagenetic control on pore system evolution in the Olenekian Buntsandstein formations in the Paris Basin (Vosges and Trier areas), Campine Basin and the West Netherlands Basin. Despite similar tectonic and climatic settings, our analysis of outcrop and subsurface data reveals notable lithostratigraphic disparities over time, complicating the establishment of direct chronostratigraphic analogies between the basins.

Petrographical observations reveal the early diagenetic processes are mainly influenced by lithofacies and climatic conditions, showing similarities across the studied basins. In contrast, late-stage diagenesis involves diverse mineral dissolution and precipitation processes, resulting in distinct textural differences and variations in reservoir quality. The study identifies five types of bleaching, each associated with specific mechanisms, illustrate the complexity of the bleaching phenomena. Both depositional and diagenetic processes contribute to bleaching, contradicting previous studies that solely attributed it to diagenesis.

While bleaching is generally considered to enhance reservoir properties, this is not always the case. Petrophysical results revealed that grain size, clay content, burial depth, and diagenetic cements are key factor influencing the pore size and connectivity. These insights are critical for understanding the implications of depositional and diagenetic processes on reservoir quality, particularly for geothermal exploration and CO_2/H_2 storage in these sandstones.

A geological passport of the Flemish subsurface

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The subsurface is home to a large number of geological formations and members. In Belgium, these are formally defined by the National Commission for Stratigraphy, based on a large body of research of which a significant portion is published in the Geologica Belgica Journal. Even with these formal descriptions and publications at hand, it is often not straightforward to correctly identify geological units in temporary exposures or borehole samples. Internal variations within units, vertical as well as lateral, add further difficulty.

To aid in the correct identification of geological units and to improve the insight in the composition of the subsurface at specific locations based on geological maps and models, a reference database of the subsurface of Flanders is being built. Based on the reference database, it will be possible to make a more quantitative assessment of the composition of geological units. For the 3D modelling of lithological composition, such a database can also be a key primary resource.

Parameters currently included in the database are grain size distribution, glauconite content, inorganic carbon content and organic carbon content. More parameters may be added in the future, e.g. with respect to geotechnical and hydrogeological characteristics. All data in the reference database are collected from analyses using the same analytical methods, to ensure that all data are comparable. Currently, analyses on 372 samples from well documented exposures and boreholes are present in the database. For many units, the amount of analyses is not yet representative and not all units have been analyzed. The reference database is continually expanded, with a yearly update in an elaborate report with extra focus on new data added in the previous year. As such, over time the database will evolve to a true reference database.

The reference database is a key component of the new Geological Passport of the Flemish subsurface, available at the database for the subsurface of Flanders (DOV, dov.vlaanderen.be). For each geological formation, a geological passport is constructed which includes 1) a link to the formal definition of the formation and its members by the National Commission for Stratigraphy, 2) a link to the occurrence of the formation and its members based on the geological 3D model (G3Dv3.1) and the geological map, 3) links to the stratigraphic reference sections available on DOV, 4) links to other well documented boreholes and temporary exposures available on DOV, 5) data from the reference database if available, 6) links to other important data sources and 7) the key literature references. Consequently, the Geological Passport is the ideal starting point to explore the subsurface of Flanders and gain more insight into the composition of specific units.

SESSION 6 - PALEOBIOLOGY: BRINGING THE PAST BACK TO LIFE

Conveners

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Paleobiology lies at the intersection between Earth and life sciences, harnessing elements from both disciplines to enhance our comprehension of the evolutionary narratives of extinct organisms. Accordingly, we invite contributions across a broad spectrum, encompassing macro and micropaleontology, from diversity dynamics to evolution, from paleoclimate reconstruction to three dimensional reconstruction, and from dinosaur digs to nannofossil oozes. Our objective is to provide a session gathering forefront research endeavors within the realm of paleontology.

Invited Speaker

Impact of the land-to-water transition on mammalian backbone morphofunctional evolution

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Secondary invasions of the aquatic realm by land-dwelling vertebrates represent some of the most fascinating ecological transitions that occurred during the evolutionary history of life. These land-to-water transitions involved a shift from a limb-based to axial-driven locomotion resulting in drastic reorganization of the terrestrial vertebrate body plan (e.g., loss of limbs, streamlined body). Nonetheless, the ancestors of multiple groups of reptiles and mammals, such as ichthyosaurs, mosasaurs, whales, and manatees, independently reinvaded the aquatic environment. While most marine reptiles are extinct, more than 150 living species of mammals exhibit some level of aquatic adaptation, ranging from four-limbed amphibious species to fully aquatic fish-like species, representing an ideal group to investigate the impact of the land-to-water transitions on morphofunctional evolution. Clues to the evolution of axial-driven locomotion in water can be found in modern-day mammals, which vary in their swimming mode and degree of aquatic adaptation. The most terrestrial species (e.g., muskrats, shrews) use limb-based quadrupedal or bipedal paddling, while semiaquatic species (e.g., otters, pinnipeds) use a combination of limb and body-based movements, and fully aquatic species (e.g., cetaceans, sirenians) rely solely on backbone oscillations. Despite the central role of the backbone for aquatic locomotion, past efforts have focused on documenting changes to the limbs and skull during the land-to-water transition, with few studies exploring the transformation of the backbone. Here, we investigated the shape and function of the backbone of a variety of terrestrial, semiaquatic, and fully aquatic extant mammals. Using a combination of morphometrics, biomechanical experimental testing, and cutting-edge statistical analyses, we examine the relationship between vertebral shape, function, and swimming modes and use this to provide insight into the adaptations and constraints that shape the land-to-water transitions. Our results help to infer morphofunctional properties of the backbone, and ultimately locomotor abilities, of extinct species to reconstruct this key evolutionary transition through deep time.

Community assembly and colonization dynamics in an East Antarctic glacial lake: evidence from fossil DNA analysis

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Ice-free areas in Antarctica cover less than 0.5 % of the continent and host a suite of endemic terrestrial biota. The predicted increasing temperature and altered precipitation patterns are expected to change the spatial configuration and extent of these oases, as well as the connectivity between these regions. However, little is known about which taxa will colonize the newly formed habitats and how climate change will affect native Antarctic species in terms of their abundance and spatial distribution, as well as their ability to survive in these changing habitats. A powerful approach to assess this, is to study the changes in biological communities in lake sediment cores, in combination with independent reconstructions of the deglaciation and paleoclimate history of ice-free regions. Here we aimed to (i) reconstruct species colonization dynamics following lake formation after deglaciation, and (ii) investigate changes in community dynamics during the Holocene in Zub Lake, which is the largest landlocked lake in Schirmacher Oasis, East Antarctica. To achieve this, we applied a multidisciplinary approach combining more traditional microfossil and biogeochemical analyses of an 83 cm long sediment core, with sedimentary ancient DNA (sedaDNA) analyses, allowing to study community dynamics in nearly all organisms present in the lake and not only those leaving recognizable fossils. Based on non-destructive X-ray CT scanning, we identified two distinct sedimentary units, namely clayey glacial sediments spanning the last glacial period down to c. 34,468 cal. yr BP and post-glacial organic rich sediments. The DNA-inferred data and those obtained from the analyses of fossil diatom assemblages and photosynthetic pigments yielded consistent results and revealed a marked difference community structure between the glacial and the Holocene period. Before c. 10,650-10,300 cal yr BP, the Zub Lake basin was likely covered by ice, as evidenced by the presence of glacial sediments including rocks, extremely low chlorophyll and diatom concentrations, a low diatom species richness, and the presence of only a few eukaryotic taxa belonging to the divisions Chlorophyta and Rhizaria. After c. 10,650-10,300 cal yr BP, higher chlorophyll and diatom concentrations, relatively diverse diatom communities and the presence of pigments produced by Cyanobacteria, diatoms and green algae likely reflect local deglaciation, the start of in-lake primary production and the formation of benthic microbial mats. The sedaDNA analyses revealed the presence of eukaryotes belonging to the divisions of the Alveolata, Centroplasthelida, Chlorophyta, Cryptophyta, Evosea, Metamonada, Opisthokonta (including Fungi and Metazoa), Rhizaria and Stramenophiles. Interestingly, our preliminary analysis revealed that 45% of the eukaryotic DNA sequences being present during the past c. 10,650-10,300 cal yr BP appeared for the first

time in the first three centimetres overlying the glacial sediments. This suggests that the colonization of the lake started shortly after deglaciation and lake formation, although this should be further confirmed by additional 14C dates. The combination of the sedaDNA data with an Antarctic-wide inventory of lake communities and paleoclimate data will allow to (i) identify the source populations of these colonizing taxa, (ii) assess potential differences in colonization and succession events among different taxonomical groups, and (iii) shed light on the community assembly of Antarctic lakes in response to environmental changes during the Holocene.

Sabertooth cubs and their mighty Jaws: Unveiling the functional and shape changes during the ontogeny of Smilodon fatalis

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The evolution of organisms can be studied through the lens of developmental systems, as the timing of development of morphological features is an important aspect to consider when studying a phenotype. Such data can be challenging to obtain in fossil amniotes due to the scarcity of their fossil record. However, the numerous remains of Rancho La Brea allow a detailed study of the post-natal changes in an extinct sabertoothed felid: Smilodon fatalis. Despite numerous previous studies on the ontogeny of *Smilodon*, an important question remained open: how did the cubs of *Smilodon* acquire and process food? By applying 3D geometric morphometrics and finite element analyses to 49 mandibles at various developmental stages (22 of *Smilodon fatalis*, 23 of *Panthera leo*, and 4 of early diverging felids), we assess the changes in mandibular shape and performance during growth. Both lions and sabertooths exhibit a shift in mandibular shape, aligning with eruption of the lower carnassial. This marks the end of weaning in lions and suggests a prolonged weaning period in *S. fatalis* due to its delayed eruption sequence. We also highlight distinct ontogenetic trajectories, with *S. fatalis* undergoing more post-natal mandibular shape changes. Finally, although *S. fatalis* appears more efficient than *P. leo* at performing an anchor bite, this efficiency is acquired through ontogeny and at a quite late age. The delayed shape change compared to *P. leo* and the low biting efficiency during the growth in *Smilodon* could indicate an extended duration of the parental care compared to *P. leo*.

The diversity of shapes and structure of aquatic amniote flippers

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Moving from a terrestrial to an aquatic environment is a major anatomical challenge. Yet dozens of amniote lineages have taken the plunge. These independent transitions resulted in a plurality of ways to swim using locomotor appendages, as limbs evolved into flippers. However, no study has quantified the external shape and the structural diversity of these limbs in extant and extinct reptiles and mammals. Here, we quantify this diversity in a comparative framework by (i) studying two-dimensional foreflipper external shape using elliptical Fourier analysis in combination with skeletal organisation; and (ii) testing for relationships between these features and body proportions, swimming styles, and phylogenetic distances. Our results show that distantly related taxa share convergent external flipper shapes, likely due to strong constraints imposed by the aquatic realm. These similarities are, however, counterbalanced by the broad range of locomotor patterns and varied internal flipper anatomies characterising different amniote lineages. Surprisingly, some species with comparable flipper morphologies swim very differently. The functional implications of such similarities across species with distant evolutionary histories and different swimming styles continue to elude our understanding.

Mechanical performance indicates niche partitioning in Late Cretaceous marine reptiles from the Western Interior Seaway

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The coexistence of sympatric predatory marine reptiles in the Late Cretaceous suggests ecological partitioning of higher trophic niches. The Western Interior Seaway, a vast inland sea that stretched across a significant portion of North America, was home to a diverse array of marine life, most notably a multitude of reptilian predators. Previous studies have utilized tooth morphology and dental microwear as proxies for inferring the feeding habits of marine reptiles. However, teeth are only part of the feeding apparatus. Ecological insights may be elucidated through biomechanical simulations of craniodental remains, focusing on mechanical performance. Here, we performed the first, large-scale, comparative study on WIS marine reptile jaw performance using high-definition three-dimensional models and muscle-driven finite element analyses (FEA). The jaws of mosasaurids and polycotylid plesiosaurians from the Campanian-Maastrichtian were 3D scanned and processed for FEA simulations. For comparative purposes, mosasaur jaws were modeled with a fused symphysis and immobile intramandibular joint, forming a single functional element. Muscle insertions were identified to reconstruct jaw adductor muscles and assess respective muscle and bite force. We used Metafor to simulate realistic, muscle traction dynamics during biting, including simulations at different opening angles and biting locations. Results revealed distinct stress distributions per morphotype, demonstrating biomechanical variation between robust mosasaur mandibles (e.g. *Globidens*) and the more gracile mandibles of polycotylids and the mosasaurid *Clidastes*. Integrating mechanical efficiency with the deformation sustained by the jaws provided additional ecological inferences. High deformation values in polycotylid jaws suggest that maximum bite force (estimated from muscle attachments) was not exerted, resulting in divergent feeding techniques to mosasaurs (e.g., snapping and swallowing). Moreover, polycotylids and some mosasaurid taxa (e.g., *Clidastes* and *Jormungandr*) appear better adapted to biting at wider gape angles, whereas mosasaurids with high mechanical efficiency at wide and narrow gape angles (e.g., *Mosasaurus* and *Prognathodon*) are more suited to prey on larger items with powerful bites. Our results align with niche partition inferences from dental remains and offer deeper insight into feeding techniques in Late Cretaceous marine predators, providing a unified canvas and protocol to assess niche partitioning in sympatric marine reptiles from well-sampled (and well-preserved) regions.

Rugose corals across the Early-Middle Devonian boundary in southern Belgium

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In southern Belgium, the Emsian-Eifelian Boundary falls within the uppermost part of the Eau Noire Member of the Moulin de la Foulerie Formation, some metres below the base of the lower Eifelian Couvin Formation (Villers-la-Tour and Petigny members). The Upper Emsian strata are dominated by bioclastic limestone and calc-shale alternations whereas the Eifelian part corresponds to coral-stromatoporoid biostromes and siltstone. All these units are relatively rich in rugose and tabulate corals. The taxonomic revision of the rugose coral collected below and above the boundary led to the identification of 27 species belonging to 19 genera. The Emsian coral fauna is almost entirely composed of large solitary corals dominated by species of the genera *Acanthophyllum* and *Nardophyllum*, associated with *Calceola*, *Digonophyllum*, *Kunthia*, *Mesophyllum*, *Stringophyllum*, *Tabulophyllum*, and putative *Chostophyllum*. *Microplasma* is the only colonial genus recorded in the upper part of the Eau Noire Member. Undissepimented solitary corals are represented by *Adradosia*, *Metriophyllum* and *Neaxon*. The lower Eifelian strata yield *Adradosia*, *Digonophyllum*, *Grypophyllum*, *Lekanophyllum*, *Nardophyllum*, *Zonophyllum*, and the colonial genus *Sociophyllum*. No significant faunal change occurs across the Lower-Middle Devonian boundary, but the last occurrence of the species *Tabulophyllum lissingenense* and *Nardophyllum* originale are both coincident with the patulus-partitus conodont zones boundary. A comparison of the coral associations shows the similarity of the Ardennes and Eifel Hills, though differences exist. Emsian coral assemblages from Brittany, the Cantabrian Mountains, the Montagne Noire and the Carnic Alps are very different, notably with the occurrences of colonial genera and more endemic taxa.

New material of Pacificotaria hadromma sheds new light on a key taxon in early pinnipedmorph evolution

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The diverse pinnipedimorph assemblage of the upper Burdigalian (Lower Miocene) Astoria Formation of Oregon (USA) includes desmatophocids, early odobenids, and stem forms. Among the latter, *Pacificotaria hadromma* was previously only known from a single cranium from the Iron Mountain Bed (IMB). Here, we describe the partial cranium, mandibles, a partial scapula, humerus, and tibia of a new specimen of *P. hadromma*, also from the IMB. Unfused epiphyses of the postcranial bones suggest a juvenile or subadult. The mandible is marked by a robust gonion, suggesting a strongly developed m. pterygoideus medialis and, hence, a powerful bite. Bulbous, conical upper postcanines contrast with gracile, multicuspate lower postcanines, a unique arrangement that may suggest niche partitioning with other Miocene pinnipedimorphs of the Northwest Pacific. Phylogenetic analyses including our new specimen place *P. hadromma* close to *Pinnarctidion* as one of the latest-branching stem-pinnipedimorphs.

Clade-wide size proxies for Mesozoic marine reptiles

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Body size (and, by extension, body mass) is a crucial ecological predictor. There is growing, yet incomplete, evidence suggesting that predator body size distributions in ancient ecosystems differed greatly from nowadays, hinting at major differences in ecosystem composition, food availability, and predatory pressures. The Mesozoic marine realm is poorly known in this regard due to a general lack of complete skeletons and of robust body size proxies. To address this, we assembled a new dataset of linear measurements of body segment lengths (mandible, neck, torso, tail) and isolated element morphometrics (humerus length, dorsal centrum diameter, etc.), on ~100 species of tail-propelled marine amniotes (thalattosuchians, ichthyosaurians, mosasauroids, and raptorial cetaceans). We regressed our linear measurements against total body length to identify the best predictors for total length per clade, and we also explored the evolution of body proportions using new scripts to map ternary data.

The best size predictors differ for each taxonomic group, and strongly suggest distinct and diverse pressures and evolutionary constraints between our sampled clades. For example, orbit size scales isometrically with body length in mosasaurids, whereas it strongly varies from lineage to lineage in ichthyosaurians. Nevertheless, the proximodistal length of the humerus and the diameter of dorsal centra appear as robust, clade-wide predictors. Our ternary morphospace recovered ichthyosaurians as falling morphologically between (and partially convergent with) mosasaurids and cetaceans; this suggests a qualitative continuum, rather than a single optimal set of body proportions in fast, tail-propelled oceanic predators. This study underlines the disparity (and clade-wide evolutionary constraints) in body proportions of tail-propelled marine reptiles. We thus provide a much-needed predictive framework for confidently estimating the body size of marine amniotes, paving the way for future large scale analyses of body length evolution.

To colour or not to colour: Colour patterns and pigments in Invertebrates from the Palaeozoic of Belgium

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Almost nothing is known about the evolution of shell colour in invertebrates. This is largely due to the ultra-rarity of fossils in which colour patterns and pigments are preserved and immediately visible, and therefore easy to identify, especially when these are hundreds of millions of years old. This hampers our understanding of the role and function of colour in extinct animals, their ecology, mode of life, interactions, development, and evolution. A good example for this ultra-rarity is the Palaeozoic of Belgium, world-renowned for its exquisitely preserved fossils of the Devonian and Carboniferous, enabling to document major transitions in ecosystem dynamics and the evolution of life on Earth (e.g. nekton revolution, terrestrialisation, major climate changes, anoxic events, biodiversity crises) but from which only a few cephalopod, bivalve and gastropod mollusc and brachiopod shells were historically documented preserving coloured traces (mostly by L.-G. de Koninck and P. de Ryckholt, mid to late 19th century). However, recently, it was discovered that many more specimens preserve these traces, in particular those from Tournaisian–Viséan shallow marine reef environments, allowing to investigate its occurrence in different evolutionary lineages of marine invertebrates exactly during one of the main periods of revolution in geologic history.

In Brain project B2/P233/P2 nicknamed COLOURINPALAEO financed by Belspo, after gathering all the specimens available in the main Belgian collections, we will use different techniques (multispectral photogrammetry and spectro-imaging) to better visualise the preserved colour patterns and pigments. Furthermore, advanced spectroscopic techniques, namely Raman micro-probe spectroscopy, synchrotron trace elemental mapping and absorption spectroscopy, will be used to identify the chemical signature of the pigments as well as their mode and pathways of preservation. Some of the first results on this multidisciplinary study on a unique set of Belgian fossils will be presented.

The ciliophoran affinity of Alphonse Meunier's enigmatic Radiosperma

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The acritarch genus *Radiosperma* was originally described as an “enigmatic organism” by the Belgian biologist Alphonse Meunier (1857-1918). Two species were described: *R. corbiferum* from Arctic waters and *R. textum* from the Belgian coast. It has been widely reported from plankton and sediments since the late 19th century, with suggested biological affinities ranging from invertebrate eggs to tintinnids.

The genus description is now improved and both congeners are redescribed. Based on SSU and LSU rRNA sequences, *Radiosperma textum* is shown to be a ciliate cyst related to the ciliate genus *Askenasia* and positioned among the classes Prostomatea, Plagiopylea and Oligohymenophorea. *Radiosperma* is considered closely related to *Hexasterias* and *Halodinium*, two former acritarchs that were assigned previously to the ciliophora.

The spatiotemporal distribution and ecology of both species are discussed, revealing a common confusion in species assignment by most authors. *R. corbiferum* appears limited to Arctic waters and the Baltic Sea, while *R. textum* is found in temperate coastal waters in other parts of the world. The chemical composition is documented based on micro-Fourier Transform Infrared spectroscopy. Its refractory nature provides potential for fossilization and applicability as indicator of freshwater influence in palynological studies.

In addition, newly obtained SSU and LSU rRNA sequences for several flask shaped ciliate cysts (e.g., *Fusopsis* and *Strombidium*) are also included in the phylogenetic analysis and the occurrence of fossilizable cysts in the ciliophoran clade in the marine environment is reviewed. It is confirmed that ciliate cyst morphology has taxonomic significance and that morphological identification of cysts can be reliable. Further elucidating cyst stages in ciliate life cycles will improve understanding of ciliate biology and ecology and their applicability as (paleo)environmental tracers.

Morphometric analysis of fossil ear bones as a tool to investigate delphinoid diversity in the southern North Sea during the late Neogene

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In and around the city of Antwerp (Belgium) many paleontological discoveries were made in the context of the construction of fortification belts and the expansion of the harbour. This led to the discovery of a large amount of fossil remains of Neogene marine mammals, among others. Because the specimens are generally fragmentary and the fossil record is relatively scarce, a clear overview of the diversity and time range of these extinct species is difficult to obtain. The ear bones of cetaceans, including the periotic (housing the inner ear) are more compact than other cranial material, often resulting in a better preservation, although these elements are generally found isolated. Furthermore, the periotic preserves many diagnostic features, especially concerning delphinoids, the superfamily including delphinids (oceanic dolphins), phocoenids (porpoises), and monodontids (belugas and narwhals). Therefore, these fossils can aid improving our comprehension of the diversity of delphinoids in the southern North Sea during the late Neogene (Late Miocene and Pliocene). Based on a morphological comparative analysis of 187 fossil periotics from the Antwerp area, recovered mainly from the Pliocene Kattendijk and Lillo formations, with identified fossil and modern periotics, combined with a principal component analysis based on 13 measurements, the periotics were divided in morphological groups which, in a second step, were given a family attribution and, in most cases, affinities with one or two genera. At least nine delphinid, three phocoenid, and two monodontid genera were tentatively recognised. Additional support could be obtained for the presence in the southern North Sea during the late Neogene (mainly, but possibly not only, the Pliocene) of close relatives to the modern pilot whales *Globicephala* spp. and the extinct large dolphin *Hemisyntrachelus*, as well as porpoise species closely related to *Haborophocoena toyoshimai* and *Numataphocoena yamashitai*. Furthermore, a hypothetical extension into the Pliocene of the time range in the southern North Sea of taxa closely related to (or even within) the delphinid genera *Stenella*, *Delphinus*, *Lagenorhynchus*, and *Tursiops*, the phocoenid *Phocoena*, and the monodontids *Delphinapterus* and *Monodon* are proposed. Additional support for several trans-Arctic dispersal events of extinct porpoise lineages between the North Pacific and the northern Atlantic realm is provided, as well as for a more southern distribution for extinct relatives of the beluga and narwhal. The presence of close relatives to the delphinids *Astadelphis gastaldii* and *Arimidelphis sorbinii*, both previously only recorded from the Mediterranean, indicates a possible interchange between the latter sea and the North Sea during the Pliocene. Unfortunately, precise stratigraphic information could be obtained only for a part of the studied periotics. Furthermore, due to their isolated nature, the identifications remain tentative and do not reach the species level. As a result, there is a need to find new in situ material, as well as periotics associated to other cranial elements.

Contrasting macroevolutionary patterns in pelagic tetrapods across the Triassic–Jurassic transition

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Ichthyosauria and Eosauropterygia were the two of the most successful lineages of marine raptorial predators, co-existing in the same ecosystems throughout most of the Mesozoic. As such, these animals were affected by similar environmental, ecological, and evolutionary pressures, making them a good example in comparing macroevolutionary trajectories among contemporaneous clades of aquatic tetrapods. The very end of the Triassic represents a key period in their evolution as both groups seemingly went through a massive bottleneck that strongly reduced their morphological diversity, with pelagic lineages (e.g. Parvipelvia and Plesiosauria) as the only survivors. However, previous research analysing their evolution across the Triassic-Jurassic (T/J) transition are rare and usually focussed on coarse morphological and temporal data. In the present study, we comprehensively compare the evolution of ichthyosaurian and sauropterygian size and morphology across the Middle Triassic to Early Jurassic interval. We reveal distinct patterns in the craniodental diversification of these two lineages. The ecomorphospace of eosauropterygians is predominantly shaped by a strong phylogenetic signal, resulting in the clustering of three clades: Pachypleurosauroidea, Nothosauroidea and Pistosauroidea, with clearly distinct craniodental phenotypes, suggesting rapid 'leaps' towards novel feeding ecologies. Ichthyosaurian diversification lacks a discernible evolutionary trend, as we find evidence for a wide overlap of craniodental morphologies between Triassic forms and Early Jurassic parvipelvians, suggesting a weak effect of the T/J extinction in terms of ecological breadth. Temporal evolution of ecomorphological disparity, body size, and fin shape of ichthyosaurians and eosauropterygians during the Late Triassic does not support the hypothesis of an abrupt macroevolutionary bottleneck at or near the T/J transition. Instead, our findings suggest that a profound turnover event should be sought earlier, within the Carnian to middle Norian interval, during times of abrupt sea-level changes leading to the extinction of coastal dwellers.

Dimorphic eyebrows? Intraspecific shape variation of palpebral bones in *Iguanodon bernissartensis* (Ornithischia, Dinosauria)

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The palpebral is a bony formation crossing the orbits in ornithischian dinosaurs and constitute a synapomorphy of this group. This bone, connected to the rest of the skull by fibrous tissue, evolve in the most derived ornithischians to give rise to the supraorbital. Very rarely studied, the functional role of this bone and its shape variation within a single species remain virtually unknown, despite its potential to shape the external appearance of the head, notably prior to the evolution of elaborate nasal structures in derived ornitischians. Intraspecific variation requires a sampling threshold that is rarely met in fossil taxa to be properly investigated, notably in dinosaurs. The dozens of specimens of *Iguanodon* found in the Bernissart (Belgium) locality, still considered to this day as the largest assemblage of articulated skeletons of heavy dinosaurs worldwide, therefore constitute an excellent sample to study the intraspecific shape variation of palpebrals along an ornithischian clade. Here we used the data gathered by the project Iguanodon 2.0 to propose the first 3D exploration of the intraspecific shape variation on palpebrals in *Iguanodon*. We apply a 3D geometric morphometric approach to describe the shape variation of the palpebrals among the different specimens of *Iguanodon bernissartensis*. Our results indicate an unexpected dimorphic signal on the palpebral bones, likely reflecting a biological signal rather than taphonomic deformations. Two distinct groups emerge, one characterized by a laterally rounded palpebral bone, while the other shows a much more angular bone. This clear separation between two morphs within a population considered to be homogeneous raises questions regarding the origin of such a shape dichotomy, potentially hinting at sexual dimorphism. More generally, this provides a new background to investigate the origin and evolution of palpebrals/supraorbitals in ornithischians.

Phylogenetic signals in the postcranium of Thalattosuchia and Dyrosauridae (Crocodylomorpha)

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Crocodylomorphs have colonized a wide range of environments, from fully terrestrial to fully aquatic, making them a significant clade among archosaurs. An outstanding example of their rich historical diversity is the marine colonization achieved by several crocodylomorph lineages, notably Thalattosuchia during the Early Jurassic-Early Cretaceous and Dyrosauridae during the Late Cretaceous-Early Eocene. Thalattosuchia represents the most remarkable and unique marine radiation among Crocodylomorpha, occupying various ecological niches before mysteriously disappearing in the Cretaceous. In contrast, Dyrosauridae is notable for surviving the end-Cretaceous mass extinction in abundance but later vanished. Despite a well-preserved fossil record, research has predominantly focused on craniodental remains, often neglecting the postcranial skeleton in anatomical descriptions, diagnoses, and phylogenetic analyses. Indeed, ever expanding datasets for phylogenetic analyses on this group have long been more focused on skull shape variation and include a plethora of craniodental characters. However, craniodental morphology often presents malleability and convergence, which have previously obscured the global positioning and interrelations of extinct crocodylomorphs clades. A possible solution resides in the disregarded—yet rich—postcranial anatomy of extinct crocodylomorphs, which has generally been treated as conservative between many crocodylomorphs clades. Recent studies on the morphological variation of aquatic crocodylomorphs clades (namely Thalattosuchia and Dyrosauroidea) suggest the existence of a strong phylogenetic signal in the postcranium. Hence, we aim to test the phylogenetic informative strength of postcranial anatomy. As such, the most recent and complete Crocodylomorpha phylogenetic dataset has been repurposed: 42 new postcranial characters have been added and several other have been revised to address our phylogenetic question. We also assess the differences of topologies between our results and published works/phylogenies. We stress that postcranial anatomy constitutes an important supply to better understand the relations of extinct crocodylomorphs, but also offers insights on their development, ecology, and biomechanics.

The earliest evidence of land plants

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The earliest evidence of land plants does not come from macroscopic plant remains, but from their propagules - the miospores. The latter were produced by plants believed to be of a grade of complexity similar to bryophytes, which are difficult to fossilize.

The earliest land plant macroremains are Wenlock in age and pertain to the tracheophyte genus *Cooksonia*. However, the miospore fossil record tells a different story. Earliest evidence is coming from a type of miospores called cryptospores. That according to some authors appears as soon as the Cambrian. However, these authors use a wide definition of it and consider that cryptospores are comprised of all continental palynomorphs and thus could be produced by a wide range of organisms (including algae). Other authors, based on a more restrictive definition of the cryptospore concept, consider that they appear at the beginning of the Ordovician. It is this more restrictive concept that will be used here. There is little doubt, even though fossils are missing on what plant produced them. Indeed, cryptospores have, on rare occasions, been observed in situ and only within bryophyte and bryophyte-like plants (i.e. the Late Silurian of XX). They have never been observed within sporangia pertaining to tracheophytes. It thus appears that land plants evolve during the Ordovician. This is further supported by the observation in the Late Ordovician of Oman of a single sporangia containing cryptospores.

Trilete spores are interpreted as a more derived type of spores than the cryptospores and were considered to appear during the Silurian. However, recently, earlier occurrences have been recorded in the Late Ordovician of Saudi Arabia. It is however not clear what type of plant produced them. Indeed, trilete spores are classically considered to be produced by tracheophytes. However, in extant nature, some bryophytes may produce trilete spores. The question thus remains open whether these spores were produced by bryophytes-like plants or tracheophytes.

Carnassial Chronicles: A jawesome journey through the evolution of carnivorous placentals

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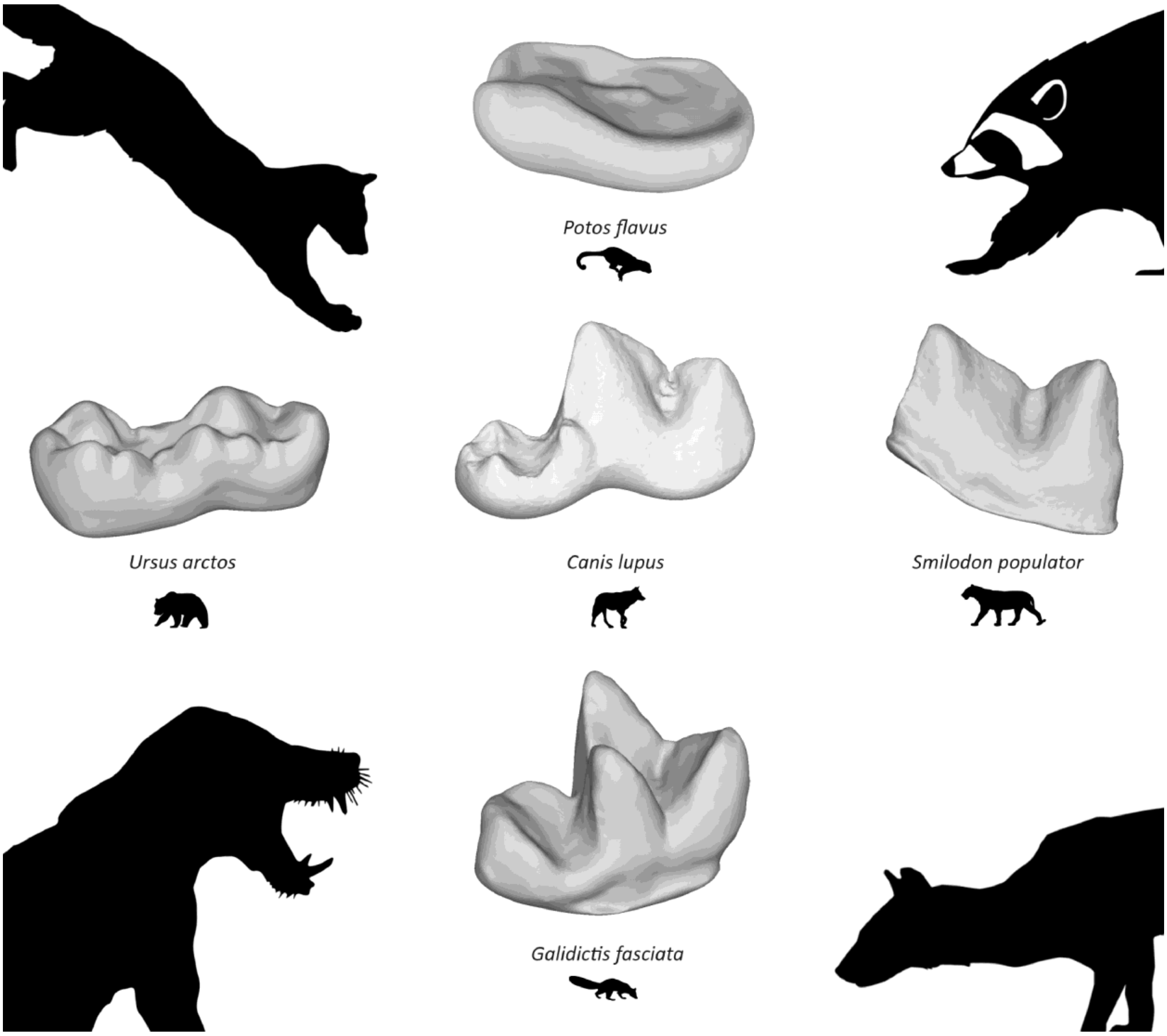
Carnivoran species exhibit remarkable diversity in their feeding habits, behavior, and morphology. A defining feature shared by carnivorans, and their stem groups (Carnivoramorpha) is the presence of a highly specialized dental complex-the carnassial complex -comprising the 4th upper premolar and the 1st lower molar. Initially evolved for efficient meat slicing, carnassials have diversified in size, shape, and use, allowing carnivorans to fill varied ecological roles from herbivorous giant pandas to malacophagous sea otters and hypercarnivorous lions. However, carnivorans represent only a fraction of the diversity of carnivorous mammals that once inhabited the Earth. Other placental clades also convergently evolved a carnassial complex, albeit with differences in the number of teeth and their arrangement; they are often collectively referred to as ‘creodonts’: Hyaenodonta and Oxyaenodonta.

Whereas the evolution of carnassial teeth in mammals has been the focus of a series of morphometric studies, the conventional wisdom for carnassial function assumes a relatively restricted use for these specialized teeth for slicing vs. crushing. However, the variety of morphologies observed among carnivoramorphans and ‘creodonts’ suggests the possibility of a higher degree of functional differentiation. In this study we use high-density 3D geometric morphometrics to quantify morphological disparity in the lower carnassial by covering each tooth in 1500 semi landmarks using a semi-automated protocol. Our dataset comprises 250 species, spanning 26 families, and encompassing both extant and fossil taxa. Our analyses reveal a discernible dietary signal in carnassial tooth shape of extant forms, with the most pronounced differences observed between herbivorous and carnivorous taxa, while there is less strong dietary signal in the carnassial shape of omnivorous taxa. Some dietary categories (e.g. piscivore) exhibit notably high disparity, which could be an example of many-to-one function. There are marked variations between feliformia and caniformia, even between taxa with a similar diet. Although displaying distinctive carnassial shapes, ‘creodonts’ demonstrate similarities with hypercarnivorous feliforms in the development of highly specialized cutting blades. However, unlike feliforms that exhibit diverse carnassial shapes, ‘creodonts’ likely remained restricted to a specialized hypercarnivorous niche throughout their evolution. These preliminary findings support the long-standing hypothesis that the greater dental plasticity of Carnivoramorpha conferred a competitive advantage, enabling them to occupy more diverse niches during the Eocene, while the morphologically constrained ‘creodonts’ went extinct.



Carnassial teeth shape diversity in Pan-Carnivora

SESSION 7 - 150TH ANNIVERSARY OF THE SOCIÉTÉ GÉOLOGIQUE DE BELGIQUE: HISTORY, HERITAGE AND COLLECTIONS IN GEOSCIENCES

Conveners

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This session is dedicated to the history of geological sciences in al their forms, from teaching to research, from promotion to industry and to the complex links between the scientists and the society. As mirror of the research, scientific collections and geoheritage as well as their historical building of knowledge are part of this two centuries-long story.

The Société Géologique de Belgique: 150 years of history

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In Belgium like in many other countries, the need for a national geological society arose in the early 1870s. At the initiative of Gustave Dewalque, professor of Geology at the University of Liège, a group of 19 members—professors in the different Belgian universities or mining engineers—founded a scientific society. The *Société Géologique de Belgique* (SGB) was officially established in Liège on January 18, 1874. By the end of the same year, 326 geologists, mining engineers, naturalists, pharmacists, and other scientists were affiliated with the Society.

The first president of the Society was Laurent-Guillaume de Koninck and the first secretary-general was Gustave Dewalque. He held this position for 25 years and was the kingpin of the Society. Among the first members of the Society was Jean-Baptiste d'Omalius d'Halloy. Charles Darwin was an honorary member.

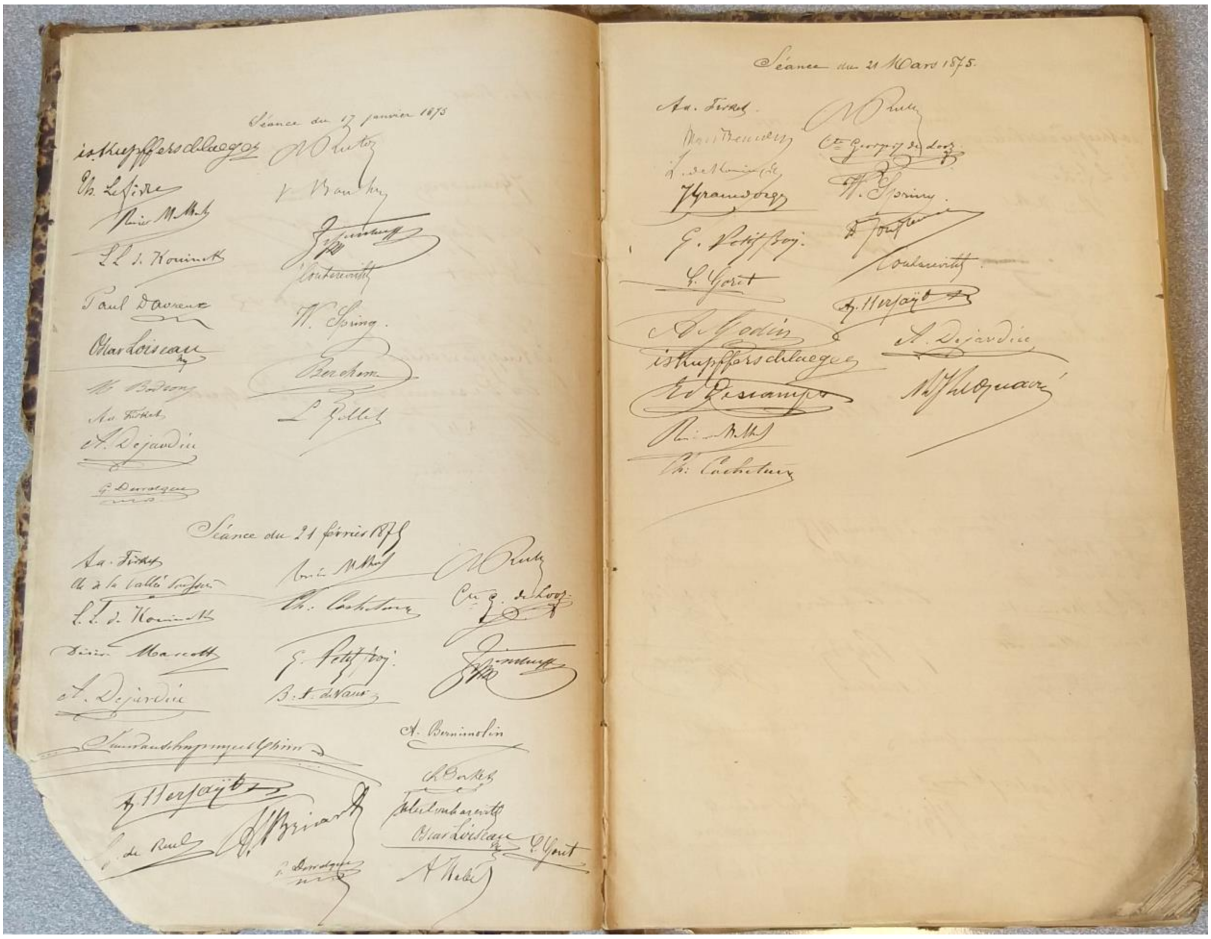
The Society aimed to gather knowledge and share discoveries about the country's geology, to inform industry engineers about advances in the earth sciences, and to promote the geological sciences. Weekly meetings were organised in Liège as well as an annual extraordinary session in the field. From the beginning, the society published a journal to spread the recent discoveries among the scientific community: the *Annales de la Société géologique de Belgique*. This journal was published monthly during the first decades then four times a year and eventually twice a year. The *Annales* were published continuously, except between 1914 and 1918, and 120 volumes were issued.

Due to different views about the large-scale geological map of Belgium, a dispute divided the Belgian geologists at the end of the 1870s and the beginning of the 1880s. This dispute led to the exclusion of several members of the SGB in 1887 and the foundation of a second geological society in the same year. This second society, the *Société belge de Géologie, de Paléontologie et d'Hydrologie*, held its own board in Brussels and published its own journal, the *Bulletin of the Société belge de Géologie, de Paléontologie et d'Hydrologie*.

This schism created unease within the Belgian geological community for twenty years. Over the years, this unease gradually subsided and the two societies organised, first in turn and then jointly, the excursions of their extraordinary sessions. This reconciliation began before the First World War and was confirmed in 1928.

In the 20th century, many geologists were members of both societies. The decline in the number of members in the community and the issues in organising activities for both societies and publishing two journals led the boards to merge the societies in the 1990s. The merger of the *Société Géologique de Belgique* and *Société belge de Géologie* resulted in the erection of *Geologica Belgica*, in 1994. The gradual pooling of all the activities of the former societies led to the cessation of their respective journals in 1997 and the publication of a new one, *Geologica Belgica*, in 1998.

Since the merger, the *Société Géologique de Belgique* has continued to manage its heritage (library, collection, prizes) and to promote geological sciences.



Signatures of the founders of the *Société Géologique de Belgique* at its first assembly in 1874.

From coal to chalk: eight centuries of water supply for the city of , Liège

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Even though coal was known in Liège since Antiquity, coal mining began in 1195. The exploitation started with “picking” coal blocks from the upper Carboniferous coal seams cropping out along the sides of the hills surrounding the city. After this early stage, shafts and galleries were dug but the groundwater occurrence was so dangerous for the miners that dewatering became necessary for in-depth exploitation.

As early as the 13th century, the first drainage galleries were developed in Liège. These galleries, called *areines* in Belgium, were built to lower the water levels occurring in the coal mines and had exit points at the lowest possible elevation so that the water could flow out into the Meuse River or the nearest stream in the valley. Each drainage gallery consisted of a network of galleries dug into the rocks. Taking advantage of the topography combined with these drainage galleries, the mines were drained mainly by gravity for five centuries.

The water from four of these gallery networks was directed as drinking water to the public and private fountains of the city. Due to their importance, these *areines*, called *areines franches*, were protected by strict laws to avoid potential physical damages or contaminations.

Until 1680, the *areines* were the only flowing water sources in Liège. In 1697, after merging two drinking water drainage galleries, Jean Roland, who requested this operation to improve the exploitation of his coal mines, was required to provide a new water source to replace the dried one. He built a new gallery to collect groundwater emerging from springs at the boundary between the Cretaceous chalk and marls (*Smectite de Herve*), northwest of Liège. This gallery carried water from the Hesbaye aquifer to the city’s mills and fountains, demonstrating an excellent knowledge of the underground at that time.

Five more galleries were built after this first one, and they supplied water collected from the Cretaceous chalk to the city. They fed public and private fountains, and the company was named the *Société des Fontaines Roland*.

In the 19th century, when the population of Liège grew to nearly 100,000 inhabitants, the drinking water supply fed by the *areines* and the *Société des Fontaines Roland* was insufficient in quantity and quality. In 1855, at the city’s request, Gustave Dumont (André Dumont’s cousin) studied the feasibility of a new network of water supply galleries in the Cretaceous chalk aquifer of the Hesbaye region. His report was published in 1856 and included the first known potentiometric map.

Dumont’s report described the best way to increase the city’s drinking water supply and to improve the quality of this water. New galleries were built, and the works were completed by 1869. Since then, drinking water in Liège mainly comes from the underground of the Hesbaye region. These galleries have been extended in several steps, resulting in more than 40 km of catchment galleries in the Hesbaye aquifer, now operated by the *Compagnie Intercommunale Liégeoise des Eaux*.

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The Birth of the Stone Industry in the Ourthe-Amblève Region during the XIXth Century

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In the 19th century, and more precisely from the 1830s, the Ourthe-Amblève region gradually transformed into a leading quarry centre for the Province of Liège. The main materials exploited there are Devonian sandstones as well as Carboniferous limestones, more commonly called *petit granit*. These stones were widely used in architecture, public works, industry and funerary art of the time. Despite its importance and its valorization in local and regional territories (museums, memories, small heritage, industrial wastelands, etc.), the long history of this lithic industry has never been studied in detail. Indeed, for the period before the First World War, it is barely impossible to paint an evolving portrait of this sector which was then in full expansion. To summarize the state of the question, we do not know, or very little, or very approximately, the decisive initiatives in this area, the first sites which were exploited, or their managers and their sociological profiles (entrepreneurs, industrialists, master quarrymen, etc.). Until today, it is true that the fragmentation of data and the absence of specific archival funds linked to the quarries had not encouraged historical research, undoubtedly considered too time-consuming, too regional and not "profitable" enough. The exhaustive research that we have been carrying out for three years in the archives has, however, revealed numerous unpublished and unexploited documents, of a very heterogeneous nature, which now make it possible to reconstruct the first large-scale industrial history of the region. As a first summary, this communication focuses on sites, peoples, as well as industrial buildings which today constitute a heritage with an often fragile and uncertain future due to lack of knowledge and acknowledgement.

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Another point of view on the history of the Carte géologique de Belgique: the personal archives of Edouard Dupont and Paul Cogels in the Royal Library of Belgium

Wouter BRACKE

Royal Library of Belgium

The paper discusses the early history of the *Carte géologique de Belgique* in the 1870s and 1880s on the basis of yet unexplored archival material kept at the Royal Library of Belgium. By and large the first years of the history of the *Carte géologique de la Belgique* are well known. In 1878 the government agreed to the realization and publication of the *Carte géologique de la Belgique* on a scale of 1:20,000 at the expense of the Belgian state. The decision's underlying idea was to finish the project started by A. Dumont, Professor at the University of Liège, who had passed away 30 years earlier. Dumont's successor at the university, G. Dewalque, founder of the *Société Géologique de Belgique*, had made it clear in his *Prodrome d'une description géologique de la Belgique* of 1868 that he wanted to continue his predecessor's project. Yet, the government appointed E. Dupont, director of the royal Museum for natural Sciences, as head of the project. Very quickly a disagreement arose between both protagonists on how the geological map should be realized. The growing tensions between both men and their respective supporters would lead eventually to the creation of a second geological society. But more importantly, the original project was aborted and had to be completely revised. Dupont was replaced by Dewalque and the map's scale changed to 1:40,000. The Royal Library of Belgium received in 2005 the personal archives of E. Dupont which together with the cartographic documents acquired at the auction of the personal library of Paul Cogels in 1912 sheds new light on these difficult years in which it is said two different visions on geology opposed each other without abatement. Both sources will be discussed in the light of their contribution to the history of the *Carte géologique de Belgique*.

Two centuries of Palaeontology collections at the University of Liège

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Universities have a long tradition of gathering material in collections with the two-fold aim of serving research and teaching. Palaeontological collections of the University of Liège date back to the establishment of the geology school in 1818-19, as reported by the oldest catalogue that survived to our days. Two collections were available for teaching at the time André Dumont became professor: the coal-measure plant fossils (Sauveur & Courtois's collection) and fossils from the Liège Province (Davreux's collection). Besides his collection, Dumont purchased many fossil specimens (the oldest being a collection of molluscs from the Paris Basin in 1850).

L.-G. de Koninck produced several monographs on Carboniferous corals but very few of the materials he studied remained in Liège because he sold many of his specimens to museums all over the world. Contrarily to his predecessor, G. Dewalque, was responsible for a dramatic increase of the collections through field work (he participated in the geological mapping program in the 1870-1880s) and purchases of reference collections from Europe and North America. Dewalque also persuaded the students and alumni to actively collect fossils in mines and quarries and to offer them to the university. Indeed, Dewalque's collection forms a significant part of the palaeontological collections nowadays. This great geologist created in the 1880s the palaeontology museum at the university that aimed to present the fossils stratigraphically.

Dewalque's successors, J. Fraipont, M. Lohest and A. Gilkinet, gathered emblematic collections, including fossils from the Black Marble of Denée, the Famennian vertebrates and the palaeoanthropological remains found in caves in southern Belgium, including Spy. During WWI, many depredations and thefts were committed by the soldiers who occupied the university and many fossils have been noted as "stolen by the enemy" in the catalogues by the curators back in their offices in 1918. In the 1930s, C. Fraipont saved Schmerling's collection of Quaternary megafauna from destruction (it was used as material for practical works in chemistry) and re-discovered the fossil Neanderthalian from Engis.

After WWII, S. Leclercq significantly increased the palaeobotanical collections through fieldwork (Goé fossil forest, coal balls) and exchanges with colleagues all around the world. As a result, the palaeobotanical collection of Liège is certainly the most diverse and significant at the global scale! Unfortunately, in the 1970s, the palaeontology museum was dismissed, and the collections were curated in inadequate places, hence many boxes of fossils have rotted whereas others were destroyed, forgotten in basements, lost or stolen. A large part of the Cretaceous and Tertiary collection disappeared this way.

Whereas Dewalque benefited from a large budget to buy fossil collections, the 20th century palaeontologists accumulated fossil material only thanks to fieldwork. E. Poty's coral collection is voluminous and sub-exhaustive whereas M. Streel's micropalaeontological one witnesses the development of palaeopalynology. Nowadays, the animal and human palaeontology, micropalaeontology and palaeobotany collections of the University of Liège gather c.1 million specimens and offer a perspective of scientific study for several generations. Although no exhaustive catalogue exists, 3D scanning and uploading to online libraries allow the world to consult and study this extraordinary collection.

Views of the Museum of Palaoeontology of the University of Liège c. 1920.

A first digitisation phase of the UMONS Earth Sciences collections in the framework of the DiSSCO-FWB project

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The collections of the Geology and Applied Geology Department of the Engineering Faculty of the University of Mons are constituted of various collections of fossils, minerals and rocks. They include groups classified according to a systematic classification, others according to their geographical origin or their inventor, and which are generally of significant heritage interest. In particular, they include regional palaeontological discoveries dating back centuries, collected and studied by e.g. Jules Cornet, François-Léopold Cornet and Alphonse Briart, and René Marlière. The tens of thousands of palaeontological samples include several dozen holotype species, particularly from the 'Montian' (i.e. Danian) and Albian periods.

Thanks to the DiSSCo-FWB project, the Department of Geology and Applied Geology was able to acquire and set-up a digitisation platform, in order to digitise the Department's collections and to make them more easily accessible to researchers and the general public.

The idea was to design a solution adapted to Earth sciences samples. The characteristics of such samples are relatively heterogeneous, in terms of size (millimetre to metre), brightness, texture and relief. The choice of equipment was therefore based on a relatively versatile solution, emphasising on the quality of the images and the efficiency and flexibility of the acquisition process. The chosen solution contains a reflex camera combined with a professional macro lens. This lens is complemented by a wide-angle lens more suited to large samples. As most of the subjects were three-dimensional objects, a focus stacking device was chosen and installed. This consists of an automated micrometric rail, which takes a series of clear photographs at different levels of the sample, and stacking software, which reconstructs a clear image from this series over the entire view of the sample.

Around 1,200 samples have been digitised so far. For each part, around 15 photos were taken at different depth of field in order to carry out the stacking operation. In all, around 18,000 photos have been taken for this initial digitisation phase.

The geological wall: a stratigraphic scale in stone from Comblain-au-Pont (Province of Liège, Belgium)

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For geologists, a stratigraphic scale is often at the very base of any study: what rocks are present in the region being studied? In what order were they deposited? These are generally fundamental questions. But for many non-experts, the stratigraphic scale is often difficult to understand and not very appealing. In Comblain-au-Pont, we have built a stratigraphic scale using native natural stones. As we had to choose a scale to represent geological units, we decided to lay down one metre of rock for every ten million years. This resulted in a 54 m long stone carpet representing 540 million years of known substratum in Belgium. It was Paolo Gasparotto, a wall builder, but also an artist, more specifically a sculptor and a painter, who was responsible for setting up the stones of the "geological wall". The natural stones come from various quarries in Belgium. Many were generously donated to us by quarry workers who gave us either the stones or organised their transport for free, sometimes both. In several cases, the material was very difficult to obtain as a large number of quarries are closed, many for a long time. However, with the help of some friends and young residents of the region, Paolo Gasparotto was able to successfully install boulders representing all geological systems present in Belgium, that is to say, all systems of the Phanerozoic Era. However, we were unable to find any Triassic rocks in Belgium. Fortunately, the Feidt Quarries from the Grand Duchy of Luxembourg provided us with boulders of Muschelkalk. Similarly, we could not find any Bajocian rocks on national soil but we obtained them from the limestone quarries in Dom-le-Mesnil in France, just a stone's throw away from our border. The Cenozoic Era presented us with another problem: most of the rocks are unconsolidated and would thus erode at the first rain. Therefore, we searched through all stages of the Tertiary for consolidated sedimentary rocks, and found and obtained both quartzarenitic and ferruginous sandstones. As for the Quaternary period, we represented it with rolling boulders from the Amblève River. The project had been in the works since 2004, but the laying of stones could only start in 2015, thankfully with the effective support from the municipal authorities of Comblain-au-Pont, and especially with the active and efficient collaboration of the non-profit organisation *Les Découvertes de Comblain-au-Pont*. The monument, completed in 2023, is already a great success among hikers who walk along the geological trail of Comblain-au-Pont since it is located on this route. It is also popular among schools now, both Dutch-speaking and French-speaking, and every day sees visitors climbing it.

Airborne view of the *Mur géologique de Comblain-au-Pont*.

The Etna volcano in Arab-Islamic Geographical Sources

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In this paper, I have tried to show how present was the volcano phenomenon in the Arab-Islamic scientific heritage in the Middle Ages. The research was limited to geographical sources, especially texts about the famous Sicilian volcano Etna.

It is clear that the care of Muslim geographers and travellers, when dealing with famous and dangerous volcanoes in various regions of the world, in that period, was extensive. They accurately described phenomena that preceded, went with, or followed many volcanic eruptions.

This heritage had taken a large background knowledge that could have been collected in that era, to the extent that much of the information, data, descriptions and even some interpretations, closely correspond to what is established in the modern volcanology.

So I can conclude that the Arab-Islamic scientific heritage represents a real basis and foundation for studying volcanoes; whereas the following contribution of the Western civilisation, represents an important and significant input in the development of volcanology.

Al-Mas'oudi A (2005). Gold Meadows and gem mines. Beirut. Dar Al-Ma'rifa. Al-Idrisi, M (2010). Picnic in Breaking Through Horizons. Cairo. Library of Religious Culture. Al-Zuhri M (2000). Geography book. Investigation: Muhammad Haj Sadiq. Cairo. Library of Religious Culture. Michel F (2007). Roches et Paysages, Reflets de l'Histoire de la Terre. Belin. Paris.

Porphyry and Man in the Land of the "Cayoteux". From paving stones to aggregates, more than three centuries of history in Quenast-Rebecq, Lessines and Bierghes

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The main product extracted from the quarries at Lessines and Rebecq (Quenast and Bierghes) is a hard rock commonly called "porphyry", due to the occurrence of crystals in a fine-grained matrix. For geologists, this porphyry is a quartz-microdiorite inserted in the form of pipes or sills within the Cambrian–Silurian slates of the Brabant Massif. It is evidence of a volcanic activity dating from approximately 420 million years.

The porphyry deposits located in Belgium constitute a mineral resource of exceptional quality. The first exploitations of this rock are poorly documented, however from the 19th and 20th centuries, numerous documents are found. Three key periods marked the history of the porphyry exploitation. The first is characterized by the extraction of rubble, blocks and badly cut cobblestones, used in Belgium for the construction of houses and to pave roads in Belgium and the Netherlands.

The second period (the golden age of cobblestones from 1840) concerns the large production of different types of cobblestones, all perfectly cut. At that time, aggregates were by-products of the manufacture of paving stones. The high quality of these cobblestones has made them a famous export product. All major European cities and some cities in North America, Australia, Egypt and South Africa imported porphyry to pave their streets. At that moment, the quarrying areas of Quenast, Lessines and Bierghes were a great source of employment, there were more than 3,200 workers in Quenast and 5,000 in Lessines! In 1900, these quarries were the largest in the world for the production of paving stones. The rise of porphyry quarries was boosted by the development of railways, the improvement of the navigability of waterways (Dendre, canals, Senne from Brussels), steam engines, then electricity and tools made from special steel alloys. This is the era of the new captains of industry who buy up the small quarries, merge them and move from the artisanal to the industrial era with major investments. Small quarries united to form huge quarries connected to each other. The quantity of paving stones produced since the beginning of porphyry mining is estimated at several billion. The third period, starting around 1950, is characterised by the concentration and modernisation (significant mechanisation) of quarries marked by the exclusive production of crushed stones (aggregates) and their related products (asphalt-blocks, bricks, clays for cement factories). The production of cobblestones becomes anecdotal and then disappears completely.

All of these periods have in common the need to remove the overburden covering the porphyry to reach the hard rock and allow the expansion of the quarries. The soft ground, essentially the clays and sands, were able to be valorized during each period, in particular for the manufacture of bricks.

The industrial extraction activity is still going on today, contrary to other materials whose extraction stopped a long time ago. As for the porphyry paving stones, they are being used again in some town centres and private homes from stocks of paving stones from the dismantling of old roads which were no longer suitable for rapid transport.

Goemaere, E, Cabidoche, M (2023). Du porphyre et des Hommes au Pays des « Cayoteux ». Des pavés aux granulats, plus de trois siècles d’histoire à Quenast-Rebecq, Lessines et Bierghes. Bruxelles, Collection Géosciences 5: 224 p.

Asbestos in Belgica ad Namurum?

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In the scope of an industrial heritage project on asbestos in collections (Januarius et al., 2022), it was found that literary sources such as the late 18th century *L'Encyclopédie* of Diderot and d'Alembert refer to an occurrence of asbestos in Belgium, more specifically "*à Namur, dans les Pays Bas*." Here, an attempt is made to trace back the reference to its origin and a tentative geological explanation is provided.

The referral to asbestos in Belgium can be traced back to the third edition of Agricola's *De Natura Fossilium* dating from 1558. Earlier editions, going back to 1546, did not mention the occurrence. Remarkably, Agricola passed away in 1555, and it is unclear how the referral entered into the third edition.

While asbestos was indeed found at the other locations mentioned by Agricola, the occurrence of asbestos in Belgium is not expected given the geological composition and history of the Belgian subsurface. Most probably, a confusion is at play with fibrous minerals (e.g. halotrichite) which originate from the weathering of pyritic shales ('ampelites') such as those of the Namurian Chokier Formation that crops out in the Meuse valley between Namur and Liège.

Agricola was well aware of the process of alum production, however, which is nothing less than the artificially induced weathering of the same shale formation and is described in his *De Re Metallica*. This early industry was also quite extensive in Agricola's times, though mostly downstream from Namur between Huy and Flémalle. This is an exemplary case illustrating the necessity of geological expertise in industrial heritage projects relating to natural resources.

Januarius J, Loocxk P, Morren D, (2022). Asbest in je erfgoedcollectie? Wegwijzer voor erfgoedvrijwilligers. Expertisecel voor Technisch, Wetenschappelijk en Industrieel Erfgoed (ETWIE), Ghent, 15 p.

The historical mineral collections of the Liège University

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The mineralogy museum of the University of Liège was constituted shortly after the foundation of the university, in 1817. Accumulated over the years by famous geologists and mineralogists André Dumont (1809-1857), Gustave Dewalque (1826-1905), Giuseppe Cesàro (1849-1939), and Henri Buttgenbach (1874-1964), the mineral samples were rare and of high historical value. In his description of the museum, Buttgenbach (1938) lists a total of 32,000 samples, among which 21,000 minerals from the systematic international collection, 4,500 specimens from Belgium, 360 samples from Congo, and 6,000 minerals from the Ungemach collection.

During the World War II, a bombing raid by the German army provoked a terrible fire in the museum that destroyed many samples, books, and mineralogy instruments. This tragic event was described in detail by Donnay (1938) who states that "The whole museum (except for a few pieces which were in the vault) and all the other facilities were burned the day the Germans left! It is a great disaster". After this publication, the international mineralogical community was extremely generous, and many donations allowed to slowly reconstruct the collection which nowadays hosts approximately 23,000 mineral specimens.

Belgian specimens are representative of all classical localities of our country, including the Pb-Zn deposits of the Moresnet region, which is the type locality for the three species willemite, fraipontite, and hopeite. Metamorphic minerals of the Stavelot Massif, as well as samples from the Visé and Blaton regions, are also extensively represented. Three very rare samples of Belgian meteorites, namely from Lesves, Tourinne-la-Grosse, and St-Denis-Westrem, occur in the collection.

The Ungemach collection, acquired by the University of Liège in 1938, was considered by the international mineralogical community as totally destroyed by the fire... but indeed, most of these samples are still preserved since they were stored in their wooden transportation boxes in 1944! Nowadays, this collection constitutes the most beautiful and rich part of the historical mineral samples belonging to the University of Liège. Henri Léon Ungemach (1879-1936) was a mineralogist from Strasbourg, friend of Giuseppe Cesàro and student of Georges Friedel. From the 6,000 samples originally reported in his catalogue, 360 are preserved in the collection of the Natural History Museum of Strasbourg, and approximately 2,500 are still in our collection. Most historical European mineral localities are represented, but the most exceptional part of the collection is constituted by the sulfosalts, among which occur many specimens from the German classical ore deposits (Freiberg, Andreasberg, ...) and from the Alsace mines (Sainte-Marie-aux-Mines, ...).

Other significant parts of the ULiège collection concern the Cesàro mineral samples, among which occur beautiful calcite crystals from Rhisnes, the Buttgenbach collection which contains many specimens collected in Katanga, as well as the holotype depository of high scientific value.

The collection is exposed in a permanent exhibition room at the *Maison de la Science* in Liège, but also in the Geology building (B18) in the Sart-Tilman campus. Don't hesitate to contact Prof. Frédéric Hatert (fhatert@uliege.be) for a visit of our mineral treasures.

Buttgenbach H (1938). Le Musée de Minéralogie de l'Université de Liège. Vaillant-Carmanne, Liège, 41 p.
Donnay J D H (1945). The destruction of the Liège museum. American Mineralogist 30: 81–83.

From François-Léopold Cornet and Alphonse Briart to Alfred Wegener and Emile Argand: from the notion of horizontal translation to the emerging plate tectonics theory

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During the 19th century, exploration of the Franco-Belgian coalfield was boosted by the development of the coal industry. Progressively, the southern boundary of the coalfield was recognised, both in the Liège district (Dumont, 1832) and in the Valenciennes and Hainaut regions (Dufrenoy & Elie de Beaumont, 1841). Finally, this boundary was attributed to a single major discontinuity along the southern edge of the Franco-Belgian coal basin (Godwin-Austen, 1856; Gosselet, 1860). At this time the discontinuity was considered to be a vertical fault, where Upper Carboniferous coalfields meet Devonian sandstones and shales. Depending on where this abnormal contact was identified, it was called *Grande Faille* from Liège to Mons (Gosselet, 1860) or *(Grande) Faille du Midi* in the Hainaut (Cornet & Briart, 1863, 1877) and *Faille eifélienne* nearby Liège (Malherbe, 1873).

However, in Hainaut, around Dour, colliery shafts began crossing this fault in the 1830s, revealing the coal measures beneath the Devonian formations. This situation, where the *Faille du Midi* is now recognised as having a gentle dip southward, is rapidly represented on several synthetic cross-sections of the western part of the Walloon coalfield, i.e. Plumat (1849) and Cavenaille (1853), while it was although still considered vertical by some geologists (e.g. Gosselet, 1860). Cornet & Briart (1863) were the first to correctly show that this main discontinuity results from a horizontal translation. This original concept, developed later in Cornet & Briart (1877), was at the origin of the theory of thrust sheets explaining mountain ranges formation. Indeed, several geologists studying the formation of the Alps rapidly reproduce the concept of Briart & Cornet, like Suess (1883), giving to them a large audience in the German-speaking world.

After the erroneous interpretation of the Glarus Alps by Heim (1878), Bertrand (1884) compared the structure of the Glarus Alps with that of the Franco-Belgian coalfield. At this time, he had not worked on the coalfield and had not yet visited the Alps. On the basis of the bibliography alone, he applied the concept published for the Franco-Belgian basin, i.e. Cornet & Briart (1863, 1877). However, Bertrand was beaten by Rothpletz (1883), who had already reinterpreted the Glarus Alps with a huge overthrust.

Outside the Alps, the application of the thrust sheet theory continued to be extended to other geographical areas, such as north-west Scotland (Lapworth, 1883, 1885), the Scandinavian Caledonides (Törnebohm, 1888, 1896), etc. Later, the continental drift theory of Wegener (1912, 1915), which is at the origin of modern plate tectonics, invoked the achievements of Alpine geologists (who had studied the thrust sheets) to show that the distance between Africa and the northwestern European continent had decreased significantly. Argand (1924) used Wegener's theory to propose that the origin of the thrust sheets was the result of the collision of drifting continents. He gave a masterly demonstration of this at the 13th session of the International Geological Congress held in Liège in 1922 and published the final text in the same city in 1924. One hundred years ago!

Co-constructing a permanent exhibit: the case of the Centre d'Interprétation de la Pierre in Sprimont, Belgium

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In September 2022, the *Centre d'Interprétation de la Pierre* (CIP) in Sprimont, Belgium, inaugurated its new permanent exhibit in an impressive heritage-listed building, next to a Tournaisian limestone quarry. The museum's diverse collection is mainly composed of paleontological specimens, stone extraction and cutting tools, and sculpted art pieces. The governing principle of the permanent exhibit is to retrace the history of Sprimont, from its Carboniferous crinoid-dominated seafloor to the industrial revolution and social turmoil. In parallel, the extensive palaeontological collections from the Université de Liège, which include material from Sprimont, are, for the most part, hidden from the public.

The creation of this permanent exhibit tackled both these challenges simultaneously, resulting from a close collaboration between scenographers, the CIP led by an art historian, and scientists. From the starting point of the scenographic process, the design and the discourse of the exhibition were created in permanent co-construction with external scientists and specifically with the geology department at University of Liège since a significant part of the exhibition area is dedicated to paleontological history and geological processes. This tale is supported by sensory experience (touch, smell, sight), by immersion (diving into the Carboniferous seas reconstructed using 3D views based on 3D scans initially made for research and teaching) and by almost empirical observation of fossils in the building stones of the CIP. The visitor therefore appropriates the material, fishes out what he wants and tests it immediately. This experiment is the actual birthplace of the successful outreach project *Fossiles en Ville*, which created city tours focussed on building stone fossils. This partnership also allowed the CIP to go beyond its walls by being integrated within one of such fossil walks in Sprimont, and became a centrepiece in the co-organization of Geodiversity day in Wallonia. This productive and mutually inspiring partnership thus maximised the museum's role as mediator and the role of the University of Liege in outreach.

Brief history of zinc mining in Wallonia during the XIXth century

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Already mentioned by Plinius and intensively worked during the Middle Ages to support the development of brass metallurgy in Dinant, the Belgian calamine deposits became the subject of a real ‘zinc rush’ during the first half of the 19th century. In this paper we will review the first traces of zinc mining in present day Belgium and will illustrate how local initiatives paved the way for the development of a world-leading metallurgical industry. We will also briefly analyse why Belgian deposits were never seriously explored and were abandonned well before being exhausted to the benefit of ores coming from Sardinia, Morocco or even Australia.

Ladeuze F, Dejonghe L, Pauquet F (1991). Historique de l’exploitation des gisements plombo- zincifères de l’Est de la Belgique : le rôle de la ‘Vieille Montagne’. Chronique de la Recherche minière 503: 37–50.

The Flemish Pottery and Stone Reference Collection (FLEPOSTORE): online open access platform and physical hands-on reference collection of geomaterials

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Pottery and stone are widely used materials in our regions since prehistoric times. These unperishable materials are found as archaeological artefacts, in architecture and in artworks. They can be considered as elementary objects of human material culture production, based on the exploitation of natural resources (stone, clay). Therefore, their scientific value in the study of the interaction between humans and their geological environment through time is crucial. As such these objects are valuable proxies to answer scientific questions in cultural heritage studies. However, for establishing such historical connections, a key factor consists in a correct mineralogical and chemical determination (‘fingerprinting’) and hence in the geological and geographical provenance of these lithic and ceramic objects. This is where the importance of a reference collection comes into play. FLEPOSTORE offers an online open access database and a physical hands-on reference collection of geo-materials. The collection’s priority is to collect locally produced as well as imported ceramics and local and imported worked stone that are encountered on Flemish archaeological sites and in historical monuments, ranging from prehistoric till pre-industrial times. Nevertheless, the collection hosts also more exotic geo-materials retrieved through international research projects and networks at the Departments of Geology and Archaeology of Ghent University.

The main aim is to collect, document and make available diagnostic reference geo-materials: clay and rock sourced from natural outcrops or quarries and ceramics from pottery production sites. FLEPOSTORE wants to facilitate the open access availability of these geo-materials: it is a scientific reference platform and a feeding-ground for future research initiatives. It will function as a pivotal network centre for geo-archaeological support of scientific research, education and heritage management projects in archaeology, geology, arts and architecture, but it also offers high quality information and images for anyone with interest in these topics. The collection strategy is based on the secured provenance principle. Only samples that have a documented find location and provenance are taken into account.

The actual presentation will focus on rock samples only. The rock collection builds on sourced sub-collections from the Department of Geology and Archaeology established in the framework of earlier and ongoing research projects. The description of each rock sample is organized in 6 tabs: classification, find location/provenance, hand specimen, microscopic features, sample info and references. Under the heading ‘classification’ the following characteristics are addressed: rock classification, rock name, rock synonyms, chronostratigraphy, lithostratigraphy and additional information. Under ‘microscopic rock features’ the following information is given: components, texture, structure, weathering, diagnostic features and additional information. The samples and their thin sections are stored at the Department of Geology (rock samples) and the Department of Archaeology (rock and ceramic samples). The physical collection is accessible on personal demand (please contact: flepostore@ugent.be).

Sandstone (BE.22.0003)

Hand specimen pictures (macro & binocular) | Thin section pictures | Find location

Classification | Find location / Provenance | Hand specimen | Micro | Sample info | References | Cite this page

Rock determination	Sedimentary rock > Siliciclastic > Sandstone > Quartzarenite
Chronostratigraphy	Phanerozoic; Cenozoic; Paleogene; Oligocene
Lithostratigraphy	Borgloon Formation; Alden Biesen Member
Rock name	Quartzarenitic sandstone
Rock synonyms	groundwater silcrete; Potamides quartzite
Additional information	Early Oligocene

− Thin section

Flepostore inventory nr.	ARCH3.L1.A16
Original inventory nr.	A0101
Collection	Archaeological Department, Ghent University
Type	Covered thin section
Comparable thin section(s)	

− Microscopic rock features

Components	quartz-rich sand grains, almost exclusively composed of monocrystalline quartz, rare polycrystalline quartz (quartzite), besides lithoclasts of chert (flint?); nice overgrowths of silica showing also dust rims; locally mouldic porosity due to dissolved mollusk shell; contamination (illuviation?) by soil particles
Texture	well-sorted and rounded quartz-rich sand grains

BE.22.0003

Excerpt of the FLEPOSTORE-database: example of the online information available for sandstone sample BE.22.003 and a zoomed-in high-resolution macroscopic photograph.

The Dumont dynasty in Liège, ideal background for the famous geologist, André-Hubert Dumont

Francis TOURNEUR

SPW / ARNE, Service géologique de Wallonie

The Dumont family settled in Liège at the end of the 17th century, coming from the Samson River, a region with many quarries. They are cited among the most important stone- and marble-workers of the principality, suppliers of many projects in religious and civil architecture, including the most prestigious ones. André-Hubert Dumont (1751-1828) married the daughter of the famous architect Barthelemy Digneffe. Among their childrens, Barthelemy-Joseph (1775-1837) was the father of the industrialist Gustave Dumont (1821-1891) and Jean-Baptiste, father of the geologist. André-Hubert Dumont provided stone and marble for many buildings, churches in Liège, townhall of Sint-Truiden, palace of the princes-bishops, among others. He created a new marble factory along the Meuse River to cut and polish stones, one of the most ingenious industrial water mills of his time. During the Revolution, he participated in the dismantling of the Saint-Lambert Cathedral to recover marble and just after the Concordate, he delivered new pieces of furniture to restore the old churches. He was close to the French administration at the beginning of the 19th century, collaborating in the creation of the Central School, ancestor of the university, and playing a role in municipal politics. He was in correspondence with famous scientists like Barthelemy Faujas de Saint-Fond. The *cabinet d'histoire naturelle* of André-Hubert Dumont was well known for the travelers, scientists and students, with special interest in mineralogy, petrography and applied geology.

In 1808 his cadet son, Jean-Baptiste Dumont (1777-1838) married Marie-Barbe, daughter of Hubert Sarton (1748-1828), prominent personality of the technical world of Liège at this time. Well known as a watchmaker (for the court of Brussels and Versailles), he was also a genial inventor in many different sectors. Close to the prince-bishop de Velbrück, he founded in 1779 the *Société libre d'Émulation*, he was active in the textile industry but also in the coal mines, where he created new machines to take off fatal water—a skill perhaps useful for the hydraulic factory of André-Hubert Dumont. Jean-Baptiste Dumont followed the courses of the Central School, to become a geometer. He applied for a job as a mining engineer, writing a long letter to the king of Netherlands, Wilhelm, with many details of his qualifications. First, scientific knowledge, in geology in studying the collections of his father and writing a treatise of mineralogy. Then, in chemistry, following with his brother the industrial activity of his father, in manufacturing alum, but also trying to obtain sugar from beets. And skills in geometry applied to topography and to architecture, civil and hydraulic one. And finally, long experience as a bureaucrat, during the French period, in the cadastre administration. He obtained the position of *sous-ingénieur des mines de la province de Liége*, working until his retirement in 1837, one year before his death. The only child of Jean-Baptiste Dumont and his wife Marie-Barbe, André-Hubert (the same first name as his grandfather), born in 1809, lived indeed in the ideal environment to become one of the most distinguished geologists of his time.

Tourneur F (2024). La famille Dumont, 'marchands de pierres et de marbres' au Pays de Liège, ancêtres du géologue André Dumont. Bulletin de l'Institut archéologique liégeois 128: 29–88.

Liège, Saint-Martin church, floor of white, grey and black ‘marbles’, Jean-Paul Dumont, 1775.

The marble-worker François Dupont of Dinant, father of the geologist Édouard Dupont

Francis TOURNEUR

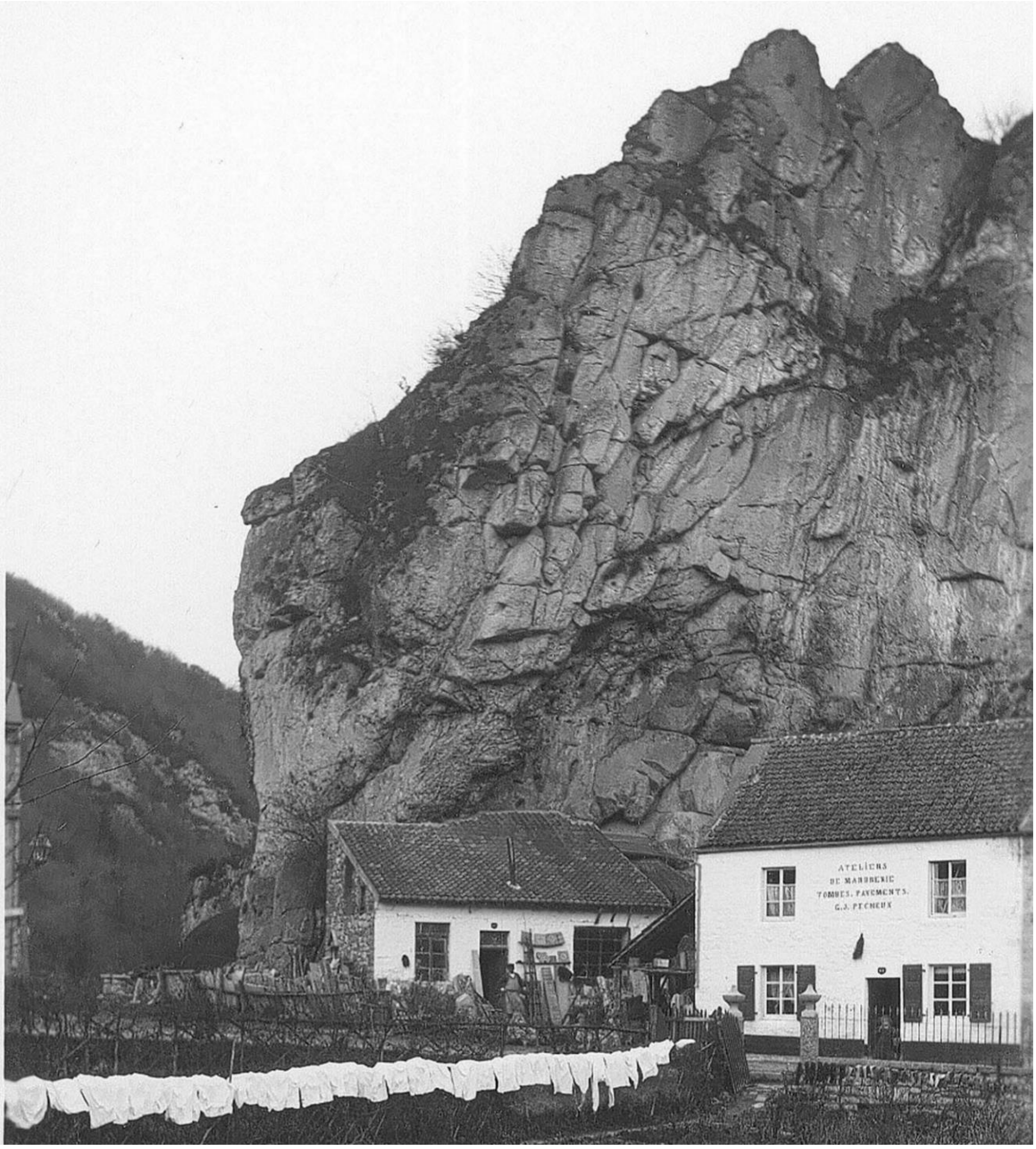
SPW / ARNE, Service géologique de Wallonie

Dinant was a rotating plate for the European marble trade since the Middle Ages. The region around the town was rich in quarries of the famous black marble, but the marble workshops also processed other types of rocks, red marble from Agimont and Gochenée, black and white marble from Charlemont (Givet) and materials imported in blocks like alabaster from England and white crystalline marble from Italy. Under the Old Regime, Dinant exported its finished products far and wide, to Holland and France via the Meuse River, but also to the North (Denmark, Poland and Baltic states, Dinant belonging to the Hanseatic network) and to the South (Florence for the *Pietre dure* marquetry). After the Revolution, this commercial activity somewhat slowed down, but it continued until the end of the 19th century, with the development of new hydraulic or steam machine factories to cut and polish marble, along the Meuse River and its affluents.

The family Dupont, coming from Normandy, settled in Dinant at the beginning of 19th century. François Dupont (1806-1864), a lawyer, associated with his colleague lawyer Victor Lion and his sister Ernestine in 1838, for the exploitation of a marble quarry in Tahaut (Hastière-Lavaux) and of the neighbouring factory to cut and transform this marble. In 1841 the marble-worker Jules Antoine, who would marry Ernestine, joined the association at the same time as the French engineer Bourguignon. Together, they registered several patents for machines cutting, sawing, and carving the marble, showing their great interest in technological progress. They also showed social considerations for the arduousness of the work in the quarries and factories, thoughtfulness then quite unusual. In 1841, they received an award at the *Exposition de l'Industrie belge* for their activity, the exploitation of their quarries, the innovative character of the factory and workshops, with a high degree of mechanisation, the quality of their production and the excellent social climate of their company. They exploited four quarries, the Waulsort breccia in Tahaut and three near Rochefort and Humain for the famous Saint-Remy red marble. They also managed a quarry of Viséan red breccia for a countess in Walzin. In 1843 the company received the new name 'F. Dupont et Compagnie', but was already dissolved in 1844, after a dispute between the associates. This dissolution was effective in 1848.

Édouard-François Dupont (1841-1911), son of François, was born into a world of marble producers. His father also gathered a large collection of stones, minerals and fossils, and he was in good contact with the palaeontologist Laurent-Guillaume de Koninck. It was so predictable that the young Édouard developed an interest in natural sciences and geology. This interest was reinforced by his relationship with Jean-Baptiste d'Omalius d'Halloy, the true mentor of the future geologist and archaeologist. This industrial environment also explains the interest of Édouard Dupont in the red marbles and its innovative interpretation of the reefal origin of these Frasnian limestones. It also explains the frequent technical and architectural notations in the geological writings of Édouard Dupont.

Tourneur F, Verbeek M (2022). Le Moulin des Batteurs, Lecomte puis Watrisse à Dinant et les derniers feux de la marbrerie dinantaise. Annales de la Société archéologique de Namur 96: 25–69.



Hastière, Fonds de Tahaut, photo Edmond Somville (IRPA E003445), end of 19th century.

SESSION 8 - NEW ANALYTICAL DEVELOPMENTS IN GEOSCIENCES

Conveners

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The technological advances over the last decades have opened new opportunities for geoscientists to solve a wide range of geological problems. Novel analytical techniques such as LA-ICP-TOF-MS (Laser Ablation Inductively Coupled Plasma Time-of-Flight Mass Spectrometry), (S-)µXRF ((Synchrotron)-Micro-X-ray Fluorescence), LIBS (Laser-Induced Breakdown Spectroscopy), PIL (Plasma-Induced Luminescence), THz (Terahertz) spectroscopy, and the development of analytical protocols to investigate new isotopic systems (using Multi-Collector or High-Resolution ICP-MS), have widened the geoscientist's toolbox significantly over the years both in the lab and in the field. In addition, the increased availability and improved performance of radiation sources, detectors, and spectrometers, together with the incorporation of new certified reference materials, have brought more traditional techniques such as electron microscopy, X-ray (XRF, XRD, CT), and Raman spectroscopy to the next level.

With these analytical techniques, large geochemical and mineralogical datasets can be quickly acquired and with relatively minimal efforts, which for instance advances the development of high-resolution 2D and 3D imaging and screening applications on a plethora of different geomaterials (rocks, meteorites, ores, soils, bone, teeth, archaeological artefacts etc.). However, due to their increased complexity, size and diversity, these datasets require dedicated processing tools such as multivariate regression, machine learning, data fusion, etc.

In this session, we encourage any contribution on the application of new analytical methods in geosciences, emphasizing their benefits, complementarity with other well-established techniques, but also to show their pitfalls. We aim to bring together scientists from various fields who are using different techniques to foster collaborations in multidisciplinary geoscience research.

Invited Speaker

Extending the applicability of quantitative 2D LA-ICP-TOF-MS multi-elemental mapping in sclerochronology and geochemistry

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Since its introduction in 1993(1), inductively coupled plasma time-of-flight mass spectrometry (ICP-TOF-MS) has become a powerful analytical technique for quasi-simultaneous monitoring of fast transient signals, detecting ions from nearly all elements of the periodic table (typical mass range: 14-254 amu) within tens of microseconds. Coupled with low-dispersion laser ablation (LA) systems, ICP-TOF-MS enables high spatial resolution 2D mapping at high repetition rates (up to 1 kHz nowadays), significantly improving mapping speed compared to what can be achieved with sequential scanning-type ICP-mass spectrometers such as quadrupole-based ICP-mass spectrometers (ICP-Q-MS). While ICP-Q-MS offers higher detection power for a few selected elements, ICP-TOF-MS provides sufficient sensitivity for most trace element applications and comprehensive spectral information for flexible data analysis(2).

In this talk, the capabilities of LA-ICP-TOF-MS will be explored through several scientific works carried out by the Atomic and Mass Spectrometry Research group (A&MS), focusing on quantitative 2D elemental mapping of various geo-related sample types such as fish otoliths, scales, oyster shells, and meteorites. For these investigations, the icpTOF 2R (TOFWERK) was coupled to a low-dispersion ablation cell mounted in the Cobalt ablation chamber of an Iridia LA-unit (Teledyne Photon Machines).

In sclerochronological studies, otoliths, scales or shells ($CaCO_3$ matrices) serve as archives of environmental history. In this work, LA-ICP-TOF-MS was used to reveal quantitative elemental distribution patterns of trace (e.g., Mn, Ca, Zn, Cd, Pb) and major elements (e.g., Ca, Sr, Ba) and their correlation with environmental changes. A matrix-matched quantification approach, employing homogeneous distributed nanoparticulate pressed pellets, was developed to obtain a reliable and robust calibration strategy for elemental mapping. Additionally, we present high spatial resolution multi-element 2D mapping of micrometeorite cross-sections(3) and a set of chondritic meteorite samples (H chondrites). For micrometeorites, an accurate and precise quantification method was developed using natural glass reference materials and 100% oxide normalization (3). The use of LA-ICP-TOF-MS allowed the analysis without prior selection of areas of interest or any chances of mixed-phase signals. In the case of H chondrite studies, the elemental mapping revealed the distribution of both major and some trace elements among the constituent minerals, using a 5×5 μm spatial resolution (pixel/data point). However, the noted high spatial resolution resulted in some trace element signals being below the limit of detection (LOD) (4).

As such, with these studies, we demonstrate the advantages of LA-ICP-TOF-MS compared to conventional LA analysis, highlighting its potential in the geological field.

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LIBS analysis of lithium in metapelites: towards a fast and field-deployable geothermometer?

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Determining metamorphism temperature often requires the application of various complex and time-consuming mineralogical and geochemical techniques in laboratory, which hampers obtaining data with high spatial density. The high sensitivity of LIBS to light elements is utilized here to explore its potential for rapidly evaluate metamorphic temperature of metapelites from the Rocroi massif, Ardennes. In the range of 250 – 650 °C and beyond, lithium tends to be leached out from metasediments and flushed by metamorphic fluids (Melleton et al., 2020). As lithium is mainly bound to clay minerals, Li/Al is therefore expected to decrease with increasing metamorphism temperature. This trend was effectively observed with the LIBS intensity ratio Li/Al of 14 siliciclastic rock samples. These samples were previously analyzed for determining their maximum metamorphism temperature using Raman Spectroscopy on Carbonaceous Material (RSCM, Beyssac et al., 2022; Lahfid et al., 2010). The results obtained with a handheld LIBS analyzer (fig. 1) were similar to the results obtained with a laboratory LIBS system with different laser wavelengths and pulse energy. Simultaneous multi-elemental analysis with LIBS is an advantage since measurements in samples, or in specific areas of a sample, that are not sufficiently rich in clay minerals (i.e. siltite and quartzite) can be easily filtered out from the dataset by thresholding the LIBS signal based on the LIBS Si/Al ratio. Portability and fast data acquisition could make LIBS an ideal tool for collecting large datasets of metamorphism temperature on the field. However, calibration is required to convert the Li/Al LIBS ratio in absolute temperature and, at his point, there is no indication that RSCM is the best method. Further investigation is thus needed to 1) better understand the elemental geochemistry of lithium in metapelites in relation to clay mineralogy and metamorphism parameters, 2) explore the rich geochemical information enclosed in LIBS spectra, which could help improving the poor precision of the method, and 3) compare Li/Al ratios with other proxies of metamorphism temperature like illite crystallinity, vitrinite reflectance, etc.

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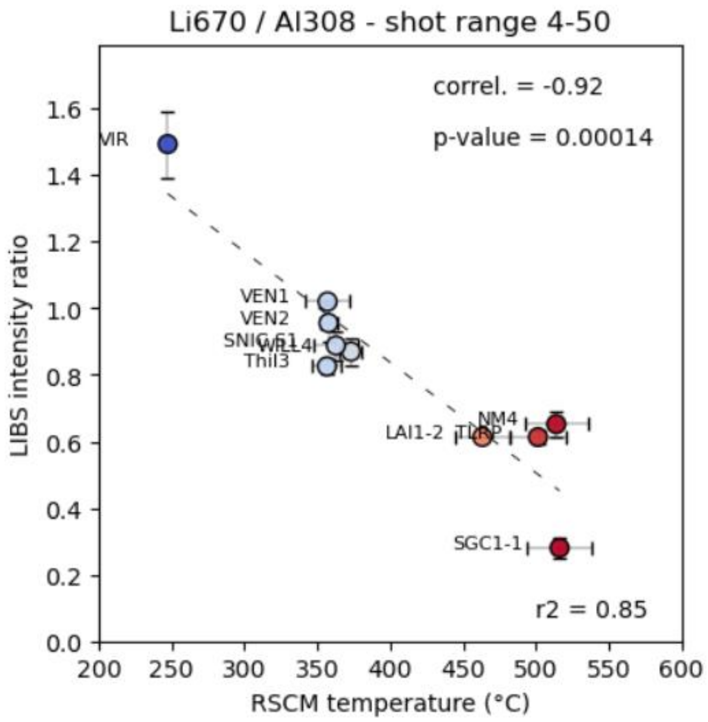

Figure1. Relation between peak metamorphism temperature as measured by Raman Spectroscopy on Carbonaceous Material (RSCM) and LIBS ratio Li/Al for Cambrian metapelites from the Rocroi massif, Ardennes. Li670: intensity of lithium atomic emission line at 670.7 nm. Al308: intensity of aluminium atomic emission line at 308.2 nm.

Testing a screening methodology to identify Critical Raw Materials with Laser-Induced Breakdown Spectroscopy

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Meeting the growing demand for Critical Raw Materials (CRM) is one of the greatest challenges for the next decades in Europe and worldwide. In this context, research and development are required regarding resource availability, multi-scale CRM identification and characterisation, and environmental impact of mining and processing CRM. Flexible, rapid and reliable measurement techniques are needed to enhance our capacity of CRM exploration, exploitation, recycling and environmental impact monitoring.

During the LIBS-Screen Brain-Be project, We tested a fast and semi-automated CRM screening methodology using Laser-Induced Breakdown Spectroscopy (LIBS) and machine learning. Samples from Belgian zinc-lead (Zn-Pb) deposits were chosen for this test since this type of mineralisation is known to potentially host elements such as germanium (Ge) and gallium (Ga), increasingly demanded for the development of green energy technologies and therefore classified with high criticality in the EU [1]. Of equal importance is the fact that many elements in these deposits can turn into contaminants for the environment as a result of their mining and beneficiation, including Zn and Pb and others such as cadmium (Cd), arsenic (As) and thallium (Tl). LIBS therefore stands out as an ideal technique since it can provide a quasi-complete geochemical characterisation of these materials.

A total of 408 hand samples from the RBINS-Uliege-UMons collections were selected for screening to represent a variety of rock and mineral types from four different Zn-Pb districts in Belgium. Samples were not prepared or cleaned in order to test the sensitivity of LIBS acquisition for minor elements (CRM and associated contaminants). The screening consisted of 30 randomised single-shot LIBS spots per sample, using a Python-based software to automatise spot data acquisition with time between measurements set up between 5 and 10 seconds depending on the sample to allow for manual navigation time between points and optimal placement for refocusing. Machine learning models were developed to handle the large volumes of spectral data generated with this approach, consisting of unsupervised methodologies for mineral identification, and a more supervised and targeted approach for elements identification and classification based on reference atomic spectra database [2].

Our results show that this screening approach of randomised LIBS spots and machine learning data processing and analyses can successfully identify many of the minor elements of interest such as Ge, Cd and As, even with no sample preparation. LIBS screening can be used as a rapid, flexible and reliable first step measurement to direct further research in these occurrences. Although being developed with a focus on Belgian deposits, this methodology is being developed further to optimise minor element identification pipelines to ensure its applicability to different geological deposits and environmental needs.

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Automated mineral sensing for robotic miners: the ROBOMINERS perception payload

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ROBOMINERS (Bio-Inspired, Modular and Reconfigurable Robot Miners, Grant Agreement No. 820971, http://www.robominers.eu) was a European project funded by the European Commission's Horizon 2020 Framework Programme. The project aimed to test and demonstrate new mining and sensing technologies on a small robot-miner prototype (~1-2T) designed to target unconventional and uneconomical mineral deposits (technology readiness level 4 to 5).

As part of the ROBOMINERS sensors payload development, a set of mineralogical and geophysical sensors were designed to provide the necessary data to achieve “selective mining”, the ability to reduce mining waste production and to increase productivity of small mining machines. The robot should have the ability to react and adapt in real time to geological changes as it progresses through a mineralized body. The perception payload technologies demonstrated in the project are based on reflectance/fluorescence spectroscopy, laser-induced breakdown spectroscopy and Electrical Resistivity Tomography.

The field trials of the sensors have been carried out in the entrance of abandoned mine (baryte and lead mine, Ave-et-Auffe, Belgium), as well as in an open pit mine (bituminous shales mine in Kunda, Estonia) and in an underground lead mine (Mezica, Slovenia). These tests allowed to demonstrate the effectiveness of these sensors to provide realtime to sub-realtime mineralogical and geophysical data to a robotic drilling platform, paving the way for more autonomy in robotized mining machines.

The ROBOMINERS "RM1" prototype during the July 2023 tests in the Kunda mine, Estonia

LIBS and PIL mapping as a tool to better understand multi-stage mineralization processes: application to the Lompret Ba-Pb occurrence (Belgium)

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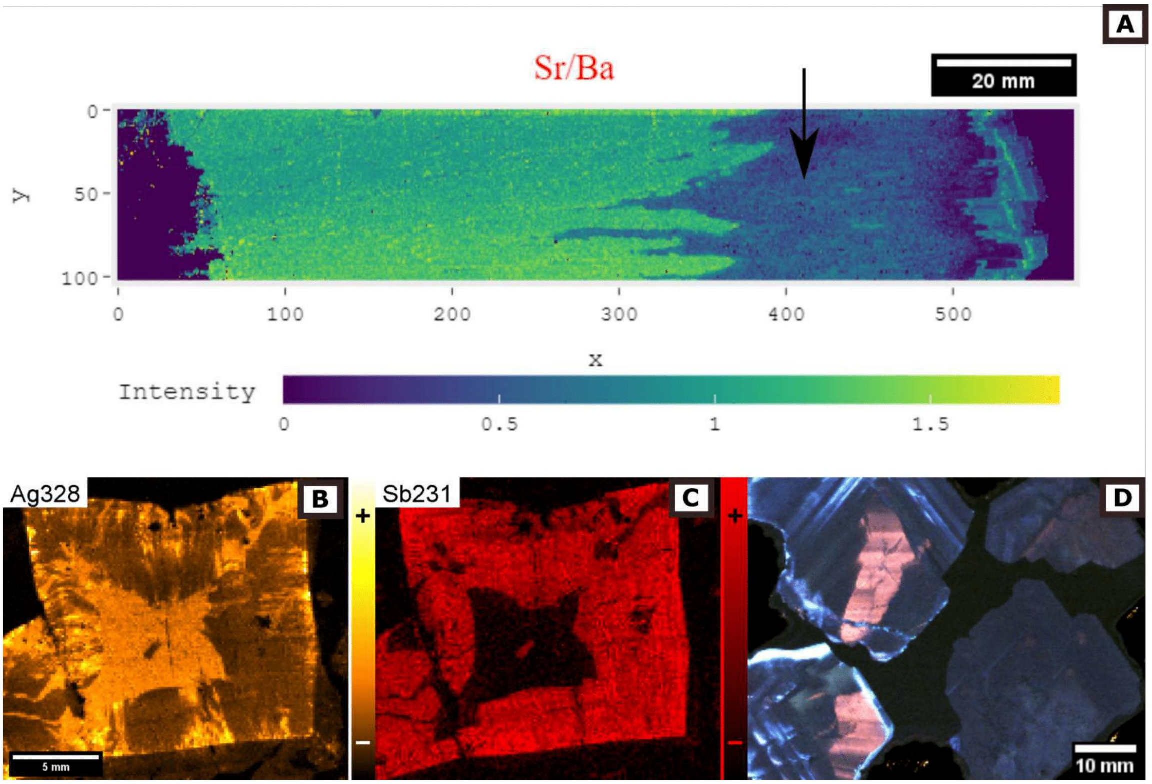
LIBS (Laser Induced Breakdown Spectroscopy) is increasingly used for elemental mapping of geomaterials. This technique has many advantages such as high acquisition speed, simultaneous detection of most elements, flexibility in terms of spatial resolution and sample size, etc. For this study, LIBS mapping was applied to a Ba-Pb mineralization in the Lompret quarry (Chimay, Belgium), in addition with standard geological investigation such as field/sample observation and polarizing/cathodoluminescence microscopy of thin sections. For a decade, many major finds of baryte and galena mineralization have been done there. These mineral species are mainly accompanied by calcite and minor accessory Fe-Cu-Zn sulfides and Cu-Pb-Zn secondary minerals. The mineralization at Lompret is characterized by its complexity and the unusual habit of some mineral species (baryte, calcite, galena). The mineralization consists of decimetric to metric pockets hosted in recrystallized/karstified limestone or in fracture infillings in a Frasnian carbonate mound. Each pocket is a partial record of a global mineralization sequence, which is proposed here based on the analysis of LIBS elemental maps of baryte, galena and calcite samples from different zones. The information yielded by LIBS and PIL (Plasma-Induced Luminescence) maps mainly consists of crystal textures revealed by the distribution of trace-elements (Ag and Sb in galena, Sr in baryte and Mn, Mg and Sr in calcite), and luminescence patterns (Fig. 1). The interpretation of crystal textures includes growth and sectoral zoning, and corrosion features. The PIL and cathodoluminescence patterns in calcite were very similar. Baryte showed no detectable cathodoluminescence but a PIL pattern similar to the PIL of baryte from Doische (Belgium). Trace-element distribution in galena was also compared to that of galena from a few other occurrences in Europe and it was found similar to galena from MVT deposit at Corbières (France).



Selected LIBS and PIL maps from Lompret mineralization, Belgium. A) Sr/Ba map of baryte showing growth zoning and corrosion features (arrow). LIBS intensity scale is in arbitrary units. B) and C) Ag and Sb maps of a galena crystal exhibiting complex zonation. D) PIL map showing that baryte from Lompret (right) displays similar but darker luminescence pattern and color than baryte from Doische (left).

Using optimized portable X-ray fluorescence (pXRF) analysis to differentiate continental flood basalt formations

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Portable X-ray fluorescence (pXRF) is a rapid, cost-efficient, and non-destructive geochemical technique that has shown over the last two decades an explosion in lab and field applications ranging, e.g. from ore geology to (geo)archaeology. The use of pXRF in mapping and characterizing large igneous provinces has been underexplored so far, whereas volcanic rocks from these areas can provide a suitable target for chemostratigraphic correlations. Here, we present a quantitative workflow that allows a rapid geochemical characterization of continental flood basalts, using the Bruker Tracer IV pXRF instrument (at VUB-AMGC).

For this purpose, a specific calibration method dedicated to igneous rocks was developed using repeated pXRF spot analyses on a series of certified reference materials (n=27), focusing on several key major and trace elements (Si, Al, K, Ti, Ca, Fe, Mn, Sr, Ga, Ba, Rb, Zn, Nb, Zr, and Y; following Triantafyllou et al., 2021). Subsequently, this optimized pXRF calibration was applied for spot analysis of tholeiitic basalts from the Deccan Traps Volcanic Province in India. Outcrop samples were obtained from the Ambenali Ghat road section, collected between the towns of Poladpur and Mahabaleshwar in the Western Ghats Region (derived from the paleomagnetic study of Jay et al., 2009). Drill core samples come from the 2017 ICDP (International Continental Drilling Program) Koyna cores to ensure well-preserved basalt samples and correlation with the Ambenali Ghat road section.

Based on the pXRF quantitative results, we were able to distinguish the Bushe and Poladpur formations in both these outcrop and drill core samples. We focus firstly on these two formations as these are emplaced close to the proposed Cretaceous-Paleogene (K-Pg) boundary ~66 Myr ago. Clear differences were found in the contents of TiO_2 (0.97 ± 0.11 wt% (2SD) vs 1.88 ± 0.37 wt%), K_2O (0.90 ± 0.42 wt% vs 0.34 ± 0.08 wt%), and concentrations in Sr (189 ± 17 ppm vs 215 ± 29 ppm) for the Bushe and Poladpur Fm., respectively. In addition, the effect of large phenocrysts on the chemical composition relative to the spot-size of the pXRF instrument (8 mm diameter) was checked by performing high-resolution (25 μm) element mapping using micro-X-ray fluorescence (μXRF; Bruker M4 Tornado; Figure 1). Finally, the stratigraphic correlation based on the pXRF results has been validated by independent Sr isotope data on the same samples, showing a pronounced distinction between the Bushe and Poladpur formations with a $^{87}Sr/^{86}Sr$ range for the Bushe Fm. from 0.7164 to 0.7177 and much lower values for the Poladpur Fm. between 0.7063 and 0.7077. Hence, this pXRF method shows great potential as a time-efficient chemostratigraphic and mapping tool for outcrop and drill core samples from the Deccan Traps, and by extension also for other large igneous province basalts.

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Triantafyllou, A., Mattielli, N., Clerbois, S., Da Silva, A.C., Kaskes, P., Claeys, P., Devleeschouwer, X. and Brkojewitsch, G. (2021) Optimizing multiple non-invasive techniques (PXRF, pMS, IA) to characterize coarse-grained igneous rocks used as building stones. Journal of Archaeological Science, 129, 105376.

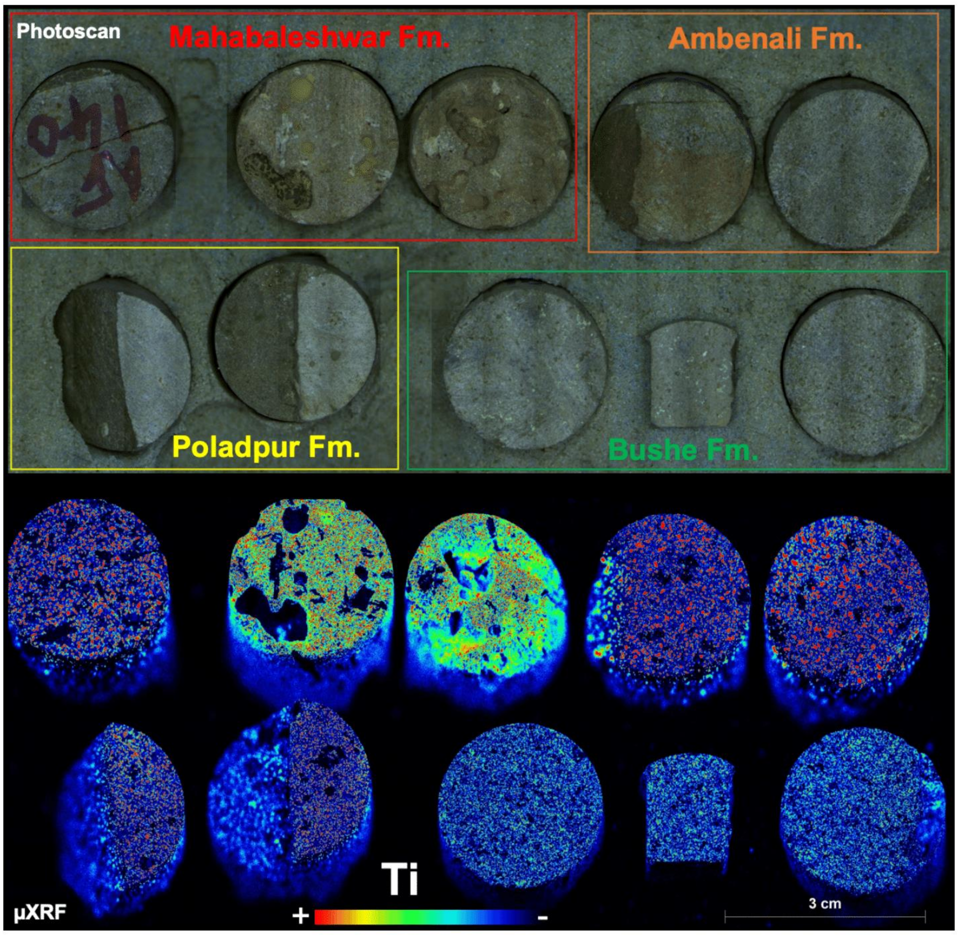

Figure 1. High-resolution µXRF element mapping results from Deccan basalt outcrop samples from four different formations (derived from Jay et al., 2009), showing a semi-quantitative single-element heatmap for Ti. The Bushe Fm. clearly yields lower abundance of Ti compared to the Poladpur, Ambenali and Mahabaleshwar formations, as also confirmed by pXRF spot

SESSION 9 - POLAR FRONTIERS

Conveners

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Polar regions are facing unprecedented challenges, experiencing a rate of warming that surpasses the global average. This accelerated warming has profound implications for the Earth's intricate systems and human society. Our session is dedicated to a comprehensive exploration of past, present, and future interactions with the polar regions, encompassing a wide array of components such as ice sheets, glaciers, ocean, sea ice, and permafrost. Our primary objective is to facilitate synergistic collaboration between modelers and observational scientists. Through this collaborative effort, we aim to pinpoint shared challenges and shape a collective vision for the advancement of Belgian research in Polar Regions.

Invited Speaker

Assessing the potential impact of subsea permafrost thaw on the Arctic Ocean carbon cycle and climate (1900-2300)

Sandra ARNDT 1,2; Constance LEFEBVRE 1; Alexis GEELS 1; Emilia RIDOLFI 1

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The Arctic is a key area of concern for carbon cycle-climate feedbacks. The rapidly warming Arctic hosts enormous, yet still poorly quantified amounts of carbon/methane that are held in thawing terrestrial and marine permafrost and associated methane hydrates. A major concern is that microbial activity in the thawing permafrost could generate carbon dioxide and methane emissions that would become sufficiently large to create a dangerous positive feedback loop in which emissions would further warm the climate, which, in turn, would accelerate permafrost thaw and release more greenhouse gases.

Yet, this potentially dangerous permafrost carbon-climate feedback currently remains one of the least quantified and most uncertain feedbacks within the climate system. In particular, carbon emissions from subsea permafrost- the relict permafrost that has been submerged by rising sea levels after the Last Glacial Maximum- remain largely unquantified and, thus, neglected in integrated assessment models and climate policy discussions.

Here, I illustrate how we developed, parametrized, and applied a fully integrated panarctic model framework including geophysical models of submarine permafrost with diagenetic models and Earth System models to track greenhouse gas production and emissions in/from thawing subsea permafrost and explore its impact on the Arctic Ocean and climate system. Model results indicate that substantial amounts of biogenic methane could be released from the Arctic shelf under the worst-case climate warming scenarios. However, effective climate mitigation strategies would prevent such large-scale emissions. Nevertheless, results also underscore that there are still significant uncertainties associated with these estimates.

Why is Greenland melting?

Sibylle BOXHO 1,2*, Nadine MATTIELLI 1, Karine DEBOUDT 3, Barbara DELMONTE 4, François FRIPIAT 5, Denis GILLES 6, Nathan GOFFART 6, Steeve BONNEVILLE 2

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Climate change is magnified in polar regions where temperatures have increased at a rate twice as fast as the global mean, with important implications for the length of melting season, ice cover, hydrology, precipitation patterns, and ice caps. Greenland, in particular, is experiencing an acceleration [1] of ice melting across its surface, due notably to the presence of a "Dark Zone" (DZ) in summer, on the west coast of its ice sheet. This zone is composed of algae bloom growths governed by inputs of phosphorus from atmospheric dust [2]. These algae darken [3] the ice and accelerate melting. Hence, the study of atmospheric dust deposition in Greenland is vital to characterize, given the importance of our polar regions.

The Nanok expedition in spring 2022 allowed sampling along a 460km transect from west to east of Greenland. With these valuable snow dust samples, two fundamental questions will be addressed by our study: 1) What is the nature of phosphorus, the primary nutrient, contained in these mineral dust deposits; 2) How far could this DZ extend? By coupling atmospheric particle analyses and phosphorus concentration, this will help better understand the hitherto neglected aspect of these dust-ice algae interactions, namely the extent of dust transport containing sourced P in the DZ, and further understand the DZ eastwards development onto the ice cap.

[1] Cook J.M., et al. (2020): "Glacier algae accelerate melt rates on the south-western Greenland Ice Sheet". The Cryosphere 14, 309-303: https://doi.org/10.5194/tc-14-309-2020 [2] McCutcheon J., et al. (2021): "Mineral phosphorus drives glacier algal blooms on the Greenland Ice Sheet". Nat. Commun. 12, 570 https://doi.org/10.1038/s41467-020-20627-w [3] Weintjes I.G., et al. (2011): ''Dust from the dark region in the western ablation zone of the Greenland ice sheet''. The Cryosphere 5, 589-601: www.the-cryosphere.net/5/589/2011/

IMAQA: Bridging Exploration and Science for Polar Research

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1 IMAQA, Brussels, Belgium ; 2 Université Libre de Bruxelles, Belgium ; 3 Université catholique de Louvain, Belgium ; 4 Université de Liège, Belgium ; 5 Observatoire Royal de Belgique, Belgium ; 6 GEUS, Copenhagen, Denmark

IMAQA emerges from a collaborative effort among explorers, scientists, and communication specialists.As polar explorers, we venture on pioneering expeditions in extreme environments and provide scientific field services. IMAQA also serves as a disruptive platform for scientific communication and facilitates educational outreach and public awareness initiatives on pressing issues. To achieve this, we harness the power of human and sporting adventures in the pursuit of scientific advancement, with a primary focus on polar regions as our preferred terrain.

Nanok Expedition 2022 : IMAQA's origins trace back to the Nanok Expedition led by Gilles Denis, where explorers and researchers worked hand in hand adding a scientific dimension to the adventure. The team included researchers from ULB, UCLouvain, ULiège, the Royal Observatory of Belgium and GEUS (see author list). On-site, the team used GNSS systems from Septentrio to measure ground deformations, providing ground-truth data to improve satellite models. The explorers also collected snow samples to analyze particle chemistry and sources, tracing origins to as far as north China and the Sahara. This analysis included assessing phosphorus concentrations, indicating nutrient inputs feeding local algae and bacteria. In total, there were 5 scientific experiments performed on-site during the 6 months long expedition.

Greenland Mission 2023 : In Greenland, IMAQA supported the ULiège's KATABATA project, aimed at gathering data crucial for establishing a wind farm in southern Greenland. ULB and UCLouvain continued their mineralogical and biogeochemical characterization of Greenlandic fjords, initiated during the Nanok Expedition. IMAQA team collected 30 fjord water samples to study glacier impacts on biomass production. Filtered samples are analyzed for dissolved organic carbon and mineral elements concentrations. Preliminary findings suggest higher biogeochemical production near marine-terminating glaciers, where nutrient-rich cold water from subglacial rivers supports vibrant marine life. Conversely, this production decreases as glaciers transition from marine to terrestrial termini, significantly impacting fjord ecosystems.

Recent Alaska Winter Mission 2024 : The recent Alaska expedition, led by Pr. Sophie Opfergelt from UCLouvain, aimed to detect and analyze taliks - perennially thawed soil in a permafrost environment - during winter using advanced radar technology and core sampling. Taliks, previously unrecognized in winter, potentially influence greenhouse gas emissions. Additionally, the team examined water dynamics beneath the ice by studying a frozen river downstream from the area studied. These efforts aimed to illuminate overlooked hydrological processes in Arctic regions during winter. The results surpassed expectations. Successfully detecting taliks and acquiring soil and river water samples unveiled new avenues for understanding geochemical processes within Arctic permafrost. These findings herald a new era of insight into polar ecosystem dynamics, prompting researchers to plan future missions to deepen these revelations and expand our comprehension of evolving polar landscapes. This field mission was made possible through the technical, logistical and safety support of IMAQA.

Future Projects and Collaborations: IMAQA continues to develop collaborations with the scientific community. Future projects aim to expand these initial findings, focusing on long-term monitoring and deeper analysis of polar hydrological and ecological processes. By bridging exploration and scientific research, IMAQA endeavors to provide critical insights and data, supporting the understanding and preservation of polar regions amid climate change. This ongoing collaboration will further integrate advanced technologies and methodologies, fostering broader understanding of these fragile ecosystems and promoting informed conservation strategies.

Identifying causes of Arctic and Antarctic sea-ice lows using causality analysis

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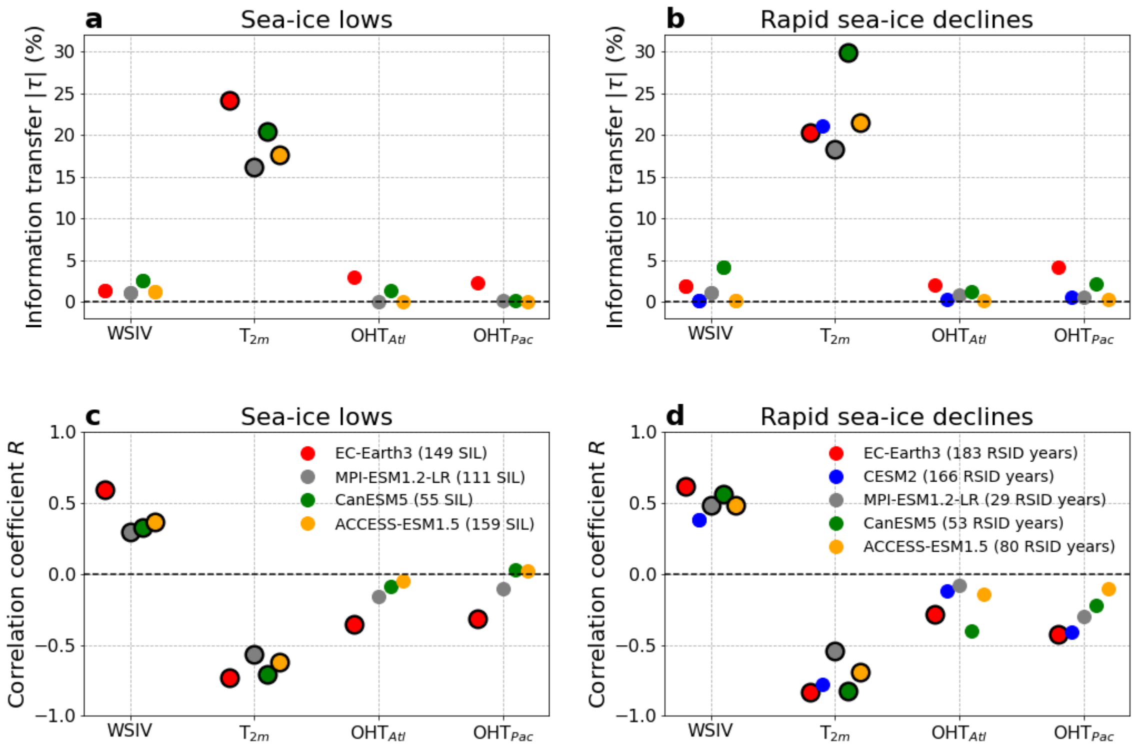
Large reductions in Arctic sea-ice extent have occurred since the beginning of satellite observations in the late 1970s, including two extreme lows in 2007 and 2012. On the opposite side of the globe, Antarctic sea-ice extent has been slightly expanding between 1979 and 2014, but then unprecedented losses of sea ice have also occurred, including sea-ice lows in 2017, 2022, 2023 and 2024. The exact drivers influencing these large sea-ice reductions and their respective contributions are not fully understood. In our study, we make use of five different large ensembles from the Coupled Model Intercomparison Project Phase 6 (CMIP6) over the 1970-2100 period, combining both historical and scenario model simulations. We investigate the impact of several factors, including air temperature, ocean heat transport and winter sea-ice extent and volume, on summer sea-ice extent in both hemispheres by using the Liang-Kleeman information flow method. This allows us to go beyond classical correlation analyses and identify causal links between variables. We separate periods including a large amount of sea-ice lows from more stable periods, and apply our causal method to these different periods, making use of the large number of ensemble members. Our study demonstrates the usefulness of causality analysis in identifying causes of sea-ice lows.



(a) Rate of information transfer from winter Arctic sea-ice volume (WSIV), 2m Arctic air temperature (T2m), Atlantic Ocean heat transport (OHT_Atl) and Pacific OHT (OHT_Pac) to summer Arctic sea-ice extent over 1970-2060, only considering sea-ice lows. (

High-Resolution insights into permafrost thaw: Remote Sensing and Geochemical Techniques for Understanding Carbon Cycle Feedbacks

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The Arctic is warming at an unprecedented rate, leading to significant changes in permafrost regions such as the deepening of the active layer. The thawing of previously frozen soil organic carbon (OC) releases greenhouse gases, exacerbating global warming. Understanding the vulnerability of OC to mineralization is crucial for predicting the magnitude of this feedback loop. This study aims to create an active layer depth map across a site and assess the vulnerability of OC to mineralization using a combination of remote sensing and geochemical techniques. The study site is located at Eight Mile Lake, Alaska (USA), where a natural permafrost thawing gradient is present. Multispectral, LiDAR, and thermal UAV data were collected across the site during the end of the summer 2023 (September-October) to capture key indicators of permafrost degradation, including vegetation, microtopography, and surface hydrology. Along the thawing gradient, at the profile-scale, soil water content (SWC) and temperature were continuously measured at three locations over three depths and coupled with dissolved OC concentration of the soil pore water. The use of UAV remote sensing techniques will provide a very-high resolution map of the active layer depth, while profile-scale geochemistry will assess the vulnerability of OC to mineralization along the permafrost thawing gradient. This multidisciplinary approach will provide valuable insights into the state of permafrost degradation and the potential for OC mineralization, ultimately informing on the impacts of climate change on these critical ecosystems.

Modern mineral dust depositions in East Antarctica: faithful geochemical tracers of Southern Africa dust contributions and evolution of the climate during the Holocene

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Natural mineral dust are composed of reactive species affecting directly or indirectly the global climate through aerosol-radiation-cloud-chemistry interactions. They are also efficient suppliers of organic or inorganic components that can influence the primary productivity in oceans, such as the Austral Ocean.

The present study attempts to solve the puzzle of the origin (the potential source areas - PSA) of dust deposition in East Antarctica (EA). We combine analyses of size, shape, mineralogy, geochemistry (trace element, and especially REE data), as well as strontium (Sr), neodymium (Nd) and lead (Pb) isotopes, performed on modern snow dust samples collected along a ~200km transect in the Dronning Maud Land area (from the Belgian Station Princess Elisabeth Antarctica to the coast). A statistical mixing model was specifically developed to fit the Rare Earth Elements (REE) patterns of Antarctic dust samples (Vanderstraeten et al., 2023) by combining REE profiles from PSA in Southern South America (Patagonia, Puna-Altiplano plateau), Southern Africa (Namibia, SAF), Australia and New-Zealand. In addition to REE, PSA isotopic compositions of Sr, Nd and Pb were analysed, specifically in 30 samples from the Namibian coast (Gili et al., 2022) where an evident lack of analyzed samples was detected in the literature data collection.

The atmospheric particles mainly show a submicronic size (> 98% of particles < 5µm, n=2500) and angular shape. SEM-EDS observations suggest spatial variations in mineralogy, reflecting the influence of input from the local Sør Rondanes mountains for the inland sites (Fe-Mg silicate > 50 %) and distal source' input at the coast (predominance of aluminosilicates and quartz, with <20% of Fe-Mg silicates). The REE profiles and the Sr, Nd and Pb isotopic variability observed in present-day dust depositions at the EA coast, as it was demonstrated for the Holocene interglacial depositions (at Vostok and EDC; Gili et al., 2022) in East Antarctica and the South Atlantic Ocean, can be related to the contributions of two main PSAs: Southern South America, dominated by the major contribution of Patagonia and important % of the Puna–Altiplano Plateau, in combination with Southern Africa in response to the plausible transport by the strong Berg Winds. This work presents an innovative and multi-proxy approach for the identification of potential dust source contributions in the Southern Hemisphere, and East Antarctica in particular, which provides major implications for the reconstruction of atmospheric circulation and implications on climate evolution.

Vanderstraeten et al., (2023), Science of the Total Environment, 881, 163450, http://dx.doi.org/10.1016/j.scitotenv.2023.163450

Gili et al., (2022), Nature Communications earth & environment, 3 :129, https://doi.org/10.1038/s43247-022-00464

Influence of Arctic sea ice extent on permafrost regions

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The Arctic has been warming two to four times more rapidly than the global mean in the last decades – a phenomenon known as Arctic Amplification. This warming induces changes for the whole cryosphere, including the permafrost and the Arctic sea ice.

A main driver of permafrost degradation is air temperature. An hypothesis is formulated that sea ice concentration plays a role through the atmospheric circulation on the air temperature in Arctic, and thus on the permafrost degradation. This study aims to evaluate if rapid sea ice loss events – events where the sea ice concentration is way lower than expected according to the climatology during several years – impacts snowfall, air and soil temperatures in permafrost region, leading to permafrost degradation. These sea ice loss events are expected to happen more frequently in the future, with summer regularly ice-free from 2050 on. The potential link between sea ice concentration and permafrost may thus have a great impact on the Arctic environment, now and in the future.

Granger causalities are used to determine if the sea ice extent in different Arctic seas could have an impact on the snowfall, air and soil temperature in the following month in the surrounding permafrost areas.

Ice mass budget for Arctic and Antarctic sea ice lows: where does the melt come from?

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While the Arctic has seen a rapid and widespread decline of sea ice over the recent decades, the Antarctic has followed a different evolution, with a slow increase in ice extent until 2014 and a rapid decline since, with strong spatial and temporal disparities. Understanding how and why sea ice behaviours are similar or differ between both poles might therefore help to anticipate the evolution of Antarctic sea ice. In particular, it remains to be seen if the recent summer sea ice lows in the Arctic and Antarctic share the same causes. To this aim, a global coupled ice-ocean model based on NEMO-SI3 is forced at different horizontal resolutions with ERA5, to calculate a sea ice mass budget from 1979 to 2023. The relative importance of surface, lateral and bottom melt, as well as the roles of bottom growth, open-water formation and snow-to-ice conversion provide insights on the dominant mechanisms leading to sea ice lows in both polar regions. A further analysis in sectors of the Arctic and Antarctic regions also uncovers the importance of ice dynamics to identify the drivers of ice loss. Preliminary results indicate that while the resolution does not exhibit a strong influence on the climatological regimes, higher horizontal resolution does provide a stronger influence of dynamics on ice evolution during specific years, as could be expected. A comparison of the sources and sinks of ice between Arctic and Antarctic reflects the current knowledge of sea ice and related processes difference between both hemisphere, with an overall dominance of bottom melt for the ice loss, but with non-negligible influence of surface melt in the Arctic only, while the Antarctic shows a strong snow-to-ice conversion during summer, due to flooding. A further decomposition of anomalies into sectors highlights the main regions of ice melt and the spatial heterogeneity of preconditioning via lack of ice growth. Those preliminary results foster further investigation with an eddy-resolving configuration and more analysis of the oceanic state prior, during and after sea ice lows.

Biogeochemical disconnection between rivers and permafrost soils during winter: evidence from Sr isotopes

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Arctic permafrost soils are estimated to hold approximately 1,440-1,600 petagrams (Pg) of organic carbon (OC), which is equivalent to more than twice the carbon content of the current atmospheric carbon (C). As this permafrost OC thaws into the contemporary C cycle, it can be decomposed by soil microorganisms and subsequently transported to aquatic ecosystems where further microbial degradation and photochemical processes can occur.

Climate warming is predicted to accelerate the release of northern permafrost carbon with 24-69% of permafrost soils expected to thaw by 2100. As a result, around 5% of permafrost soil organic carbon has been estimated to being lost annually through hydrological pathways, thus leading significant positive feedback to global warming. However, the mechanisms of these carbon releases are not well-defined.

Recent research highlights that shoulder seasons, particularly spring thaw and autumn freezing, are pivotal for the lateral movement of soil constituents into Arctic rivers. As soil active layers freezes and thaws during yearly shoulder seasons, their contribution to riverine export changes, yet no clear data exists as to indicate when a biogeochemical connection exists between permafrost soils and rivers.

In this study, we used radiogenic strontium (Sr) isotopes to trace the sources of mineral nutrients in Panguigue creek, a first-order river, directly draining permafrost soils near Eight Mile Lake, Healy, Alaska, USA. The data reveal a distinct mixing pattern between surface and subsurface inputs from nearby permafrost soils, which gradually decreases during the Autumn shoulder season, transitioning to a baseflow likely originating from deeper groundwater. Conversely, this trend reverses during Spring thaw. These findings demonstrate a clear biogeochemical disconnection between permafrost soils and river systems throughout the winter, a pattern that can be effectively traced using Sr isotopes. This provides a timely approach to detect ongoing and future changes in biogeochemical connectivity between permafrost soils and rivers in a warming Arctic.

Mineral – Organic Carbon interactions in Arctic permafrost: spatialization and meta-analysis

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The northern permafrost's extent covers 21 million square kilometers which represents 22% of the Northern Hemisphere's exposed land area. Within these 22%, it is estimated that 1460 to 1600 GT of organic carbon (OC) are stored. This estimation is yet growing as new research refines and adds new components to existing studies. With current climate change - occurring at a greater rate in the Arctic regions than the global average - there is a crucial need to further investigate the possible fates of this OC. A key element to consider in this regard concerns OC-mineral interactions. Among the mechanisms of OC-mineral interactions, OC complexation with metals is one of the main mechanisms and constitutes a pool of organic carbon that is not directly accessible to microbial decomposition. Here, we aim to use existing methods for quantifying OC stocks at the Arctic scale to (i) integrate new data for the total OC stock estimation and (ii) provide a first assessment of the OC storage in the form of organo-metallic complexes at the Arctic scale. This method partitions OC in three pools, each of which is assessed using different methods: the surface (0-3m) pool using a database coupled with soil taxonomy, the Yedoma domain (deep ice-rich sediment deposit) through a bootstrapping method and the Deltaic alluviums (thick river sediments) whose stock of complexed OC is assessed from existing total OC data and general trends. Our calculations led to a count of 360 GT of OC stabilized in the form of complexes across the Arctic, subdivided into (i) 263 GT for the 0-3 m pool with peak concentrations in Canada and Eastern Russia, (ii) ~75 GT within the Yedoma sediments and (iii) ~ 25 GT in the deltaic alluviums. Overall, it implies that 20-25% of the total OC pool is stabilized within metals complexes in the Arctic, and that this carbon is not directly available for microbial decomposition. Further assessments are therefore required, particularly regarding the behaviour of these complexes over time and under changing physico-chemical conditions induced by climate change. Our research highlights the crucial need to incorporate mineral-OC interactions into climate models to enhance the accuracy of future permafrost carbon emission predictions.

Thawed soil portions during deep winter in permafrost regions (Eight Mile Lake, Alaska): studying talik connectivity with silicon isotopes

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In permafrost regions from the Arctic, soils are composed of permafrost (i.e., perennially frozen ground) located below an active layer (i.e., seasonally frozen ground). In deep winter, portions of soil remain unfrozen in the active layer, leading to talik formation. These portions of unfrozen soils can be surrounded by frozen soil (closed talik), or connected to each other (open talik) which drives lateral water pathways. Maintaining lateral water flow during deep winter has potential implications for soil biogeochemical connectivity, but the extent of talik connectivity remains poorly quantified and difficult to assess. Here, we use silicon (Si) isotope measurements in soil pore water to identify open and closed taliks. Silicon isotopes are analyzed on soil pore water collected in February-March 2024 at Eight Mile Lake, Alaska, USA in soils from water tracks where taliks were identified. Our hypothesis to use Si isotopes to distinguish the two systems is the following : in a closed talik, silicic acid concentration is increasing upon freezing, leading to amorphous silica precipitation that induces Si isotope fractionation with ^{28}Si preferentially incorporated into the colloidal amorphous silica, leaving the residual solution enriched in ^{30}Si. In an open talik, the saturation for amorphous silica precipitation is not reached, which does not lead to Si isotope fractionation. Soil pore waters are therefore expected to present different $\delta^{30}Si$ values whether the talik is open or closed. These data will allow us to better understand the biogeochemical connectivity in arctic soils during deep winter, which notably influences the release of permafrost carbon into the atmosphere.

SESSION 10 - QUATERNARY AND GEOARCHAEOLOGY (BELQUA)

Conveners

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Stephane Pirson, Agence wallonne du Patrimoine - AWaP (stephane.pirson@awap.be)

This session aims to review ongoing Quaternary research in Belgium and abroad. Since 2009, the Quaternary has been redefined by the International Union of Geological Sciences (IUGS) and the International Commission of Stratigraphy (ICS) as the youngest system within the Cenozoic erathem. It is composed by the Pleistocene and the Holocene series and its base is fixed at 2.65 Ma (Gibbard et al., 2010). The Quaternary is characterized by a peculiar high climate variability, with a succession of cold (glacial) and warm (interglacial) periods. These environmental changes influence all the compartments of the Earth system, i.e. atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere. The Quaternary also corresponds to a major evolution of the Hominids with the appearance of the earliest Homo genus, and its evolution to Anatomically Modern Humans. While geology has been strongly involved in the early developments of prehistorical archaeology and palaeoanthropology since the 18th Century, the earth sciences applied to archaeological problematics progressively constituted a new discipline which is called geoarchaeology since the 1970s (Renfrew, 1976). In this session, we invite any contributions dealing with any field of the Quaternary, from fieldwork studies to climate modelling, and including geoarchaeology.

Invited Speaker

Dating the Middle to Upper Palaeolithic transition in Belgium using advanced radiocarbon methodologies

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Belgium represents a key region for studying the Middle to Upper Palaeolithic transition (MUPT) in North-West Europe. This area sits at the crossroads between Palaeolithic cultural facies with influences from eastern, western and southern Europe intermingling during the Late Middle Palaeolithic and the MUPT. Until recently, a temporal gap believed to be around 4ka (ca 42-38 ky calBP) existed between the Late Mousterian and the earliest dated Aurignacian settlements in the region [1, 2]. The dates obtained on Neanderthal remains from Spy fell into this gap, making them the latest Neanderthals in the region [3]. Including the dates from Spy, a gap of two millennia remained between the dates on Neanderthals and the beginning of the Aurignacian. Based on this chronological evidence, the transition from Neanderthals to Anatomically Modern Humans (AMH) in this region was believed to have been without contact between species. AMH would have settled in an area Neanderthals abandoned long before.

We have redated the Neanderthal specimens from Spy (tooth, maxilla and scapula), Engis 2 (skull and tooth) and Fond-de-Forêt (femur) [4]. We also redated bone implements such as bone points and retouchers from the same region [5]. In both cases, we employed the compound specific radiocarbon dating method which is based on the extraction using preparative liquid chromatography of the amino acid hydroxyproline (HYP) that occurs in mammalian collagen. This method is more efficient than others in eliminating modern carbon contamination such as conservation materials.

Here, we report these new radiocarbon dates obtained on the Belgian Neanderthal specimens and bone implements. These results show how much impact sample preparation can have on the AMS measurement when specimens have been heavily preserved with conservation materials, which is often the case for human remains. These results also now place the Belgian Neanderthal remains from Spy, Engis and Fond-de-Forêt in their proper chronometric context and allow us to refine our understanding of the disappearance of Neanderthals in north-western Europe and integrate this with other evidence for the human occupation of this region during the Palaeolithic.

The new HYP dates on the Mousterian bone implements, combined with the recently published HYP dates on the late Neanderthals, confirms the persistence in the region of these Neanderthals beyond the latest dated Mousterian occurrences. Although Neanderthals appear to have lasted beyond the Mousterian, their possible association with the LRJ, as previously suggested needs to be reconsidered in the light of the latest discoveries made at Ranis.

[1] Di Modica, et al. (2016). The Middle Palaeolithic from Belgium: Chronostratigraphy, territorial management and culture on a mosaic of contrasting environments. Quaternary International 411, Part A, 77-106. 10.1016/j.quaint.2015.12.072

[2] Pirson, et al. (2012) Chronostratigraphic context of the Middle to Upper Palaeolithic transition: Recent data from Belgium. Quaternary International 259, 78-94. 10.1016/j.quaint.2011.03.035

[3] Higham, et al. (2014) The timing and spatiotemporal patterning of Neanderthal disappearance. Nature 512(7514), 306-309. 10.1038/nature13621

[4] Devièse, et al. (2021). Reevaluating the timing of Neanderthal disappearance in Northwest Europe. PNAS 118(12):e2022466118. 10.1073/pnas.2022466118

[5] Abrams, et al. (2024) Investigating the co-occurrence of Neanderthals and modern humans in Belgium through direct radiocarbon dating of bone implements. Journal of Human Evolution 186:103471. 10.1016/j.jhevol.2023.103471

Geoarchaeological approach in Scladina cave (Belgium): new results on the chronostratigraphy of the Late Middle Palaeolithic and Middle to Upper Palaeolithic transition in North-West Europe

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Scladina Cave (Belgium) is one of the few sites where ongoing excavations can contribute to a better understanding of the palaeolithic human settlements in Northwest Europe, in close relation with their chronological and palaeoenvironmental context. The cave belongs to a karstic network filled with sediments encompassing the last 400 ky. The site is famous because it has yielded the remains of a juvenile Neanderthal individual related to MIS 5 as well as two main archaeological assemblages attributed respectively to MIS 5 and MIS 3 [1].

Over the last decade, Scladina has been subject to a multidisciplinary project focusing on the latest Neanderthal and earliest Anatomically Modern Human (AMH) occurrences comprised in the upper 4m of the sequence, covering from MIS 4 to MIS 1. The aim of this project was to collect new archaeological evidence, refine the stratigraphic and chronologic positions of the assemblages and reach a better understanding of both depositional and post-depositional processes affecting the artefacts. The recent excavations yielded abundant faunal assemblages, artefacts from the Middle Palaeolithic and the Upper Palaeolithic as well as new human remains.

Through this project, the sedimentary sequence has been subject to a rigorous stratigraphic survey and a chronological approach combining multiple dating techniques (14C, U-Th, OSL) and integrating paleoenvironmental data, notably from palaeobotany, vertebrate palaeontology, and sedimentary dynamics. Our new results suggest that MIS 4 is barely represented in the cave, while the age of the Middle Palaeolithic assemblages related to MIS 3 are older by thousands of years than previously thought [2]. One Middle Palaeolithic assemblage (1B) possibly bears witness to the recolonisation of the northern latitude early in MIS 3 after the lack of Neanderthal occupations in the North of Europe during at least part of MIS 4. Another assemblage (1A) previously dated as one of the youngest assemblages representing the typical Middle Palaeolithic in NW Europe seems now to be dated to more than 45 ka BP, an age anterior to the latest Neanderthals in Belgium, recently dated to between 44.2 ka and 40.6 ka calBP [3]. Regarding the Upper Palaeolithic in Scladina cave, the multidisciplinary approach as well as the direct dating of anthropogenically modified bones [4] suggest an age in range with the Aurignacian in Europe. The newly found human remains have been retrieved in two distinct sedimentary contexts related to the Middle Palaeolithic and their possible association with the archaeological assemblages is still under discussion.

These new results challenge the published cultural and chronological interpretations [5]. Our study therefore leads to a renewed understanding of the Scladina Cave sequence and sheds new light on the latest Neanderthal populations as well as the arrival of AMH in North-West Europe.

1.Pirson, S., M. Toussaint, D. Bonjean, and K. Di Modica, Spy and Scladina Caves: A Neandertal's Story, in Landscapes and Landforms of Belgium and Luxembourg, A. Demoulin, Editor. 2018, Springer International Publishing: Cham. p. 357-383.

2.Di Modica, K., M. Toussaint, G. Abrams, and S. Pirson, The Middle Palaeolithic from Belgium: Chronostratigraphy, territorial management and culture on a mosaic of contrasting environments. Quaternary International, 2016. 411, Part A: p. 77-106.

3.Devièse, T., et al., Reevaluating the timing of Neanderthal disappearance in Northwest Europe. Proceedings of the National Academy of Sciences, 2021. 118(12): p. e2022466118.

4.Abrams, G., et al., Investigating the co-occurrence of Neanderthals and modern humans in Belgium through direct radiocarbon dating of bone implements. Journal of Human Evolution, 2024. 186: p. 103471.

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A window on the geomorphological evolution of the Dyle Valley, central Belgium: from late Pleistocene to Holocene

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During road widening works in the Dyle Valley, central Belgium, in 2022, various Quaternary geological layers were exposed (Fig. 1). These layers included gravel deposits generally believed to have been laid by braided rivers during the Saale glaciation or the Eemian interglacial (De Smedt, 1980; Goossens et al., 2007). A layer of reddish silt intercalated between these gravel layers could represent an Eemian paleosol. Additionally, large filled-in erosion gullies were also apparent. This study aimed to gain better insights into the geomorphic evolution of the Dyle Valley, which is crucial for both geomorphologic and archaeological research.

Two reference profiles (Fig. 1) were described and sampled for soil texture, CaCO3, soil organic carbon, and total nitrogen content. Additionally, five samples were taken for OSL dating using sand-sized quartz from profile 1, and six samples from profile 2.

Only partial results of the OSL dating are available yet, but combined with the field observations and physico-chemical laboratory analyses, they reveal interesting findings. In profile 1 (Fig. 1b), a 4.5 m deep infilled erosion gully was observed with calcareous loess at its base. This loess is provisionally dated to 23.4 ± 2.2 ka. A first paleosol filled the gully, with the humus-rich top layer dating to 10.9 ± 2.2 ka. This soil is covered by a second paleosol with a clay illuviation horizon, awaiting dating, and in turn, covered by decalcified colluvium. Profile 2 (Fig. 1c) has decalcified marine sands of the Brussels Formation at its base. Above this Tertiary deposit is a ca. 2 m thick layer of reddish silt, with rounded gravel deposits at both its base and top, with the silt deposits dating 74 ± 6 to 76 ± 9 ka. The upper part of the profile consists of calcareous intercalations of silt-loam and reworked Tertiary sands from 17.8 ± 1.3 to 22.6 ± 1.7 ka.

The large infilled erosion gullies highlight episodes of landscape dynamics from the late Pleistocene to the early Holocene. This research is the first attempt at numerical dating of river terraces in the Dyle Valley. Such river terraces, both in the Dyle Valley and the nearby Senne Valley, are generally attributed to the Saale glaciation or Eemian interglaciation (De Smedt, 1980; Goossens et al., 2007; Schroyen et al., 2003). The gravel deposits in Neerijse, which cap a reddish paleosol that we had hypothesized to be an

Eemian paleosol, seem instead to have been deposited during a Middle Weichselian interstadial. Our finding aligns with the dating of a soil profile correlated to the Rocourt paleosol, which has been dated to the period 50-60 ka (Van Den Haute et al., 1998). The road cut in Neerijse provides a window into the geomorphological evolution of the Dyle Valley. Such a geo-heritage site is much cherished by the newly created National Park of the 'Brabantse Wouden' (Vercoutere, 2023). Once the dating is complete, the site will also serve as a geo-archaeological benchmark for correlation with human activities and environmental changes over the last 70,000 years.

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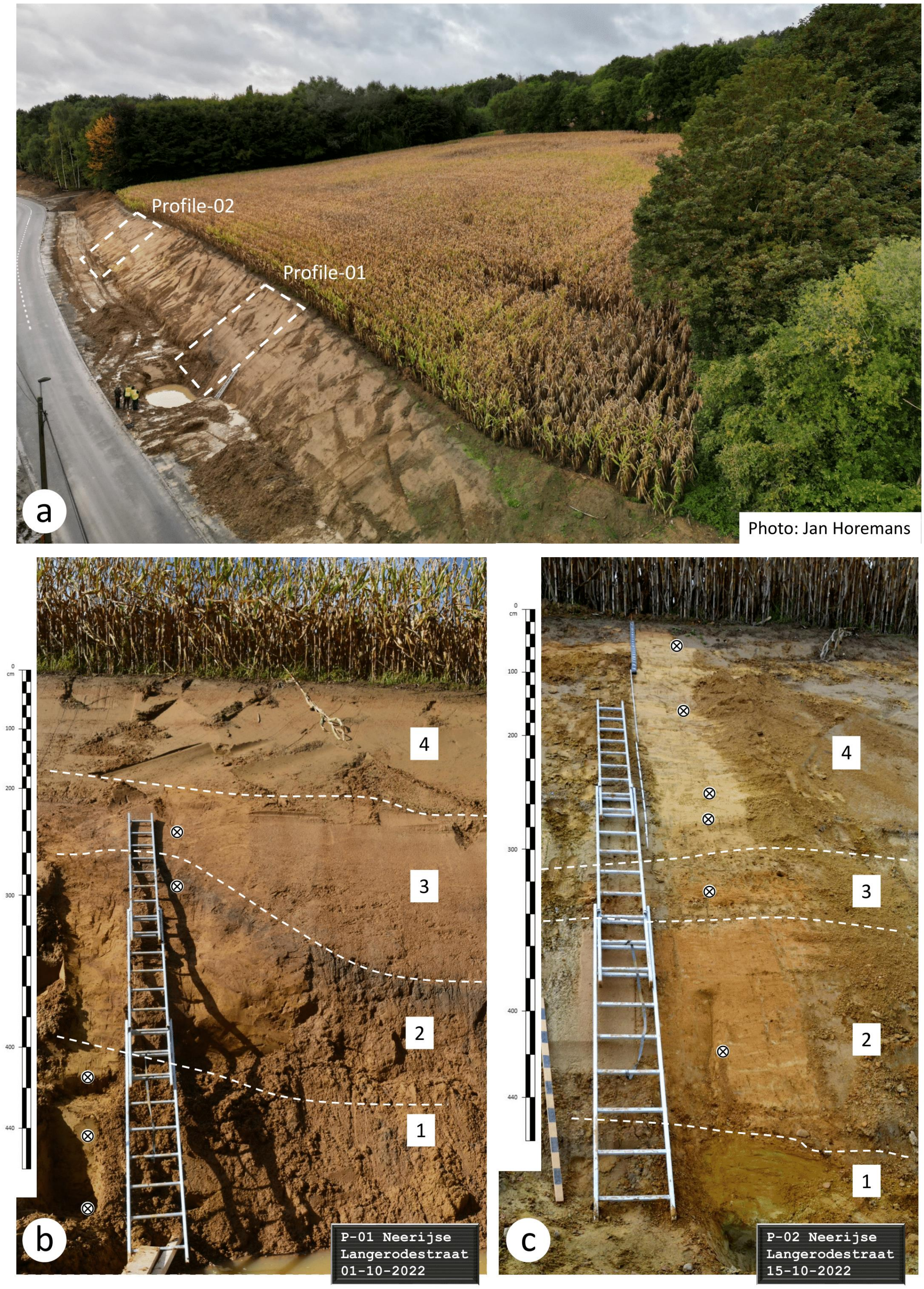

Figure 1 – (a) Overview of the road cut along the Dyle Valley in central Belgium. (b) Profile 1: [1] calcareous loess at the base (dated 23.4 ± 2.2 ka old), [2] buried soil with Ah horizon at its top (10.9 ± 2.2 ka), [3] truncated buried soil with a clay

Environmental evolution of Lake Santa Maria del Oro (west-central Mexico) over the last millennium inferred from mineralogical and geochemical proxies

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The Trans-Mexican Volcanic Belt (TMVB) has widespread closed-system crater lakes whose sedimentary sequences are unique archives of past climate variability in the tropical North American Monsoon domain. Lake Santa Maria del Oro is situated close to the Pacific coast. The lake, stratified during most of the year, is characterized by warm, subsaline and alkaline waters. This study was conducted on a core retrieved in the central part of Lake Santa Maria del Oro (21°21'N, 104°34'W, area 370 ha, water depth 65 m) in the TMVB. The core LSMo22-1 was analyzed for inorganic geochemistry by ITRAX XRF core scanning, organic geochemistry by isotope ratio mass spectrometry and bulk mineralogy by X-ray diffraction. According to 210Pb and 14C data, the 97-cm long sediment core covers the last millennium.

The bulk mineralogy of Santa Maria del Oro is mainly made of soil-derived clay minerals (smectite 68±4%, illite 3.6±1% and kaolinite 2.6±1.7%), magmatic-derived minerals (albite 5.8±2% associated with traces of amphibole, pyroxene and cristobalite) and quartz (5.3±2%). These minerals, all detected in soil samples collected around the crater lake, represent the detrital fraction supplied to the lake by surface runoff. In addition to those detrital minerals, the sedimentary mineralogy contains variable amounts of carbonates (calcite 8±6%, aragonite 3±6%) and traces of sulfates (gypsum).

XRF data reveal an inverse correlation between Ca and Ti ($r = -0.82$). Variations in Ca correspond to changes in biogenic minerals and green algae, indicating its association with lake primary productivity. On the other hand, variations in Ti are linked to detrital minerals. The strong inverse correlation between Ca and Ti suggests that lake primary productivity influences the abundance of detrital components (Ti intensity). A marked decrease in lake primary productivity is observed between approximately 60 and 25 cm (1385-1860 AD), which corresponds to the Little Ice Age (LIA). A slight decrease in tree cover during the LIA suggests that climate conditions became less favorable for forests, likely due to either lower temperatures or reduced moisture availability.

According to the tentative age model, the highest productivity period, marked by up to 25% of calcite, is observed in the lowest core section (97-76 cm, ca. 772-1128 AD), an interval consistent with the Medieval Warm period. The increase in aragonite observed in the uppermost section of core LSMo22-1 (i.e. 0-13 cm, 1957-2022 AD), is probably favored by stronger evaporation conditions leading to the precipitation of authigenic minerals during lower lake levels.

An interdisciplinary study of natural and anthropogenic environmental changes recorded in the Grand-Passage peat bog (Plateau des Tailles, Houffalize, Belgian Ardennes) over the Holocene

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The Holocene (starting around 11 700 cal yrs BP) has been marked by strong climatic events (8.2 ka, 4.2 ka…), alongside the growing influence of human activities on ecosystems. Characterising these environmental changes in Europe at local, regional and global scales and understanding mechanisms behind them are essential.

In this frame, the ANTHROPEAT project aims to enrich the precision of current research by supplementing existing studies and filling a gap by modelling landscapes in Belgium. The aims are to produce a high-resolution study of landscape evolution, climate variability and anthropization in Belgium throughout the Holocene.

The project is based on a high-resolution study of a sedimentary sequence from the Grand-Passage peat bog on the Plateau des Tailles (Houffalize, Belgian Ardennes). This sequence will cover the last 8,000 yrs. Peat bogs are particular deposits marked by a high accumulation of organic elements, which constitute invaluable archives for vegetation and climate reconstructions. This bog is one of the best preserved from human impact in Europe. These formations, with specific humidity and acidity, allow numerous environmental markers (proxies) to be well preserved. Here we provide a multi-proxy approach including biological (pollen and spores, testate amoebae, diatoms), sedimentological (humification, granulometry) and geochemical (elemental concentration, Pb, Nd isotope ratios) data. Multivariate analyses of these tracers will lead to palaeoecological and paleoclimatic reconstructions and interpretations, to understand global environmental dynamics and human effects on them, such as agriculture and forestry (e.g. analysis of pollen) or the use of fossil fuels and/or mineral resource (e.g. analysis of elemental content).

This approach, based on multi-proxy paleoenvironmental studies of a peat bog in Wallonia, will offer an exhaustive overview of possible interactions between human activities and environmental changes at regional and Northern European scales.

Mineralogical composition as the soil-forming factor – a case study from Zmajevac loess-palaeosol sedimentary complex, Croatia

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This work will present the results of the mineralogical analysis of loess sediment and its intraformational palaeosols from the area of Zmajevac in the easternmost part of Croatia with its implication to paleoenvironmental and climate conditions. The investigated sediment succession is 28.5 m thick and consists of four palaeosols, six loess layers, fluvial sediment, and the modern soil on top. For mineralogical analyses, a total of 17 samples were collected. The samples were taken from two horizons of recent soil (ZN-REC) and horizons of three palaeosols (ZN-1, ZN-2, ZN-3). The mineral composition of the soil samples of the fractions < 2 mm (bulk samples) and < 2μm (clay fraction) was measured by X-ray powder diffractometer (XRD) PAnalytical X' Pert PRO, equipped with a Cu-tube, graphite monochromator, and Pixel detector. XRD patterns of the carbonate-free clay fraction were obtained on oriented mounts after the (a) air drying, (b) K+ saturation with 4M KCl solution, (c) Mg2+ saturation with 4M MgCl2 solution, (d) ethylene glycol solvation of K and Mg saturated samples, (e) DMSO solvation of K-saturated samples, (f) solvation of Mg-saturated samples with glycerol, (g) heating to 400°C for 1h, and (h) heating to 550°C for 1h.

The bulk mineralogy is dominated by quartz, followed by plagioclases and micas. Carbonates are found in varying amounts in the form of calcite and dolomite. In addition, potassium feldspars, phyllosilicates, amphiboles, and, in some horizons, pyroxenes are also present. Phyllosilicates make up a very small proportion of the total mineral composition of samples, but they are very important features in explaining pedogenetic processes and reconstructing of environmental or paleoclimate conditions. The most abundant clay minerals in all profiles are illite and chlorite. Well-crystallized kaolinite and low charge vermiculite/high charge smectite are present in almost all horizons but to a slightly lesser extent. In some horizons, vermiculite and smectite were also detected. Besides phyllosilicates, some other minerals such as quartz, K-feldspars, plagioclase, and goethite were also present in the clay mineral fraction. Obtained results of mineralogical composition, both the bulk and clay fractions, show a predominance of weatherable minerals, with a surprisingly high muscovite content in paleosol ZN-3, and with a fairly uniform clay composition throughout the whole profile, which discards a distinct clay neoformation in the most clayey horizons. However, certain differences in clay mineralogy between the paleosols and the recent soil based on this new results and also with some previous results (Galović et al., 2023; Galović et al., 2024) point to different degrees of pedogenetic processes, which is a consequence of the different durations and conditions within the warm and cold periods.

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North Sea Tsunami Archives: Understanding the Sedimentary Evidence in the Offshore region of the Shetland Islands

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Assessing the long-term tsunami hazard in the North Sea region requires studying the sedimentary evidence of past tsunamis at key locations. The Shetland Islands have emerged as a crucial field laboratory for studying tsunami deposits. However, up until now, focus has been mostly on onshore tsunami deposits and much less on their offshore counterparts, eventhough these have a higher likelihood of being preserved in the sedimentary record, especially in sufficiently deep marine environments, below the storm wave base. Within the NORSEAT Project (North Sea Tsunami Deposits Offshore Shetland Island), we aim to identify and trace tsunami deposits offshore, study their sedimentary characteristics and extent, and determine whether the offshore record holds evidence of events additional to those already known from the onshore record (i.e. the Storrega tsunami, a ca. 5500 yr old and ca. 1500 yr old event), which would offer new insights into recurrence intervals.

Two surveys with RV Belgica have been conducted in 2022 and 2023, during which high-resolution geophysical data (multibeam bathymetry, subbottom data) was collected, along with vibrocores from 32 sites, spread over three embayment areas around the Shetland Islands. In many of the cores, we observe coarse-grained graded beds sandwiched between finer-grained shell hash deposits. These coarser layers, often with sharp basal contacts are normally graded, and suggest temporary interruptions of the steady-state sedimentary regime and are interpreted as possible event deposits based on their contrasting textural and lithological characteristics. Preliminary luminescence ages indicate that some of these graded beds are in the range of the 8150 cal yrs BP Storegga tsunami and the 1400 cal yrs BP tsunami event.

The next phase of our analysis will focus on determining the precise ages and depositional patterns of these layers through radiocarbon dating, grain-size analysis, geochemical analysis, microtextural analysis, heavy mineral distribution patterns, and microfossil distribution within the sediment cores. These aim to establish a robust tsunami event stratigraphy for the region. Combined with planned relative sea-level reconstructions, this stratigraphy will enable us to improve the paleotsunami run-up height assessment by correlating onshore and offshore deposits.

Biogeochemical evidence of Late Holocene climate variability and human influences archived in tropical crater lake sediments

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Biogeochemical signatures archived in the sediment profiles of crater lakes have proven to be a valuable source of information of past environmental variability in the tropical North American Monsoon (NAM) region that has been strongly influenced by both climate changes and human activities during the Late Holocene. Owing to the regional climatic complexity, interwoven natural and anthropogenic impacts and scant long-term data, our understanding of these environmental forcings and their ecosystem consequences remains poorly understood. Here, we investigated four centuries of biogeochemical variability in the sediments of two crater lakes situated in central Mexico to advance knowledge of regional environmental dynamics. High-resolution elemental records obtained from core scanner X-ray fluorescence analysis were combined with lower resolution analyses characterizing lake physical and chemical aspects and the productivity and composition of algal communities that often respond sensitively to natural and anthropogenic environmental forcings. Broadscale biogeochemical trends in the sediments of both lakes depicted the transition from the Little Ice Age (LIA) to a warming world around the turn of the past century, marked by distinct increases in lake productivity and overall organic enrichment. Finescale synchronous biogeochemical fluctuations across the past four centuries displayed multidecadal periodic characteristics illustrating the strong influence of recurring ocean-atmosphere climate patterns on the region. Towards the turn of the millennium, the biogeochemical records became dominated by signals of increasing watershed disturbances demonstrating the pervasive impact of humans on ecosystems over the recent decades.

Sedimentary record of the pedo-sedimentary profile in Privlaka, Croatia

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The subject of this investigation is pedo-sedimentary profile developed in Privlaka, Croatia. The objective was describing the succession of the paleosols and sediments (glacio-fluvial materials) and unravel the mechanism of sedimentation within investigated profile. This profile (8 meters) is divided in four main units: reddish paleosols and three sediment packages, each indicating a different pedo-sedimentological context. To conduct a high-resolution investigation, each distinctive horizon was sampled for sedimentological, physico-chemical and mineralogical analyses.

The results of the grain-size analysis show that the paleosols are characterized by an increase in fine-grained components, even though the coarse component is present as well. Silt is the dominant grain-size fraction in the paleosol. Clay content is higher in the paleosol, where pedogenetic processes were the most intensive.

The CaCO3 content is generally decreasing from upper to lower part of investigated profile. All analysed samples had an alkaline reaction. Organic matter is higher in paleosol part of profile which relates to pedogenetic development. The proportion of the light mineral fraction (LMF) in almost all samples is roughly 98 % with the quartz as the dominant component, followed by lithic particles (5 – 15 %) and feldspars (3 - 7 %). Volcanic glass is accessory (<3 %). The distribution of weight share for heavy mineral fraction (HMF) is mostly uniform across the profile and ranges from 1.08 to 2.51 %. Among the HMF, opaque grains predominate. Along with opaque grains that cannot be determined (30 - 57 %), goethite grains make up a significant proportion (12 – 33 %). The most abundant transparent heavy minerals are resistant grains like dominant garnet (27 – 51 %), followed by zircon (9 – 24 %) and rutile (6 – 21 %). Petrographic analysis of glacio-fluvial material revealed that rock fragments are represented by angular to rounded carbonates (2/3 of grains) and rounded dark chert pebbles (1/3 of grains). The carbonates have a polygenetic origin. They are equally represented by highly spherical subrounded to rounded upper Cretaceous rudist limestones, Eocene nummulitic limestones and low spherical angular to subangular pedogenic carbonate concretions. Angular and subangular carbonate concretions indicate local transport. Since such carbonate concretions are a product of translocation and precipitation of carbonates during pedogenesis, it could be concluded that those concretions were precipitated at the bottom of pedological profile during paleopedogenesis in vicinity of the Privlaka location.

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Late Holocene climate changes in east-central Mexico (Oriental Basin): Multiproxy evidence from Lake Alchichica

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The Oriental Basin in east-central Mexico is a sensitive region to climate change; however, little is known about its past hydroclimate variability. Here, we present multiproxy evidence, comprising pollen and stable isotope records (δ18O and δ13C of bulk carbonates, δ2H of sedimentary leaf waxes), from a short (57 cm) 210Pb-dated lacustrine sediment core retrieved from Lake Alchichica. Pollen data indicate an alteration in vegetation composition from 30 cm upwards, when herbaceous pollen increased at the expense of arboreal species. This transition aligns with variations in the δ2H isotopes of leaf waxes. The lower segment of the core (57-30 cm) displays comparatively more depleted δ2H isotope values, indicating relatively wetter conditions than the upper section of the core (30 cm upward) with more enriched values. Furthermore, bulk carbonate δ18O and δ13C records exhibit a consistent trend ($r=0.68$) throughout the core, which is explained by the evaporation-induced isotope enrichment of the lake water. An overall increasing trend in the δ18O and δ13C profiles suggests intensified climate aridity from the bottom to the top of the core. Based on the current age model, the significant shifts in vegetation and hydroclimate conditions at a depth of 30 cm are estimated to have occurred around the early first millennium CE. However, obtaining additional radiocarbon dates to refine the age-depth model will provide a more precise estimation of the timing of this major environmental change.

Using modern associations of microfauna to improve local relative sea-level reconstructions – a local transfer function for the Shetland Islands (UK)

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High-resolution relative sea-level (RSL) reconstructions are important for managing coastal-protection challenges and for a complete hazard assessment. For the determination of palaeo-tsunami run-up heights in the Shetland Islands, United Kingdom, within the NORSEAT Project (Storegga and beyond – North Sea tsunami deposits offshore Shetland Islands), RSL reconstructions far beyond existing data are needed. Existing RSL data are limited to two time periods (ca. 7900–5990 cal BP and around 3500 cal BP) and are associated with a large vertical error (±8 m around the time of the Storegga tsunami). More detailed Holocene RSL reconstructions shall be enabled by a combined modern training set of foraminifers and ostracods from three different voes of Shetlands largest island, Mainland. The training set serves as a basis for a RSL transfer function, which relates the elevation, hence the duration of water coverage, of surface samples to the modern microfaunal associations. This transfer function will be a valuable tool for high-resolution RSL reconstructions from the Holocene stratigraphic record around the Shetland Islands.

Investigations of 44 surface samples, which were collected from three salt marshes and adjacent tidal flats (southern Dales Voe, Dury Voe and northern Dales Voe), are in progress. Preliminary results show low microfauna occurrences in the upper marsh, exclusively agglutinated foraminifer associations in the mid- to low marsh, low occurrences of foraminifers and ostracods in the transition from salt marsh to lower intertidal and highly diverse associations of foraminifers and ostracods in lower parts of the tidal flat. Small areas of very muddy tidal flats suggest higher abundances, whereas coarser areas are almost void of microfauna. Aside from the investigation of the microfaunal distribution, analyses of environmental parameters like the grain-size distribution and the carbonate and organic matter content are still in progress. Multivariate statistics will determine the main influencing factor of the microfauna distribution between these environmental proxies and the elevation relative to mean sea level.

The final transfer function will be applied to Holocene deposits from offshore cores around Shetland that were conducted within the NORSEAT Project. The resulting new RSL reconstructions will enable a more accurate determination of run ups of the currently identified palaeo-tsunamis (Storegga and two younger events).

Revisiting the stratotype for Middle and Upper Pleistocene loess at Romont (Belgium): First results from a multi-method approach at a high spatial resolution

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The Middle and Upper Pleistocene loess deposits as exposed in the Romont quarry at Eben-Emael (NE Belgium) have been the subject of several studies, including lithostratigraphic surveys, geotechnical characterization through cone penetration tests, sedimentological and pedological analyses (heavy mineralogy, grain-size, soil micromorphology...), and some numerical dating. Although these investigations resulted in an important lithostratigraphic and broad chronostratigraphic framework, several primary research questions have remained unanswered with respect to the origin, formation, detailed chronology and significance of this locally preserved, highly detailed but extremely complex archive.

In this contribution, we first outline the stratigraphic importance of the sequence. Indeed, the combined record as archived in the western and eastern walls of the quarry have been defined as the stratotype for the Belgian loess lithostratigraphy. In its turn, this provides a framework for human occupation and migration in the Belgian loess belt during the Palaeolithic. Secondly, we briefly outline the general rationale and aims of our interdisciplinary and multi-method approach (e.g. stratigraphy, chronology, proxy-analyses, provenancing...), after which we focus on some issues pertaining to the chronostratigraphic framework. We present newly obtained quartz OSL ages for samples that were collected at vertical intervals of 10 cm from the top 5 m of a sequence preserved in the NW limit of the Romont quarry (i.e. some 50 samples in total) and complement this with detailed stratigraphic and pedosedimentary descriptions as well as results from proxy-analyses (magnetic susceptibility and granulometry) at a 5 cm vertical resolution. These results are then used to obtain unprecedented insights into, for instance, detailed dust mass accumulation rates and the recognition of short phases of enhanced dust deposition and hiatuses during the last glacial; such insights are quintessential towards an improved understanding of the record at Romont in terms of its broader significance and relevance for understanding past dust-dynamics and their relation to climatic change in an ice-marginal region. By extension, our first results once more illustrate how future studies that seek to access the palaeoenvironmental information preserved in sedimentary archives may significantly benefit from systematic multi-method analyses of spatially highly re-solved samples in a sequence accurately studied in terms of lithostratigraphy and sedimentary dynamics. In terms of chronology, this has become feasible through relatively recent developments in OSL-dating methodology and technology, which have led to increased precision and sample throughput.

The RETS Project - Revealing the Senne. A hidden landmark in the historical center of Brussels, Belgium

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Throughout history, the Senne river has always been an important landmark for Brussels. In the past, the river served multiple functions. It was essential for providing food and water, for waste disposal, navigation and transport. Infrastructures such as mills, breweries, fortifications and fishponds could be found along its banks. The course of the river Senne and its side branches has changed drastically across history. As the landscape and the city developed, the river's flow was adapted in natural and artificial ways. Today, many questions remain unanswered concerning the evolution of the Senneriver valley, and the general human-environment interactions across history. Recent (geo)archaeological research conducted under the auspices of urban.brussels, the Brussels Regional Administration in charge of the archaeological heritage, has shown the tremendous archaeological potential of the river valley to reach a renewed understanding of the development of the Senne and its branches. Therefore, the RETS project aims to provide a synthesis of the archaeological, environmental and historical data from the Senne valley within the historical center of Brussels, starting from the Holocene until the 19th century. The research will generate maps and 3D-models which will be integrated in the publicly accessible regional cartographic platform BruGIS. These newly developed tools will as such contribute to an optimal management of the archaeological heritage in the research area.

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Tracing human incursions into the Bruniquel cave 176,000 years ago

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The Bruniquel Cave, located along the Aveyron River in southern France, is renowned for its extraordinary archaeological significance, particularly due to the Neanderthal structures composed of broken stalagmites. Uranium-thorium dating of these stalagmites within the structures has established the age of the constructions at approximately 176,500 years, with an uncertainty of ± 2,100 years (Jaubert, Verheyden, Genty et al., 2016). This finding was unexpected and has significantly revised our understanding of Neanderthal behavior. Neanderthals are now recognized as the earliest known cave dwellers, predating modern humans in Europe by roughly 140,000 years, and demonstrating a remarkable knowledge of their subterranean environment. Furthermore, these early Neanderthals had mastered the use of fire, a crucial skill for venturing underground, ~300 meters from the cave entrance.

Recent research has concentrated on the areas surrounding the structures and the entrance zone. Given the absence of wall traces (paintings or engravings in Europe only appear at ~60 ka) and the minimal environmental impact left 176,000 years later, the primary focus is on identifying and characterizing non-natural formations and distinguishing them from natural ones.

Dating potential anthropogenic formations is also essential in supporting the argument for their human origin. Uranium/thorium dating of the broken bases of speleothems, with subsequent calcite regrowth near the structures (Salle de la Structure, Bruniquel Cave), indicated at least one set of formations that were broken around 173,000 years ago, providing strong evidence for the anthropogenic origin of the breakage. Several stalagmites within the structures may correspond to the tops of the broken stalagmites. However, since parts of the structures are covered with recent calcite, it is challenging to precisely identify the missing stalagmite tops within the structures.

Speleothems have been instrumental in dating various levels of a trench excavated in the entrance collapse of the Bruniquel Cave. These analyses suggest an ancient age for at least part of the scree, corresponding to Marine Isotope Stage (MIS) 10, a conclusion supported by the discovery of animal remains in the trenches, which date back to at least MIS 6. The upper level in the trench is a calcite flowstone dated at ~ 180 ka confirming that this area did not change much since MIS 6. Further uranium-thorium dating within the cave is expected to clarify the sequence of human and animal, primarily bear, entries into the cave. Moreover, it will aid in reconstructing the cave environment during the human occupation around 176,000 years ago.

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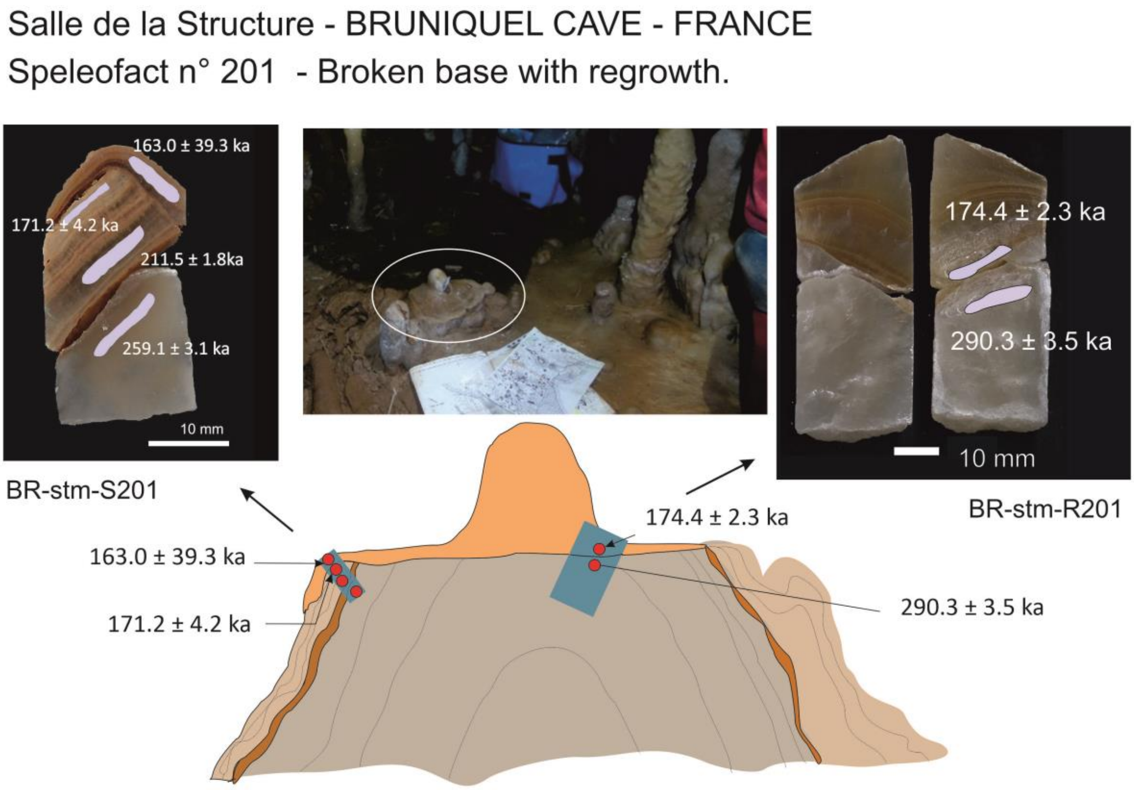

Figure: Bruniquel cave – France. Schematic view of sample 201. U/Th dating in two cores of a broken stalagmite base with calcite regrowth indicates that the stalagmite was broken at 173.8 ± 1.7 ka

SESSION 11 - GEOPHYSICS AND SEISMOLOGY

Conveners

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Geophysical techniques are widely used to characterise structures and dynamic processes in the subsurface. While numerous advances in experimental design, instrumentation, data acquisition and processing, numerical modeling, and inversion constantly push the limits of spatial and temporal resolution, the interpretation of the results often remains ambiguous. We invite contributions covering (but not limited to): Geophysical imaging or monitoring approaches such as seismic, electrical resistivity, electromagnetic or ground-penetrating radar. Seismological studies using ambient noise to characterise subsurface structures and dynamic processes are welcome including volcano- and induced seismicity aspects; earthquake source studies; or groundwater related studies.

Invited Speaker

Geophysical surveys to improve landslides characterization: examples from around the world

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Characterize a landslide means try to answer some questions like: which are the constituent materials? How are the material inhomogeneities distributed? Which are their properties? What are the deformation processes? How large are the boundaries or how depth is/are the slip surface/s? Answering these questions is not a simple goal. Moreover, to model the landslide behavior an efficient landslide stability analysis is needed, that means reliable geotechnical parameters have to be assigned to the identified layers. However, it is not always possible to determine the geotechnical parameters from direct tests. Since the '70s, the international community has begun to employ, together with other techniques, active and passive geophysical methods. Both the associated advantages and limitations have been highlighted over the years, and even geophysical techniques are usually defined time- and cost-effective, some drawbacks are still open (Pazzi et al 2019). This work presents different case studies from around the world (Italy, Bolivia, and Belgium) where geophysical techniques have been successfully employed to characterize landslides.

The Italian case study (Innocenti et al 2023) shows how geophysical methods (ERT, SRT, HV, MASW, and GPR) allow to identify the landslide stratigraphy and the shear wave velocity (Vs) values can be used in empirical equation to reliable estimate the friction angle values used in the stability analysis. Although, this indirect estimation is subject to a higher level of error, it could be very useful in the early stages of an emergency, when direct data are not available, and a preliminary forward and backward stability analysis could be performed to assess landslide evolution and civil protection actions.

Seismic noise measurements, integrated with InSAR observations and geotechnical data, were employed in the Bolivian case study to determine the depth of the failure surface and to assess the ground surface deformation (Song et al 2021). The seismic noise measurements (more than one hundred spread over the whole landslide), analysed according to the HV technique, calibrated and validated by means of the geotechnical data derived by boreholes and soil samples, allowed to identify shallow and deep slip surfaces and thus define the different dynamic characteristics of the landslide sub-blocks. The landslides caused damage to the buildings, probably mainly caused by the shallow slip interface (located at a mean depth of 5 m). In the town centre a deeper failure surfaces, approximatively with depth between 15 m and 75 m, can be identified which may be responsible for its different direction and acceleration magnitude of sliding (inferred by InSAR) compared to the other parts of the landslides.

ERT, SRT, and HV data have been integrated in the Belgium case study to reconstruct the stratigraphy and to create a 3D landslide geological model. The three geophysical methods agree in identifying the presence of two main layers: a superficial one of loose material overlying an intact conglomerate one. The contact between the two media would probably be attributable to the sliding surface because of the accumulation of water following significant rainfall events.

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Processing of a new detailed Bouguer anomaly map in the Mons area, SW-Belgium, looking for deep-seated anomalies

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In the Mons area, a new detailed Bouguer anomaly map has been computed following new data acquisition in the scope of the MoreGeo 2019-2022 survey (EDRF funding) [Campeol et al., 2024] . This new dataset consist in 13,000 measurements in 4,200 stations spread over an area of 820 km^2 processed using open-source Python libraries and integrated to the gravity databases of Belgium [Verbeurgt et al., 2019] and France [Martelet & al 2002]. The anomaly map, based on a reprocessed dataset of 69,000 measurements, covers about 5,000 km^2 on a regular grid of 50 m resolution.

Particular attention has been paid to topographical correction using prisms gravity method [Harmonica 2023]. However, in the Mons area, due to the presence of the cretaceous Mons Basin and the residual tertiary relief, varying correction densities should be applied. In order to tackle this difficulty, a two step approach has been adopted. First, positive and negative anomalies of the Bouguer map are compared with the extent and thickness of the meso-cenozoic deposits of the Mons Basin unit. Second, the effect of this sedimentary basin on the gravity field is modelled, compared with the Bouguer map. Finally, a gravity anomaly map where the effect of the meso-cenozoic deposits of the Mons Basin unit are subtracted in order to highlight the deeper anomalies is computed.

This new map paves the way for the search of density contrasts in the carboniferous limestone geothermal reservoir that could distinguish karstified and brecciated limestones from massive anhydrite layers.

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Stochastic inversion of the fresh-/saltwater interface from electromagnetic data

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Investigating the subsurface is crucial for numerous geological and hydrogeological endeavors. Geophysical techniques provide a cost-effective alternative to expensive boreholes traditionally employed for subsurface exploration. Nonetheless, the interpretation of geophysical data typically relies on deterministic inversion, which is an inherently ill-posed inverse problem with a non-unique solution. As a contrast, stochastic inversions explore the model parameter space and search for all solutions associated with the observed data, albeit at a higher computational cost.

In this study, we focus on probing the fresh-/saltwater zone using Time-Domain Electromagnetic sounding recorded with the WalkTEM system in the Belgian coastal area. Classical inversion approaches are not adapted to the expected medium-sharp transitions and therefore commonly fail at detecting the exact depth of this transition . This research therefore introduces a novel approach combining a parameterization of the transition zone allowing to characterize it with just two parameters (the depth of the interface and the thickness of the transition zone) and to use stochastic inversion. We employ the robust Bayesian Evidential Learning with Thresholding method (BEL1D-T) Ahmed et al., 2024.

Our findings indicate that using this parameterization in BEL1D-T, for both synthetic and actual field surveys, yields accurate posterior distributions that delineate the uncertainty range of the transition zone at a limited computational cost. Employing this approach for stochastic TDEM inversion proves to be an efficient strategy, facilitating the estimation of the transition zone's uncertainty at a manageable cost. Extending the application to airborne electromagnetic methods will allow the estimation of uncertainty for the recent salinity map of the Belgian coast, taking into account the uncertainty related to the flight altitude.

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Landslide characterization by geophysical and seismological measurements: application to Eagle's Lake landslide, Carpathian Mountains

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Assessing the geometry and volume of mass movements is essential in the evaluation of slope stability and the understanding of slope failure trigger mechanisms. At this purpose , we conducted abundant geophysical and seismological measurements in order to better characterize the subsurface of the deep-seated landslide of Eagle's Lake (RO: Lacul Vulturilor) in the Carpathian Mountains (Buzau-Vrancea region) in Romania. This region, seismically active, hosts numerous mass movements with a large variety of morphologies and sizes. These mass movements find generally their origin in climatic, seismic or both sources sizes.

Eagle's lake site has been object of debate for decades in the literature as its genesis is not fully understood. Therefore, we performed, over two geophysical campaigns, abundant HVSR measurements, installed seismic arrays to retrieve the dispersion of the surface waves, performed seismic active measurements to build seismic refraction tomographies and apply multichannel analysis of the surface waves, geoelectrical measurements were also performed, and UAV flights were conducted to establish a 3D model of the investigated site. These measurements were accompanied by a thorough geomorphic mapping of the area, which highlighted several surface features indicating structural weaknesses.

Combining both active and passive seismic measurements, we were able to better interpret the results provided by the surface wave analyses. Jointly inverting the above information, we retrieve the shear-wave velocity profiles in three positions over the landslide. We identified lateral variations in seismic velocities, as higher P-wave velocity (Vp) values in proximity of the edge of the landslide and low Vp values at the crest, indicating a rock fatigue due to dynamic processes. HVSR measurements present several resonance peaks, including peaks associated with impedance contrasts, possibly deriving from landslide shearing horizons and lithological contacts. The rich dataset helped reconstructing the geometry of the Eagle's Lake landslide and identifying zones of weaknesses at depth.

This work aims, in prospect, at reconstructing the conditions and the energy needed for triggering the mass movement and provide clarification on the mechanism at its origin.

Mapping salinity estimation in the coastal aquifers of the Luy River, Vietnam using indicator kriging

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Mapping the distribution of saltwater intrusion (SI) in coastal areas is imperative for the implementation of sustainable water resource management but requires complicated endeavors. SI can be evaluated based on borehole or geophysical data. The former provides direct salinity measurements but has limited local spatial representativeness. The latter allows mapping salinity in a more spatially continuous way but only provides indirect insights, due to the application of a petrophysical relationship impacted by the heterogeneity of the depositional formations. Integrating borehole and geophysical datasets for salinity mapping is therefore a complex task.

In this study, we apply indicator kriging (IK) to combine total dissolved solids (TDS) concentration data derived from water sample analysis (70 well observations in the depth interval of 5–10 m) and electrical resistivity tomography (ERT, 28 transects) data to deduce the probability distribution of salinity. Two different petrophysical relationships derived at the laboratory scale for clay-free and clay-bearing sediments are applied to link electrical resistivity to salinity. The uncertainty arising from either one of the relationships being more applicable – depending on the unknown absence/presence of clay – is captured by expressing each unique resistivity value into a possible corresponding range of salinity values. The hard TDS and interval ERT-derived salinity data are then translated into indicator data according to a fixed set of salinity thresholds chosen based on the TDS data distribution. Compared with ordinary kriging of TDS data only, adding the geophysical information provides a more meaningful delineation of the extent of saltwater intrusions, with the associated uncertainty of exceeding a critical salinity threshold.

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From oceanic waves to seismic wiggles, then and now

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Since the early days of instrumental seismology, seismometers have been recording various continuous natural and human-generated sources. The oceanic microseisms caused by the atmosphere-ocean-solid Earth coupling mechanisms are the main natural source of seismic ambient noise. Because these microseisms are directly related to the oceanic climate, the legacy seismograms, recorded on analog instruments, are a unique repository of quantitative observations of past storm events, most of which occurred before modern global satellite observation became available.

However, the analog nature of these records has limited their accessibility and utility in contemporary research. These challenges are now addressed using advanced image processing and machine learning techniques to digitize and vectorize these historical seismograms. This process involves scanning the analog records, extracting seismic waveforms, and transforming them into calibrated, time-coded digital time series. A critical step also involves compiling detailed metadata about historical seismic instruments to construct accurate instrument response functions, ensuring that the digitized data meets modern scientific standards.

The vectorized seismic data are validated through a first-order comparison between the extracted microseismic signals and the theoretical microseismic ground motions derived from the WaveWatch III oceanic models. This validation process helps confirm the reliability of the digitized data by focusing on the significant storms that impacted the Atlantic North East. Once implemented in large numbers of seismic observatories, this will help improve existing ocean models by integrating quantitative observations currently lacking for most of the 20th century. This potential to help improve climate reanalysis for the pre-satellite era motivates the digitization and vectorization of old seismic data. Nevertheless, bringing these legacy seismic data to the digital age will, in turn, also help implement modern seismic analysis on these datasets, bringing a fresh look at old natural and human-made sources ranging from earthquakes to nuclear explosions.

The Dutch seismic network and guidelines for seismic monitoring

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The Dutch mining industry is large and diverse: companies have been extracting oil, gas, and salt from the subsurface for decades. In recent years, new uses of the subsurface have emerged, such as geothermal heat extraction and subsurface storage of for instance CO_2 in depleted gas fields. All these mining activities can potentially lead to induced seismicity and these operations need to be properly monitored.

The Royal Netherlands Meteorological Institute (KNMI) is the governmental institute responsible for seismic monitoring. KNMI's legal task is informing the public about natural and induced earthquakes. For that purpose, KNMI operates a national network of seismic stations. The seismic monitoring data is disseminated in the public domain via websites, fdsn webservices and the KNMI Data Platform. The current station locations are not uniformly distributed over the country. Some regions have a dense network, e.g. Groningen. Other regions, such as the central part, have a rather sparse network. Because of the growing use of the subsurface, KNMI will extend the network in the next 5 years. The aim is to provide a basic network covering the regions where subsurface activities take place.

Operators are often obliged to locally improve the monitoring in addition to the KNMI network. This locally denser network enables the localization and characterization of lower magnitude earthquakes and informs Traffic Light Systems. KNMI encourages operators to transfer their stations and data to KNMI. This improves transparency, accessibility, and uniformity of earthquake records. For the sake of smooth transfer, KNMI developed a guideline for installing a seismic station, presenting requirements for sites, instruments, data communication and legal aspects.

Seismic monitoring takes place in an organizational landscape of two Ministries, a regulator, various knowledge institutes and the operators, each with their own responsibilities. The network and guideline will be discussed in this context.

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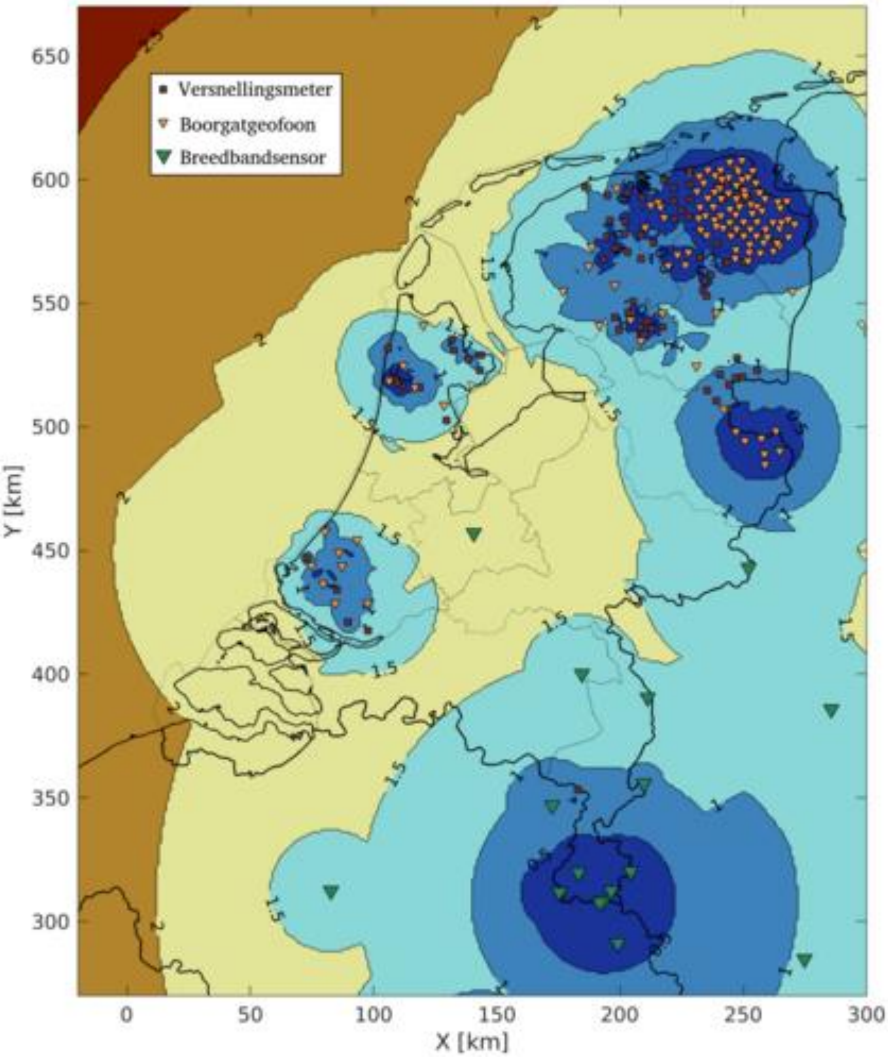

Current seismic network of which the data are registered at KNMI. Most are KNMI-stations and some are operated by third parties. The contours represent the lowest earthquake magnitude that can be localized (magnitude of completeness).

Imaging large-scale geological structures using Deep ERT in EMR for the Einstein Telescope

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The geophysical investigation of geologic structures is an essential prerequisite in early stages of large subsurface construction projects, like caverns or tunnels, as well as for understanding the present structural geology. Geophysical methods are also crucial for directing borehole locations to obtain optimized ground truth and adjusting the positioning of underground constructions.

The Einstein Telescope is one of these structures: a future gravitational wave detector consisting of a set of laser interferometer in a triangular shape with a side length of 10 km. To attenuate the instrument from diverse noise sources the detector will be constructed in caverns and tunnels at a depth of ~300 m.

Common techniques for the investigation of large-scale geologic structures are seismic reflection surveys and Airborne Electromagnetic surveys (AEM). However, both methods may be unsuited for specific settings as seismics surveys might deliver insufficient data due to an absorbing soft top layer or steeply inclined layers and AEM surveys might be disturbed by urbanized zones. To address these limitations, Deep Electrical Resistivity Tomography (Deep ERT) can be applied. This recent approach uses a system where the current injection and voltage measurement is completely separated. The setup facilitates the injection of high currents on large injections dipoles providing information at depth.

Due to the dimensions of the structure and the complex local geology several Deep ERT surveys were and will be conducted in the Euregio Rhine-Meuse to investigate the area for the optimal location. Here, we present our latest results and their indication for the Einstein Telescope. We discuss the potential of Deep ERT for large scale structures, the limitations, and challenges of performance and data processing.

Seismic hazard assessment for the 3-border region, Belgium, the Netherlands, and Germany

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In the frame of an Interreg MR project (2020-2023 – targeting the prospection of a site for a potential Einstein Telescope), seismic hazard calculations have been completed, and combined with some potential site amplification effects for eastern Belgium, southern Netherlands, and western Germany (about 60 * 60 km).

Therefore, the earthquake catalogue of Royal Observatory of Belgium of March 2021 has been used. Three seismic zones were defined for the Gutenberg-Richter (seismicity) calculation: the Rug-Graben zone in the east, the Eifel-Ardennes zone in the southeast (including the Hockai Fault Zone, HFZ), and the Liege-Maastricht zone in the west and northwest.

Probabilistic seismic hazard maps have been computed by using the R-Crisis (Ordaz et al., 2021) software, where the pre-determined seismicity parameters had to be introduced for the three zones and attenuation laws had to be chosen for the calculations. In addition to the probabilistic approach of seismic hazard assessment we computed also deterministic earthquake scenarios based on ‘maximum possible’ event simulations. Therefore, we selected the Ms=6.3 Verviers earthquake of 1692 as example. That earthquake occurred most likely when the eastern border of the Hockai Fault Zone (HFZ) ruptured. We computed two scenarios, one M=6.0 and one M=6.5 event on that fault. The new probabilistic seismic hazard maps indicate values of peak ground acceleration (PGA), with a return period of 475 years ranging from 0.05 g (low seismic hazard) in the west of Liege, Belgium, up to more than 0.2 g (medium seismic hazard) in the east of Aachen, Germany. Scenario calculations produced high PGA values of up to 0.5 g in the Verviers region for a M=6.5 event.

As the target region is also marked by the presence of a serious of hill crests, some being formed within thick soft Cretaceous deposits, both topographic and surface layer amplification effects can be expected to increase seismic ground shaking over those places. The latter effects have also been confirmed by numerous ambient noise measurements that had been completed over the past years in that region. For those regions the probabilistic seismic hazard maps indicate PGA values (475 year return period) of up to 0.5 g (so about three times larger than without site effects) and the scenario calculations produce up to 1 g PGA values.

Concluding, it can be said that areas in the 3-border region of Belgium, the Netherlands, and Germany, covered by thick (> 20 m) Cretaceous deposits along the morphological crests, are marked by a medium to high seismic hazard.

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Mapping and monitoring a Belgian Hautes Fagnes peatland using Ground-Penetrating Radar and Electromagnetic Induction

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Peatlands are critical ecosystems, offering essential ecological services such as substantial carbon storage. These ecosystems, however, are facing degradation due to land use and climate change. The Hautes Fagnes reserve contains an important part of Belgium's peatlands and is a key ecosystem for carbon storage, biodiversity support and act as a centre for tourism and educational activities. Peat extraction and peatland drainage for spruce forestry caused environmental degradation, and passive and active restoration are currently ongoing. The actual status of these peatlands in not yet well documented, and is one of the motivations for this research.

This study focuses on one of these peatlands, showing a clear topographic gradient, in the headwaters of the Hoëgne River. The objective is to investigate the use of Ground-Penetrating Radar (GPR) and Electromagnetic Induction (EMI) techniques to characterize such peatlands. The study particularly focused on peat depth and electrical conductivity assessments, both related to peatland degradation. The use of GPR with a 200 MHz centre frequency antenna allowed to map peat depth. The peat depth on the chosen toposequence is exhibiting a high spatial variability and is ranging from 0.2 to 2.1 m. The EMI measurements allowed to delineate zones of mineral soil. The EMI measurements were also useful to determine the impact of static and dynamic soil properties on bulk soil electrical conductivity. The links between soil static physical and chemical properties and its electrical conductivity are complex in zones of shallow peat. The main factor influencing electrical conductivity dynamics is the pore water conductivity. The results show how peat depth, topography and electrical conductivity are related, and demonstrate how geophysical techniques can be used for non-destructive characterization of peatlands conditions which is of interest in the context of their restoration.

The Belgian Seismic Noise Model

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1 Royal Observatory of Belgium

The Belgian seismic network (FDSN code BE) currently consists of 59 seismometers and accelerometers installed in Belgium and is operated by the Royal Observatory of Belgium (ROB). Short-period and broad-band stations are installed at the surface, in (man-made) galleries and in shallow and deep boreholes. In this contribution, the details of the BE network and its relation with the Belgian local geology are presented. We report on an analysis of the continuous seismic records by the BE network for which continuous seismic data has been archived since 2005. The analysis consists of Power Spectral Density estimates for the 36 seismic stations and for three stations in Luxembourg that were historically operated by the ROB. For five consecutive years (2015 to 2019), the seasonal, weekly and diurnal patterns and characteristics of the BE noise levels recorded at low and high frequencies are discussed. We present the Belgian Low and High Noise models and discuss the interest in installing seismic sensors at depth. We propose a model explaining the noise difference between stations by analysing characteristics of the level of anthropisation around each station (population density, roads and rail networks, etc).

Improved Bouger gravity anomaly mapping in the EMR Region

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We unveil updated maps showing gravity anomalies in the Euregio Maas-Rhine (EMR) region. These new maps are based on recent gravity measurements conducted in the frame of the E-Test project for the Einstein Telescope (ET) geological exploration.

FREMEN GEO collected the corresponding gravity data between late 2023 and early 2024. They consist of 8500 observation points spread over a 10 by 15 km area. Additionally, 500 points were repeated to gauge the accuracy of the new map. Our updated simple Bouguer gravity anomaly map closely aligns with the latest update of the simple Bouguer gravity anomaly map of Belgium (Everaerts M and De Vos W., 2012). However, the denser dataset reveals finer variations.

While no distinct variations can be directly linked to known geological features, regional-residual anomaly separation reveals a clear southwest-northeast-oriented negative gravity anomaly. It may be related to to the Booze-Val Dieu block, supposedly present beneath Cenozoic formations in the area. To test this hypothesis, we plan to construct a density model using the new dataset as a basis, employing a stochastic 3D geological model (Chudalla et al., 2021).

This dataset marks a critical milestone in the ET proposal for the EMR region, as density mapping is essential for Newtonian Noise modeling, which is crucial for low-frequency gravitational wave interferometry.

Chudalla, N., Wellmann, F., Jüstel, A., & Harten, J. von. (2021). Implicit geological modeling for the Einstein Telescope (Meuse-Rhine Euroregion). EGU21. https://doi.org/10.5194/EGUSPHERE-EGU21-15814

Everaerts, M., De Vos, W.: Gravity acquisition in Belgium and the resulting Bouger anomaly map. Geological Survey of Belgium, 2012-58.

E-TEST : challenges in future site characterization studies towards a candidacy to host the Einstein Telescope

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E-TEST is part of the overall context of the design, construction and operation of the Gravitational-Wave Observatory (GW) ET. The ET project (https://www.et-gw.eu/index.php) is a future underground laser interferometric detector for GW research.

GWs are deformations of space-time traveling at the speed of light. GWs are produced by any accelerated mass satisfying a few simple conditions, but the GW signals that can currently be observed by man-made instruments are only those produced by very fast, massive astrophysical systems such as pairs of black holes or neutron stars orbiting each other, even if these systems are billions of light-years away (the GW signal amplitude decreases linearly with distance from the source).

GWs are detected by large L-shaped laser interferometers based on Earth or in space. Because of the complexity of these experimental infrastructures, they are developed by international collaborations of considerable size (over 700 scientists for Virgo and over 1500 for LIGO) and the next generation is planned to be installed at depths over 200m to lower the impact of ambient vibrations.

The choice of site for the ET infrastructure is expected around 2026, and the Euregio Meuse Rhine is one of two or three possible candidate sites for ET but displays a complex geology resulting in challenging geophysical, geotechnical, and hydrogeological conditions to characterize. We report here the results of a three-year investigation project that encompassed a large set of methods to get an overall better understanding of the subsurface to study the feasibility and optimize of installing a large scientific infrastructure in the EMR.

Fiber-optic sensing for environmental seismology and energy applications

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In recent years, fiber-optic sensing technologies have and are continuing to grow in popularity throughout all areas of geosciences.

By sending laser pulses into a glass fiber optic cable and analyzing the backscattered light, these cables can be turned into sensitive strain and temperature sensors. Fiber Bragg gratings (FBG) offer highly accurate point measurements of local temperature and strain allowing to assess long term deformation and temperature changes. Distributed strain sensing (DSS) on the other hand provides measurements of relative strain with high resolution in space and time. Cable deployment is undemanding, less invasive and more inexpensive compared to conventional sensors. Specialized cables and their robustness enable measuring in extreme conditions and DSS additionally allows the usage of preexisting telecom infrastructure. Therefore, these techniques are highly effective tools to monitor a wide scope of environmental and anthropogenic processes.

In this presentation, we showcase a diverse range of applications and initial analyses of fiber-optic measurements from deployments in Belgium and abroad. One notable example is our investigation of fiber-ground coupling effects during a DSS deployment at De Panne, where the fiber was installed along the seashore. Additionally, we will present and compare results from both FBG and DSS technologies for measuring strain and temperature changes both in a shallow geothermal site in Brussels and a deep geothermal site in Iceland.

Furthermore, we explore the potential of fiber-optic solutions using already installed telecommunication fiber for monitoring hazardous environments, such as active volcanoes, demonstrating their capability to provide continuous and precise data in challenging conditions.

We aim to demonstrate the ability of these new sensing technologies to better our understanding of earth surface processes and hazard monitoring. We also emphasize the potential role in supporting the energy transition by helping to optimize geothermal energy production.

3D imaging of clay tectonic deformations in the Kortrijk Formation through (ultra-)high-resolution acoustic and seismic reflection profiling in the Princess Elisabeth Zone, offshore Belgium

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In the Princess Elisabeth Zone (PEZ), on the Belgian Continental Shelf, new offshore windfarms (with a total capacity of up to 3.5 GW) will be built in the coming years. The substrate of this zone consists of a thin Quaternary cover overlying Early Eocene (Ypresian) clays that are part of the Kortrijk Formation. Clay tectonic deformations, manifesting as faults and folds, are known to exist in this formation since the 1980's (Henriet et al., 1983; Henriet et al., 1988), yet potential repercussions for the design, installation and operation of the planned windfarms in the PEZ have not been studied so far. The cSBO-project "Clay Tectonics" (2023-2025), funded by VLAIO through the Blue Cluster, therefore aims to investigate this topic through a combination of geophysical measurements, geological analyses and geotechnical simulations.

A first, essential step in this evaluation is the acquisition of adequate geophysical data for imaging and characterizing the clay tectonic deformations. Several surveys have therefore been performed in the PEZ, to acquire high-resolution sparker seismic reflection profiles and ultra-high-resolution parametric sub-bottom profiling data over four tightly spaced grids (called Block A, B, C and D). The location of these study areas and the survey strategy were carefully selected, based on previously known geological/geophysical factors (e.g. variations in deformation style, Quaternary cover thickness, bottom penetration, presence of identifiable reflectors, Palaeogene subcrop stratigraphy) and practical constraints (e.g. available shiptime, parcel division of the PEZ). This has resulted in >1,000 km of high-quality 2D seismic/acoustic profiles. The processing of these data adopted a particular focus on optimizing the visualisation of the clay tectonic features.

The next step encompasses integrating the processed 2D seismic and acoustic profiles per survey block into (pseudo-)3D sub-bottom volumes. These cubes should allow to properly reconstruct the 3D distribution and characteristics of the deformations, which will be important knowledge for the development of the new offshore windfarms. Preliminary tests performed for Block B (a 2.5 x 2.5 km network of 39 SW-NE and 38 NW-SE 2D profiles, intersecting at approximately 50 m) show promising results, clearly revealing a set of SW-NE trending normal faults. Relevant fault characteristics (e.g. dip, orientation, displacement, length) can readily be obtained from the generated 3D seismic volume and the derived structure and time maps, down to a depth of ~40 m below the seabed. Below this depth multiples obscure the interpretation, despite applying multiple suppression methods (such as surface related multiple elimination, pre-stack deconvolution and zero offset demultiple) in the data processing phase. That said, the adopted geophysical data acquisition, processing and integration methodology can be considered successful in creating a 3D visualization of the clay tectonic features in Block B. Future work will focus on automating the interpretation workflow and applying this approach to the other blocks

(Blocks A, C and D) as well, from which the observations will continue to feed into the geological analyses and geotechnical evaluation of clay tectonic deformations in the PEZ.

Henriet JP, D'Olier B, Auffret JP, Andersen HL (1983) Seismic tracking of geological hazards related to clay tectonics in the Southern Bight of the North Sea. In: Symposium Engineering in Marine Environment 1.5–1.15.

Henriet JP, De Batist M, Van Vaerenbergh W, Verschuren M (1988) Seismic facies and clay tectonic features of the Ypresian clay in the southern North Sea. Bulletin de la Societe Belge de Geologie 97(3-4): 457–472.

Estimating hydrological variations from geophysical insights

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The water cycle exerts a significant influence on geophysical signals. Through an extensive hydrogeophysical investigation at the geodynamic station in Membach, Belgium, we aim to estimate hydrological variations in the surrounding area. Our focus is on integrating gravity and ambient seismic noise measurements to develop a detailed hydrological numerical model at a local scale. The first step of the study is to examine the correlations between the geophysics and hydrological observations of the area. Then, we employ stochastic sampling methods to examine subsurface parameters, allowing us to reproduce diverse observables such as gravity anomalies, seismic velocity changes, and water balance variations best. This comprehensive approach enables us to obtain a more accurate understanding of the hydrological processes occurring beneath the surface. By combining ambient seismic noise with gravimetry, we aim to address current instrumental limitations in hydrology, particularly for studying deep and complex critical zones. These critical zones are essential for understanding the interaction between the Earth's surface and subsurface, as well as the variation in water storage. Our research anticipates that this integrated method will provide more precise and detailed insights into hydrological dynamics, ultimately contributing to improved water resource management and a better understanding of geophysical signals influenced by the water cycle.

First results of the GeoCOND2022 seismic reflection campaign in central Wallonia

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In December 2022, two seismic reflection profiles from the GeoCOND2022 campaign were shot in the central part of Wallonia. This acquisition was conducted as part of the DGE-ROLLOUT project (Interreg North-West Europe), which aims to map deep Dinantian limestone to support the development of deep geothermal projects in North-West Europe.

The GeoCOND2022 seismic lines were oriented orthogonally to the structural trends. The first line (L1), oriented NW-SE, extends from Fernelmont to the outskirts of Marche-en-Famenne. The second line (L2) stretches from the region of Gembloux in the north to Anhée in the south. The imaged tectonostratigraphic units include the Brabant Massif and its southern extension, the Brabant Parautochthon and associated tectonic slices and the Dinant Synclinorium.

The acquisition took place from 14th December 2022 to 1st January 2023, using typically three vibrator trucks. A total of 3,027 vibrated points (VP) were conducted at intervals of 10 or 20 meters along a cumulative length of 63 kilometres. 6732 STRYDE receivers (RP) were deployed at 10-meter spacing with a maximum offset of 8 kilometres. The recording length was 20 seconds plus 6 seconds of listening time.

Strong reflectors along L1 were recorded even at the deepest parts of the profile. Re-processing of sonic data from the Havelange borehole indicates that rock velocities in the Dinant Synclinorium range between 5,000 and 7,500 m/s. Given the 6-second listening period and these velocity values, some reflectors are likely located down to the middle crust. The distribution of these reflectors outlines a large open synform structure, with the southern limb intersected by the Midi Thrust reflector. This thrust is flat at a depth of 5 kilometres under the central part of the Dinant Synclinorium. In the northern part of this unit, the dip angle of the Midi Thrust increases significantly, reaching about 55°S at ground level. Other strong reflectors in the Dinant Synclinorium are interpreted as Devonian limestones, organized into an imbricated structure.

The analysis of this seismic campaign's results suggests that the southward extension of the Dinantian limestone beneath the Midi Thrust in central Wallonia is probably limited. This contrasts with the situation in Northern France and the Mons basin, where Dinantian limestones extend several tens of kilometres under the Midi Thrust. This lateral variation can be attributed to differences in the dip angle of the Midi Thrust, the depth of the Dinantian limestones, and their thickness.

A geophysical database for Belgium

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In the last decades, seismologists at the Royal Observatory of Belgium (ROB) have installed single station and seismometer arrays all over the country for various purposes such as measuring noise levels around potential permanent station locations, deciphering earthquake site effects, performing shallow geological investigations, characterizing the geology around borehole and geothermal wells, outreach events, etc. Applied techniques for data analysis include predominantly HVSR (Horizontal-to-Vertical Spectral Ratio) analysis of ambient noise and constructing frequency – velocity dispersion curves for deciphering the variation of shear-wave velocity with depth. Many of the single station and array datasets, however, remained hidden in publications and projects databases and were difficult to access for the geoscientific community. Until today!

In this work, we present the launch of the HVSR and Array database for Belgium. This database includes at the moment of writing the raw and processed data of 3468 single stations and 1577 array locations. From 2002 until 2018, most single station data was acquired using a Lennartz LE-3D/5s seismometer coupled to a Cityshark acquisition system. However, from 2018 onwards, nodal seismic sensors revolutionized seismology and geophysics with their affordability, portability, and ease of deployment and their installation in various projects rapidly increased the spatial and data volume in the HVSR and Array database. Our purpose is to openly share the data and results of efforts for geological and geophysical applications in and around Belgium. The HVSR database is especially of interest as HVSR curves and resonance frequency can be converted into virtual boreholes (Van Noten et al. 2022) with limited prior knowledge obtained from station installations above boreholes, strongly complementing borehole information for 3D geological subsurface modelling.

Apart from seismological data, the Royal Observatory of Belgium has also strongly invested in the field of palaeoseismology, and detection of faults and earthquakes in the geological record. In these works, numerous electrical resistivity tomography (ERT) profiles have been acquired to image and study the shallow geological structure around faults. Efforts have been made to homogenize all ERT data that has ever been gathered by the ROB. This resulted in the birth of our Electrical Resistivity Tomography database. This database contains more than 50 kilometers of ERT profiles acquired by planting almost 10 000 electrodes.

We acknowledge that the ROB is off course not the only geophysical institution that gathers geophysical data, but by opening these databases to the scientific community, we want to trigger and lead efforts to develop and gather data for an open geophysical database for Belgium.

Van Noten, K., Devleeschouwer, X., Goffin, C., Meyvis, B., Molron, J., Debacker, T.N. & Lecocq, T. (2022) Brussels' bedrock paleorelief from borehole-controlled powerlaws linking polarised H/V resonance frequencies and sediment thickness. Journal of Seismology 26: 35-55.

How geophysics can help unravel the heterogeneity of the intertidal zone

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The groundwater salinity distribution in coastal areas is the result of the interaction between fresh water recharging on land and saline seawater. A natural equilibrium exists in coastal areas leading to typical seawater intrusion (SI) into freshwater aquifers due to the higher density of salt water, and fresh submarine groundwater discharge (FSGD) into the sea. The fresh-/saltwater distribution is further influenced by the lithological heterogeneity of the aquifer, the sedimentary evolution of the coastal area, human activities such as pumping, drainage and irrigation, and Climate Change (droughts and sea level rise). FSGD is of major ecological importance, since it constitutes the entry gate for nutrients and potentially contaminated groundwater towards the seas (e.g., Luijendijk et al., 2020), while SI decreases the quality of the aquifers water as it becomes more brackish and reduces the availability of potable water resources.

At the Belgian coastal zone, the distribution of the fresh-/saltwater interface is complex and results from the evolution of the Quaternary coastal aquifer due to geological (Baeteman et al., 1999) and anthropogenic factors (e.g., polders and urbanization). The tidal regime results in salty/brackish pore water at shallow depth in the Belgian coastal phreatic aquifer, making the fresher groundwater underneath the coastal dunes an important drinking water resource. The discharge of freshwater – which originates in the dunes – is directly affected by the recharge from precipitation, the dune width, and the aquifer composition (Vandenbohede & Lebbe, 2006).

Paepen et al. (2020, 2023) recently demonstrated that freshwater discharge can occur up to several hundred meter from the Belgian coast shore by using electrical resistivity tomography (ERT) and continuous resistivity profiling. Parallel to the Belgian coast, the location where FSGD occurs moves land- or seaward, which can be due to changes in the dune width or groundwater extraction. However, groundwater modelling has shown that in some areas (e.g., in front of De Westhoek and near-coast in front of the city of Knokke) the salinity distribution can only be obtained when the coastal aquifer is not homogeneous. There, the footprint of the FSGD seems only compatible with the hypothesis that less pervious layers are present underneath the intertidal zone.

The hydrogeology of the Belgian coast is, therefore, investigated by the combination of the geophysical methods ERT and induced polarization (IP). Both methods are sensitive to the electrical conductivity of the pore fluid composition and therefore the salinity. However, IP is less sensitive to the pore fluid and more sensitive to the rock and soil texture compared to ERT. Profiles are collected parallel and perpendicular to the coastline in the areas of De Panne, Koksijde and Raversijde. The FSGD can be observed by mapping the distribution of the fresh-/saltwater interface using ERT, while fine-grained shallow clay layers creating lithological heterogeneity can be observed with IP. Using the geophysical methods ERT and IP, the heterogeneity of the intertidal zone in Belgium is investigated.

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Luijendijk, E., Gleeson, T., & Moosdorf, N. (2020). Fresh groundwater discharge insignificant for the world's oceans but important for coastal ecosystems. Nature Communications, 11(1).

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Paepen, M., Walraevens, K., & Hermans, T. (2023). Footprint of fresh submarine groundwater discharge in the Belgian coastal zone: An overview study. The Leading Edge, 42(9), 598–607.

Vandenbohede, A., & Lebbe, L. (2006). Occurrence of salt water above fresh water in dynamic equilibrium in a coastal groundwater flow system near De Panne, Belgium. Hydrogeology Journal, 14(4), 462–472.

OhmPi: an open-source, open-hardware resistivity meter for lab and small-scale field applications

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In the toolbox of techniques available to investigate the shallow subsurface, geoelectrical tools, and Electrical Resistivity Tomography (ERT) in particular, are increasingly being applied in (hydro)geology, ecology, and beyond. ERT monitoring has also become more popular to track subsurface processes with a high spatial resolution and in a non-invasive way. In this context, the accessibility of geophysical equipment is key to expanding the use of geophysical monitoring, at least for research purposes, and to developing innovative acquisition strategies. Commercial geophysical equipments are practical, robust and user-oriented tools which are largely suitable for industrial applications, however their limited flexibility can hinder creative research applications. In an attempt to tackle this issue, the OhmPi project was initiated to provide an alternative open-source, open-hardware resistivity meter to the research community. Designed in a do-it-yourself approach, the OhmPi resistivity meter is controlled via a Raspberry Pi which pilots (1) an acquisition board managing the current injection and voltage readings, (2) a series of multiplexers addressing a range of electrodes, and (3) a programmable digital power supply allowing to regulate the injection on applied voltage of up to 50 V. Being entirely programmed in Python, OhmPi can be interfaced directly via the Python API or using a web interface. A more advanced IoT interface also enables sensor-controlled acquisition. Developed as an open-source project, new collaborations are warmly welcomed. This presentation will focus on detailing the main capabilities of the instrument and present field applications including a monitoring experiment illuminating 3D soil moisture dynamics in a forest site at the Rochefort Cave Observatory (Belgium).

Passive noise interferometry towards monitoring volcanic and geothermal environments

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Passive noise interferometry has become a popular technique towards monitoring subsurface activities in a variety of settings. By cross-correlating continuously recorded seismic noise, changes in seismic velocity may be recovered that reflect subtle variations in the medium. One common use case is the monitoring of volcanoes with pre-cursory velocity changes detected prior to eruptive activity at a number of volcanoes. Two such examples include Stromboli (Italy) and Ruapehu (New Zealand). At Stromboli, we observe an anomalous increase in velocity close to the active crater — relative to the volcano flanks — during the two years prior to major paroxysmal activity in 2019. This corresponds to a period of heightened activity at the volcano, with the velocity peaking in the months prior to the first paroxysm. At Ruapehu, analysis of the eruption chronology suggests a higher probability of small eruptions in spring. Comparing seasonally-induced velocity changes with the timing of the previous two eruptions shows both eruptions occurred as velocities began to decrease at depth. We hypothesize this could reflect the removal of the seasonal snow-load and represent a possible trigger for greater spring-time eruptive activity. Finally, recent advancements in fiber-optic technologies (e.g. Distributed Acoustic Sensing or DAS) are providing new opportunities in the field of passive seismic interferometry. Specifically, it is possible to turn fiber-optic cables into thousands of seismic sensors, providing unprecedented spatial resolution. We acquire DAS data in geothermal environments spanning a large range of temperatures (15C to 250C) in Belgium and Iceland, and present preliminary measurements of velocity changes. Future work will continue to explore the integration of noise interferometry and DAS technologies, with significant potential towards improved monitoring of volcanic and geothermal activities.

SESSION 12 - GEO-ENERGY

Conveners

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Energy plays a vital role in sustaining society, encompassing functions like home heating, food production, and transportation. However, energy consumption poses significant challenges. First, heavy reliance on fossil fuels escalates CO_2 levels, accelerating climate change. Second, dwindling domestic energy production increases dependence on external, sometimes unreliable, suppliers. To tackle these issues, the European Union (EU) is pursuing solutions through the Green Deal initiative. This strategy boosts domestic renewable energy, reduces consumption, and lowers greenhouse gas emissions, striving for a sustainable and resilient energy future.

The Geo-Energy session will delve into a comprehensive examination of sustainable energy sources and their implications for the future for Belgium and neighboring countries:

Geothermal Energy: Assess the feasibility of geothermal energy, including shallow and deep sources, as a cornerstone of future energy strategies, and understand its role as a local, reliable, and cost-effective energy source.

Underground (Energy) Storage (natural gas, hydrogen, CO_2, heat/cold): Explore various storage solutions and their contributions a secure and carbon-lean future.

Invited Speaker

What role should the subsurface play in the energy transition?

Sylvie GENTIER 1

1 Ex-BRGM

By offering both resources and storage solutions, the subsurface can play a crucial role in the energy transition. The aim of this presentation is to review the various aspects of its contribution based on the French approach and experience, while highlighting the importance of geological knowledge. The energy transition concerns the shallow and deep subsurface, and urban as well as non-urban areas.

First, urban and peri-urban underground space is a precious resource, a space for the implementation of energetic structures and infrastructures and geothermal energy. The pressures of changing environment, including climate and increasingly limited land availability, should place urban underground spaces at the forefront of innovative urban development priorities. However, a strategy for an alternative to surface urban growth has yet to be properly elaborated or even discussed. This strategy will have to be based on a knowledge of a still little-explored geology that could be described as "urban" geology. It is most often based on the most superficial formations, which have been remodeled by centuries of development and a complexity of underground flows. The potential of urban underground space remains to be explored.

More broadly, the subsurface offers an excellent opportunity for both surface and deep geothermal energy. By harnessing the heat of the subsurface, we can produce both heating at different scales and electricity. This renewable energy source can be exploited by means of wells or heat exchangers but requires a geological approach in line with the technologies for exploiting this heat. The evolution of geothermal energy aims to generalize the exploitation of heat, aiming to go beyond the geothermal reservoirs traditionally exploited until the end of the 20th century.

Underground spaces are also valuable reservoirs for energy vectors and other substances. Consider, for example, the storage of energy vectors such as hydrogen or compressed air. It seems that underground heat storage could be of the utmost importance in the future, on different scales and in wide temperature ranges. These vectors can be produced during periods of excess renewable energy and stored underground in cavities or geological layers (aquifers) for later recovery or reconversion into usable energy when needed.

In addition to its direct energetic role, the subsurface constitutes a storage and containment area for CO_2, by injecting it into geological formations located at great depths, thus reducing emissions into the atmosphere and contributing to climate change. It is also the place where radioactive waste has been stored since the 1980s in various geological formations to ensure long-term containment and minimize environmental impact.

To define and specify these different uses, geological knowledge combined with increasingly complex numerical modeling (couplings) is the challenge of the coming decades. These models must help us to understand subsurface behavior, predict storage capacity and optimize long-term management. By simulating various scenarios, we will be able to make informed decisions on the use of resources and storage strategies to be developed.

Finally, the subsurface offers immense potential for sustainable energy solutions by harnessing geothermal energy and underground storage.

Quantification of the Brussels geothermal energy potential

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As part of the elaboration of a global decarbonation strategy for heating and cooling supply in the Brussels-Capital Region, Bruxelles Environnement has piloted a study to quantify the technical potential of the various renewable and recovered energy sources in the heating and cooling sector available in Brussels. One of the main input of this study was the quantification of the Brussel's raw technical potential for geothermal energy, more precisely for both:

1. open loop systems (using groundwater as a thermal resource through geothermal doublets);

2. closed-loop systems (using subsoil as a thermal resource through geothermal vertical probes).

Indeed, Brussels has a recognized geothermal energy potential within a depth between 200 to 300 meters. Beyond 300 meters deep, the geothermal potential is considered to be very limited, making deep geothermal potential unlikely (deep rocks of the Paleozoic basement are considered to have a low permeability according to current knowledge). In this context, the kind of geothermal energy systems that can be deployed in Brussels is limited to very low-enthalpy (heating assisted by heat pumps and/or cooling).

The Brussels' raw technical potential for geothermal energy corresponds to the raw accessible potential, i.e. considering all available space and resources without any other constraints. Its interpretation at regional level is based on an optimistic approach.

The raw technical geothermal potential is defined by quantifying the following parameters:

- Maximum power that can be extracted from the Brussels subsoil (kW), for heating or cooling;
- Maximum energy that can be extracted annually from the Brussels subsoil (kWh/year), for heating and cooling (combined).

The raw technical geothermal potential:

- for closed-loop system was quantified using an analytical approach based on assumptions of extractable energy per borehole and probe density per unit area;
- for open-loop system was quantified using a numerical approach. The general methodology applied consisted in building a numerical model reproducing the "average" hydrogeological environment of each targeted aquifer in Brussels, and running hydrodynamic and thermal simulations using FEFLOW software to reproduce a 30-year operation of a "typical doublet" (pumping/reinjection) under conditions considered as representative of an "average" operation in Brussels. This kind of simulation ultimately enabled to quantify a “unit geothermal exploitation area" for each targeted aquifer in Brussels. By extrapolating the latter over the entire Brussels territory, it was then possible to quantify an extractable geothermal potential at a regional scale.

Other more superficial geothermal technologies, such as energy piles, shallow horizontal systems and compact systems (geothermal baskets or walls) were outside the scope of this study.

Deep Geothermal Energy in the Netherlands: Resources, Development and Design Characteristics

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To date, there are approximately 30 established deep geothermal doublets in the Netherlands, with many more being actively progressed through the project maturation pipeline. The extracted brine temperature ranges from 60 to 90 °C, for assets delivering between ~10 and ~40 MWth. Historically, these have helped decarbonise greenhouse agricultural projects, with a gradual shift and future push toward feeding urban district heating networks.

Dutch deep geothermal systems typically target thick saline sandstone aquifers in fault-bounded structural lows with one or more producer-injector pairs. These open systems must have a demonstrated cap rock seal and importantly, they must be designed away from fault zones. They also need to avoid hydrocarbon accumulations and migration pathways.

There are four main resource plays distributed across distinct structural elements, each play having its specific characteristics and particularly prospective sweet spot areas. The target sandstones are found in formations of Permian, Triassic, Late Jurassic and Early Cretaceous age.

The Permian Slochteren Formation is a thick epicontinental aeolian sandstone accumulation that is widely distributed in the north of the country. Its properties are well defined and predictable, although extrapolating reservoir quality into the deeper graben structures can prove challenging. The targets in the Triassic Hardegsen, Detfurth and Volpriehausen Formations consist of continental early rift fluvial, lacustrine and occasionally aeolian sandstones that display a significant lateral variability and whose properties are particularly impacted by burial. As a result, the play is most attractive along the southern flank of the West Netherlands Basin (WNB). The Late Jurassic – Early Cretaceous Nieuwerkerk Formation contains lower coastal plain and marginal marine deposits whose distribution patterns were constrained by the extensional fault systems that were active during the rifting phase. As a result, the lateral extent of the high-quality mouthbar and stacked distributary channel sands making up the Delft, as well as the locally stacked fluvial channel sands of the Alblasserdam are limited to the boundaries of the WNB. The post-rift Early Cretaceous Vlieland Group has three main plays: the IJsselmonde, Berkel and Rijswijk sands. These are shallow marine sediments, making up relatively narrow bands of east-west trending good quality sandstones, with a prospective region located across the western end of the WNB.

At this stage the Delft is by far the dominant geothermal resource in the Netherlands, supplying heat for about ten established geothermal assets in the southwest of the country, with three more already in the commissioning phase. The Slochteren Formation is also important, with five producing assets. Most upcoming projects are targeting these two high-quality resources. The Triassic and Early Cretaceous are secondary resources, each currently supporting a few producing assets. A few upcoming projects are targeting these lower grade or more challenging reservoirs.

Boosted by a strong government financial incentives and geological exploration de-risking programs, these saline sandstone aquifers will continue to be developed by a dynamic industry aiming to fill a growing demand for a decarbonised heat supply.

The Dutch Geothermal Asset Catalogue

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In 2024 PanTerra Geoconsultants initiated a project aimed at documenting and summarising the characteristics of the deep geothermal resources and geothermal assets of the Netherlands, exclusively using publicly available data. This project relies on two work streams. The first is a Dutch Geothermal Play Atlas, which looks at the subsurface characterization of the various geothermal resources at a regional scale, with focus on the saline sandstone aquifers of the Permian, Triassic, and Late Jurassic-Early Cretaceous. The second work stream investigates the local level and summarises publicly available information about established producing geothermal assets and various geothermal exploration license areas.

This poster introduces the overall project and provides preliminary results, with illustrations from both an exploration license and a producing asset, both targeting the Permian Slochteren Formation. The national-level geographical distribution of geothermal assets and licenses provides context, together with the outlines of the dominant structural elements. At the local exploration or production license level, the summarised (publicly) available data includes evaluation results and illustrations from seismic and well data, correlation panels, schematic structural cross section, and an overview of reservoir and fluid characteristics. For producing assets, an in-house analytical tool has been developed to monitor production performance and trends, with examples provided at a doublet and asset level (if the asset has two or more doublets). This production performance monitoring tool is also rolled-up at a play level, and one can compare performance between assets extracting geothermal brine from the same resource.

At this stage this poster provides an oversight of data and information available in the Dutch public domain about two typical exploration and production licenses targeting to develop – or already developing – the world-class Slochteren reservoir. As such it provides a good introduction to typical deep geothermal systems of the Netherlands and a framework for discussions. The completed Dutch Geothermal Play Atlas and Geothermal Asset Catalogue for the saline aquifers of Permian, Triassic and Late Jurassic-Early Cretaceous age will be available by end 2024.

Development of a fast geothermal simulation tool designed to the Lower Carboniferous reservoir of Hainaut in the framework of the BRAIN-Be 2.0 DESIGNATE project

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The DESIGNATE project (Decision Support under Uncertainty for Geothermal Applications) investigates geothermal applications for direct heat use from deep geological reservoirs and abandoned mines. The core of the project is the development of a geothermal techno-economic simulator. This simulator is designed to serve as a decision-making-tool for the implementation of new geothermal projects in Belgium, taking into account the existing uncertainties both on the technical-economic parameters and on the considered geothermal reservoirs.

In Wallonia, the main deep geothermal reservoir is in the Lower Carboniferous rocks. In Hainaut, it has been recognized mainly by a few boreholes and by seismic surveys. In the area targeted for geothermal projects, the carbonate reservoir is more than 2 km thick, dipping southwards, and containing at least one high-transmissivity level linked to interstratal karstification of anhydrite. Where the anhydrite has been entirely dissolved, brecciated layers are observed.

To model the reservoir, a synthetic hydrogeologic model was built. Some features of the reservoir are set as parameters that may vary depending on the simulations to mimic geological uncertainties concerning the depth of the top of the reservoir, its thickness and permeability as well as the local geothermal gradient. The range of these parameters is based on the current knowledge of the reservoir.

While analytic modelling can be a fast way to simulate geothermal scenarios, this type of method is only suitable for very simple reservoir geometries. For more complex settings, numerical flow and heat modelling is necessary but requires a much longer resolution time.

Since the simulator relies on the exploration of a large number of cases to simulate, computing time was a critical issue. To allow for reasonable runtimes of the simulator, our strategy was (1) to precompute a set of hydrogeological simulations exploring the range of parameters describing the reservoir and a range of pumping rates kept constant over the simulation and store the results in a look-up table, (2) to build an interpolator function based on the look-up table, and (3) to combine the results of interpolations to approximate the evolutions when pumping rates vary over time.

Reservoir modelling and simulations have been carried out in ModFlow6 using the FloPy python package. Due to the range of parameters to be explored (including the required geothermal flowrate), more than 50,000 simulations have been performed. While the simulations have been conducted at constant flowrates, the techno-economic simulator needs to test scenarios with varying flowrates. To obtain an approximate response when flowrates are susceptible to change from one year to another, we divide the simulation timespan into periods of constant flowrates. For each period, we use the interpolator to identify how many years would have be needed to extract the total energy produced until the beginning of this period given the production history but considering a geothermal production with the flowrate of the current period. The subsequent evolution during this period is then approximated by time series returned by the interpolation function but shifted in time by the number of years determined before.

New insights into the sedimentology and diagenesis of the Dinantian carbonates in the Campine Basin

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The Dinantian in the Campine Basin has been studied extensively in the past, but exploration for subsurface reservoir applications has brought new data and has led to new insights into the sedimentary and diagenetic evolution of the Campine Basin.

In total five deep wells have been drilled in Flanders over the last ten years and several seismic surveys have been undertaken.

Reprocessed seismic sections and 3D modelling by VITO, biostratigraphic analyses by Luc Hance, log analyses and integration of data by PanTerra Consultants, valuable input from a board of experts at several occasions, as well as own research over the years have brought new insights into the sedimentology of the basin. Whereas the presence of Tournaisian strata was questioned in the past for a large part of the basin, its development with strong thickness differences and typical Waulsort facies has been recognized. Also, the late Dinantian to Namurian transition can be better constrained. The combination of tectonics and a major relative sealevel fall led to erosion of the exposed northwest part of the shelf, while MFZ15 aged sediments were deposited in a restricted environment east of it. In the Mol setting, a weaker calcite signature and a more important contribution of clay, organic material and schizohaline minerals prevailed. This phase is followed by carbonates with many chert intercalations and finally by important shale contribution. The rapid transition from restricted environment to deep marine conditions (Souvré Formation) in a short period of time may be explained by the particular setting of Mol close to the platform edge and slope.

Diagenetic study of core samples from the West and East margin of the Campine Basin revealed an important meteoric influx with karstification during early Cretaceous. This was the most important phase for todays reservoir development. In some cases, the end Visean paleokarst at the top of the carbonates – closed after an intensive burial phase with pressure-dissolution and cementation – is overprinted by this younger karst phase. In other cases, the lateral fluid influx played at a different level. In the case of the California (Netherlands) geothermal project, the predicted lateral meteoric phase has been confirmed. In Poederlee, the top paleokarst appeared to be closed, but an open karst might be expected at a lower level.

Diagenesis in the Mol wells is completely different, as expected from their basinward position, far from a potential meteoric recharge zone. A microscopic study of cutting fragments revealed the presence of schizohaline minerals, calcite pseudomorphs, fluorite, quartz, pyrite, oil stains and bitumen. The paragenesis, together with the large burial depth of the telogenetic system suggests thermochemical sulfate reduction (TSR).

Diagenetic study of the Beerse wells shows an extensively developed karst along a fault zone with shale infills. Also here, euhedral quartz and bitumen are found. This setting is highly prospective due to excellent connectivity, but instability during drilling may be expected.

AVO analyses can be used in the future to predict prospective zones and the presence of gases.

Status of the VITO geothermal project in Mol - Donk

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In October 2023 VITO invited experts to discuss the project's status and potential future scenarios for VITO's geothermal facilities in Mol. VITO launched the development of the facilities end 2009 on the assumption that deep geothermal energy can make an important contribution to the energy transition in Flanders. To find out whether this assumption is correct, the project should provide information and data on:

- the reservoir properties and geothermal potential of the Lower Carboniferous Limestone Group, which is the main deep geothermal reservoir in Flanders (Berckmans & Vandenberghe, 1998);
- the technical and economic feasibility of deep geothermal energy in Flanders;
- the technical and non-technical challenges for the development of deep geothermal energy in Flanders and neighboring regions;
- the social and ecological potential of deep geothermal energy in the Flemish energy system.

From the start, it was VITO's intention to use the geothermal facilities to supply heat to the district heating network on the research campus of SCK.CEN - VITO, a nearby residential area, neighboring companies and potentially, new developments in Mol and Dessel.

Although the project generated important data on e.g., the Lower Carboniferous reservoir (Broothaers et al., 2021), the chemical composition and NORM-content of the formation fluid, induced seismicity (Kinscher et al., 2023), the impact of deep geothermal (Gkousis et al., 2022) and the viability of geothermal heat delivery (Van Erdeweghe et al., 2018), VITO did not yet succeed in running the plant at its design capacity. The main question about the plant's operability is the seismic activity during the extraction of geothermal heat. Since the start of the heat production, two felt earthquakes were recorded, the last one on 16 November 2022. These two seismic events resulted in a red-light situation according to the traffic light safety procedures and requested for a shut-down of the operations and an in-depth analysis of the situation.

Based on the current understanding and after consultation with multiple partners VITO identified actions to reduce this seismic risk. In November 2024, VITO's board of directors gave permission to adjust the installation and to implement a predictive traffic light protocol with a view to new production tests in winter 2024 - 2025. In addition, a 3D seismic survey is being prepared to better understand the geothermal reservoir's structure and the origin of the seismic activity.

It remains VITO's ambition to use the geothermal facilities in Mol as a demonstrator and test site to advance the uptake of geothermal in Flanders and the neighboring regions and to convert the knowledge and experiences gained into tangible value propositions for all stakeholders. Central to this ambition is stable heat production and delivery in a way that is acceptable for the stakeholders. Besides, the project should continue to contribute to the international research on removing the technical and non-technical barriers to the development of deep geothermal energy. To this end, VITO is currently investigating options for making the data accessible according to the FAIR data principles.

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Implementing geological and economic uncertainty in a techno-economic analysis of deep geothermal energy projects

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Although there is a high potential for deep geothermal energy in Europe, investment in these projects is hampered by a high upfront investment cost combined with multiple sources of uncertainty. Within the Belspo-funded Designate project, the impact of different policy measures is evaluated using a techno-economic analysis consisting of a Monte Carlo simulation model PSS (Welkenhuysen et al., 2017) that integrates both market and geological uncertainties and a project developers' option to wait or abandon the geothermal project development at different steps in the development of the project (Welkenhuysen et al., 2021). The combination of a real option analysis with two levels of Monte Carlo simulations ensures a realistic inclusion of uncertainty with managerial freedom to take decisions to e.g. cut losses. This study focusses mainly on the different uncertainties, how they can be implemented in a realistic way in the techno-economic analysis and how they influence the project profitability. Accurately modelling the balance between these uncertainties and the flexibility that can be applied will help making more realistic decision simulations.

The main uncertainties at play can be divided in two groups with distinctive properties: economic or market uncertainties such as the heat price and the electricity price (external), and geological uncertainties, such as permeability and depth of the reservoir (internal). Economic parameters can be modelled starting with a known fixed value, the current market price; the uncertainty increases when looking further into the future. This increase is only dependent on the market conditions and is not influenced by the project itself. The uncertainty is projected using an uncertainty envelope to ensure extreme values are excluded.

In reality, geological uncertainty decreases with exploration for a deep geothermal project starting. When progressing, new information becomes available. Without activity, the uncertainty remains equal or only slightly decreases due to overall geological knowledge increase.

We have developed a model for the evolution of geological uncertainty using a combination of a step function and a power law. A step function is used to represent exploration phases where a lot of knowledge is gathered in a relatively short period, such as well drilling. During the production phase the uncertainty decrease is modelled using a power law, Henderson's law. Depth, thickness and permeability of the reservoir and the geothermal gradient were selected as the main geological variables. The uncertainty of the depth and thickness is assumed to be completely resolved after completion of the second well. For the permeability and geothermal gradient, a small uncertainty remains after the second drilling, decreasing during the production phase. This uncertainty model is developed primarily for the analysis of deep geothermal projects but has potential for wider applications in the deep subsurface.

In the Designate project, threshold values for economic and geological parameters are determined together with the influence of reduced geologic uncertainty when the project progresses. Our results will help policy and decision makers taking more effective measures to boost investment in deep geothermal energy projects.

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Modelling the geometry of abandoned coal mines for inter-seasonal underground storage of heat and cold

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Wallonia (southern Belgium) experienced intense coal mining in the 19th and 20th centuries. The depths of these abandoned coal mines range from the ground surface to more than 1000 m. These abandoned mines are now being studied as potential reservoirs for inter-seasonal geothermal storage operations as part of the operation of 5th generation heating networks. In the scope of feasibility studies, a major challenge is to reconstruct the geometry of former structures and works, a preliminary but essential step in modelling flows and heat transport underground.

As these mines have been closed for a long time and are no longer accessible, this work is essentially based on archive documents such as mining maps from the former coal mines and cross-sections conserved by the mining administration. The information available in these documents is invaluable. However, this information, some of which dates back more than a century, is sometimes difficult to interpret and cannot be considered exhaustive. Moreover, it is not homogeneous and the accuracy of the topographical information varies depending on the source and the time period.

In order to reconstruct a coherent 3D model of the mine workings (galleries, panels and shafts), a geological model constrained by information from archival documents is built. Next, the elevation of panel and drift boundaries in layers is adjusted on layers derived from the geological model to preserve topological links between objects. Then, a discretized model representing areas of increased permeability around the construction sites and galleries is extracted. Finally, this model is reused to build a 3D thermo-hydrogeological model, which is used to simulate flows and heat transport in the potential geothermal reservoir, in different geothermal exploitation scenarios.

To carry out all these operations and the associated quality controls, a workflow based on developments in Python and relying on open source libraries has been developed and tested.

Five adjacent Aquifer Thermal Energy Storage (ATES) systems in Cenozoic and Palaeozoic aquifers in Brussels: numerical simulation of their possible interactions

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A first shallow open-loop system (ATES) with pumping and reinjection wells in Cenozoic mixed sandy and silty shallow formations was started in 2014 in the center of Brussels for heating and cooling an important building. A second one started in 2017, was designed with an ideal thermal energy balance of the concerned building between the heat and cold seasonal needs. However, the first simulations of the interactions between these two systems showed how the thermal imbalance of the first system was potentially affecting (i.e., warming) the aquifer in the mid- and long-term (Bulté et al., 2021) and thus also impacting the future efficiency of the second ATES system, especially in the long term if nothing was changed in the energy use of the first building.

Then, a third one, a larger ATES system was started in 2020 with 5 doublets of wells in the underlying Palaeozoic fractured phyllites and quartzites to provide heating and cooling power to a large multi-service building. Using Feflow© (as previously), the subsequent numerical simulations of the groundwater flow and heat transport in a 3D model have shown relatively small interactions between this 3rd system and the two others through the aquitard layers formed by low permeability Cretaceous base deposits and the weathered top of the bedrock (De Paoli et al., 2023).

Two additional adjacent ATES systems are projected in these Palaeozoic formations, one for a residential complex, and the other one for an office building. The model is now detailed to include these two additional ATES systems, and also calibrated to the most recent measured data (i.e. potentiometric heads, groundwater temperatures, detailed pumping, injection flow rate etc.). The first results show clearly that the sensitivity of the simulated ATES interactions depends strongly on an adequate hydrogeological characterization. Understanding better the spatial variation of hydraulic conductivity values especially in the Palaeozoic bedrock appears to be a key challenge. The model results are nevertheless very useful to guide the optimized future management of the five adjacent ATES systems to prevent losses in efficiency for some (or all) of them.

This was done with the partial support of the GEOCAMB project— Geothermal Energy potential in Cambrian rocks focusing on public buildings. Geocamb has received funding from Brain-BE 2.0 research program – BELGIAN RESEARCH ACTION THROUGH INTERDISCIPLINARY NETWORKS (2018 -2024).

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Using old coal mines for geothermal energy: underground flow and heat transfer simulations as a pre-feasibility study in Liège (Belgium)

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Groundwater pumped in abandoned coal mines can potentially be used as a renewable energy vector involving heat and cold production. Coupled with a fifth-generation heating/cooling network (5GDHC), this can provide the needed heat and cold for a low-temperature district heating/cooling system. In the Walloon Region of Belgium, three cases are currently being investigated with the financial support of the Walloon Government (through SPW Energy within the Recovery Plan) to assess the potential of a mining geothermal pilot project ('Feasibility studies in the Liège, Charleroi, and Mons basins to launch a mining geothermal pilot project'). The case located in the city of Liège is detailed here.

A study site was chosen by cross-referencing and comparing data from the surface and existing old mines. Specifically, heat and cold users/producers to be connected were identified and their current (and future) demand profiles were examined. From the hydrogeological point of view, flooded abandoned mines form highly heterogeneous aquifer compartments that are artificially and locally highly permeable around former underground works (i.e. tunnels, galleries, mined extraction zones, wells, shafts). A thermal energy storage (ATES) system is planned using an open loop with a groundwater pumping and re-injection doublet. Ideally, hot water should be pumped in the deepest parts of the open network and cold water re-injected in the shallower parts (i.e. in shallower galleries). Inversion of the system could be planned at least seasonally for example for cooling the buildings during the summer. However, optimising such a system remains a huge challenge as many uncertainties may influence the system's efficiency. The true geometry of the interconnected network made of old open galleries and shafts can be highly complex and partially unknown. Indeed, high-velocity groundwater flow and heat transport are expected in this network inducing potentially a full or partial bypass of the fractured and porous rock massif.

A model of the mine reservoir was first elaborated by digitising and conceptualising the true geometry of most of the interconnected galleries, shafts, and extracted coal panels of the flooded former mine in the fractured Westphalian formations. The mine reservoir must be described as realistically as possible to ensure the reliability and robustness of the results of the modelling of its behaviour under defined exploitation scenarios. Then, using Feflow ©, the groundwater flow coupled to heat transfer is simulated considering, step by step, an increasing complexity in the model. From a network considering just 1D and

2D elements representing old galleries and broken exploitation panels to a full 3D model including also all the heterogeneous zones of the rock massif. The simulation of short-, mid-, and long-term temperature evolution in pumping and injection zones is performed considering the temperature-dependent density and viscosity of groundwater. Those results will be crucial to assess the efficiency of the future system. At this stage, we observe a high dependence of the results on a few key system parameters including, among others, as, for example, actual hydraulic conductivity values. Accordingly, for a robust feasibility study, the priority should be to determine the hydraulic conductivity values around the future pumping and re-injection wells.

The first numerical simulations of this geothermal system show the importance of relying on modelling approaches using detailed mine data to provide predictions and sensitivity analysis allowing financial risk estimation.

This work is done with the financial support of the Walloon Government and the Energy Administration.

Geophysical investigations to evaluate the deep geothermal potential in Wallonia

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To explore the potential of geothermal energy in Wallonia, gathering primary subsurface data is essential. As part of this effort, seismic acquisition was a critical component of the DGE-ROLLOUT project (Interreg North-West Europe), which concluded in October 2023. The project's numerous new cross-border seismic lines provided significant insights into geological uncertainties, particularly in border regions (BE/DE, BE/NL). These efforts facilitated the integration of different mapping areas of the main targeted geothermal reservoir (Dinantian) and enhanced knowledge exchange on potential geothermal aquifers.

In Wallonia, the Geological Survey of Belgium (GSB) conducted 63.5 km of seismic lines in December 2022 in the eastern and western parts of Namur province. This survey aimed to investigate the extension of Dinantian limestones beneath the Midi-Eifelian Fault. The findings offered new perspectives on the geometry of the Midi-Eifelian Fault, the potential location of Dinantian limestones at depths of 4-5 km, and the presence of Givetian-Frasnian carbonates at shallower depths (2-3 km) in the Condroz area. Concurrently, the reprocessing and reinterpretation of the Dekorp 1A line indicated a high likelihood of Dinantian carbonates at suitable depths for deep geothermal energy in the Eupen region.

Encouraged by these promising results, the Walloon government has approved further geophysical investigations in 2024. The WalScan project aims to acquire approximately 400 km of seismic lines across four areas: Charleroi, Liège, Verviers/Eupen, and Wavre/Louvain-La Neuve. Coordinated by the GSB, WalScan involves experienced partners such as UMONS, ULG, and EPI Ltd, who bring extensive geophysics expertise and regional geological knowledge. Scheduled for Autumn 2025, the campaign will focus on identifying the Dinantian carbonates in the first three areas, while the London-Brabant Massif in Walloon Brabant will be investigated using a series of complementary geophysical methods.

Fault-bound AVO anomalies in Dinantian limestone of the Campine Basin

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The Dinantian (Lower Carboniferous) carbonates of the Campine Basin are of major interest for deep geothermal energy applications. One way to map their potential is by means of Amplitude Variation with Offset (AVO) analyses on seismic reflection data, which was indeed proven by Vandenberghe et al. (1986). We performed AVO analyses on a more recent 2D seismic line that runs from Beerse to Turnhout, close to the old and new geothermal wells of Merksplas and Beerse, respectively. The latter wells enabled ties with the seismic line for, among others, the Dinantian carbonates and Namurian shales. In the west of the seismic line, a major NNW-SSE oriented graben structure is present in the Carboniferous, which has its main activity during a regionally important Jurassic extensional tectonic phase. AVO analyses revealed anomalies in the upper Dinantian (Visean), mainly present within the footwall blocks of this graben structure. These anomalies indicate the presence of highly porous (colours on the attached figure), possibly gas-filled zones (red/magenta on the attached figure). Also in the nearby Merksplas well, Vandenberghe et al. (2000) found porous zones in the top of the Dinantian limestones with a high dissolved gas content (mainly CO_2) in the water. Given that the Dinantian limestones were at this time buried at minimum depths of 500 m, including a thick blanket of Namurian shales, we consider it likely that enhanced porosity in the footwalls was the result of hypogenic karst by migrating fluids along deep-seated faults. For some major Jurassic graben structures further southwest, hypogenic karstification ultimately led to roof collapse, as evidenced by major collapse structures in the upper Dinantian and superjacent strata that were identified on seismic data by Dreesen et al. (1987). Rombaut et al. (2021) inventoried the collapse structures and related them to different tectonic phases in the upper Mesozoic and lower Cenozoic. A recent modelling exercise revealed networks of cross-cutting early Dinantian, latest Dinantian to Namurian and Jurassic faults in the area (Rombaut et al., in review), which could contribute to the upwards migration of deep fluids. Indeed, the latter authors noted a prevalence of collapse structures on top of early Dinantian faults. As the ascending fluids reached the low permeability shales of the Namurian, which overlies the Dinantian carbonate aquifer, the flow deflected laterally within this aquifer, enabling dissolution.

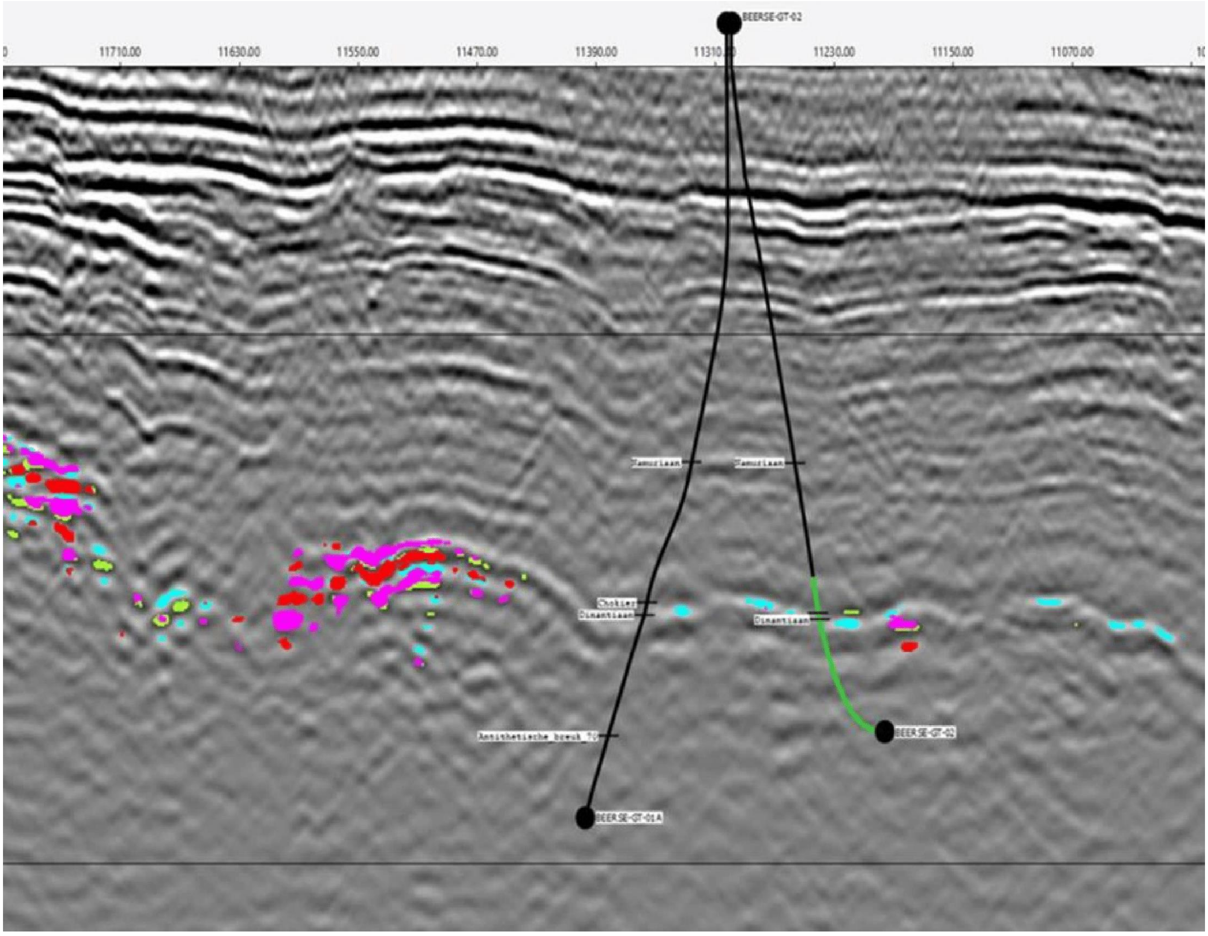
Dreesen R., Bouckaert J., Dusar M., Soille J. & Vandenberghe N. (1987) Subsurface structural analysis of the Late-Dinantian carbonate shelf at the northern flank of the Brabant Massif (Campine Basin, N.-Belgium). Toelicht. Verhand. Geologische en Mijnkaarten van België, 21, 37 p.

Rombaut, B., Deckers, J. & Dirix, K. (2021) Collapse structures on seismic in Flanders [Fact sheet]. Flemish Institute for Technological Research (VITO). https://geoera.eu/blog/collapse-structures-flanders/

Rombaut, B., Deckers, J., Dirix, K. & Van Baelen, K. (in review) Nieuwe inzichten en geologische modellen van het Dinantiaan in het Bekken van de Kempen. Studie uitgevoerd in opdracht van het Vlaams Planbureau voor Omgeving, departement Omgeving en de Vlaamse Milieumaatschappij. VITO-rapport 2024/RMA/R/2477.

Vandenberghe, N., Poggiagliolmi, E. & Watts, G. (1986) Offset-dependent seismic amplitudes from karst limestones in northern Belgium. First Break, 4 (5), 9-28.

Vandenberghe, N., Dusar, M., Boonen, P., Sun-Fan, L., Voets, R. & Bouckaert, J. (2000) The Merksplas-Beerse geothermal well (17W265) and the Dinantian reservoir. Geologica Belgica, 3, 349-367.



2D seismic line from Beerse to Turnhout with AVO anomalies within the upper Dinantian where colours indicate increased porosity (red/purple possibly associated with gas). The projection of the well tracks of the Beerse geothermal wells are indicated in black.

Unique experiments in fractured crystalline rock – GeoLaB is coming!

Ingo SASS 1* & GeoLaB Team

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GeoLaB (Geothermal Laboratory in the Crystalline Basement) is a planned Helmholtz research infrastructure. The international and interdisciplinary research platform of the Helmholtz Association focuses on the thermal-hydraulic-mechanical-chemical (THMC) processes of deep geothermal reservoirs and reservoir engineering issues. The overarching aim of the research is a safe and ecologically sustainable use of the most important geothermal resources in Germany and worldwide.

For this purpose, a generic underground geoscientific laboratory in the fractured crystalline basement of the Schwarzwald-Odenwald complex shall be built. This rock type has the greatest geothermal potential worldwide for geothermal electricity generation and heat supply and is also highly relevant for other geotechnologies.

GeoLaB is designed as a joint research infrastructure of the Helmholtz research fields "Energy" and "Earth and Environment". Only when both perspectives come together in GeoLaB can environmentally compatible technology development succeed. In this way, synergetic research combines a long-term energy supply with sustainable resource use.

Geo-techno-economic assessment of CO_2 capture, transport, and storage chain options for a cement plant in Germany

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The cement industry is responsible for around 7% of the global greenhouse gas emissions, of which 60% are process emissions released during clinker production (IEA, 2020). To decarbonize this unavoidable part of the cement-making process, CO_2 Capture and Storage (CCS) is necessary.

The LEILAC2 Project is an EU-funded H2020 project, for which a novel demonstration-scale CO_2 capture technology will be built to capture, unavoidable process emissions of the cement industry. The aim is to capture 20% of a typical cement plant's emissions and it will be installed at a Heidelberg Materials' (HM) cement plant in Germany.

The RBINS-GSB is tasked with the development of a business case for a full CCS chain, including transport and geological storage of the CO_2 captured. An evaluation of several scenarios with different option combinations for each component of the value chain is done. While the main scenario to analyse is the demo-scale capture, the full-scale and CO_2-network integration will be considered as well. Possible transport options are truck, railway, barge, ship and pipeline. Concerning geological storage, attention is given to possible connections with ongoing and planned initiatives for CO_2 infrastructure such as Aramis project (The Netherlands) and Northern Lights project (Norway) as well as potential storage options in the German North Sea.

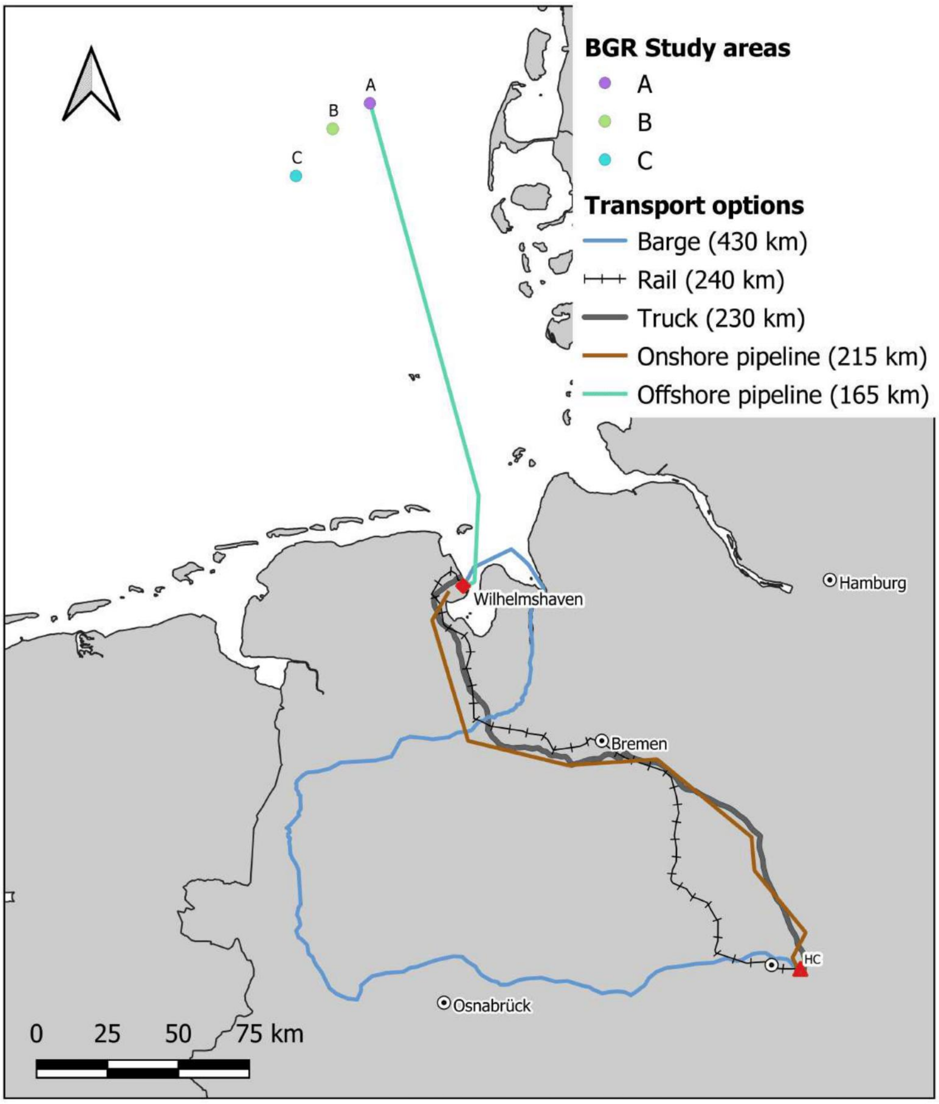
One of the main intricacies of techno-economic calculations is the handling of uncertainties. An important driver of CCS development is the geological uncertainty of potential CO_2 reservoirs, along with their properties, capacities and suitability for storage. Using a simulation tool developed in-house called PSS, geological uncertainties will be incorporated in the techno-economic calculations, playing an important part of the business case preparation. The PSS suite of geo-techno-economic simulators was specifically created to forecast the deployment of CCS technologies (Welkenhuysen et al., 2013).

A preliminary assessment was done for the demo-scale, full-scale and CO_2-hub value chains with the storage site in the German North Sea (see figure). Results indicate that the least costly route and transport modes are by railway followed by an offshore pipeline with a total cost of over €160/t CO_2 (excluding capture cost). Economies of scale start to take effect once an upscaled scenario of around 1Mt/y is considered. With this scenario the cost of CO_2 is cut by more than half, ranging between €60-70/t CO_2. When assessing a CO_2-hub scenario (>5Mt/y), the cost is further reduced to €50-60/t CO_2. However, as the volume of CO_2 captured increases, the major cost shifts to the conditioning of CO_2 instead of transport.

The coming steps include a more in-depth assessment of the scenarios described but for another HM' cement plant in Ennigerloh, Germany. This will be done with PSS, where investment decisions for the full CCS chain are simulated as a forecast while considering uncertainty and flexibility. Results will provide insight in the probability of preferred storage option development for steering exploration and development efforts, preferred transport modes and routes, the optimal timing of investments, and the influence of market parameters, such as the ETS price of CO_2 emissions.

IEA (2020) Energy Technology Perspectives 2020. https://www.iea.org/reports/energy-technology-perspectives-2020

Welkenhuysen, K., Ramírez, A., Swennen, R. & Piessens, K. (2013) Strategy for ranking potential CO_2 storage reservoirs: A case study for Belgium. International Journal of Greenhouse Gas Control, 17, 431-449. http://dx.doi.org/10.1016/j.ijggc.2013.05.025



Possible transport modes and routes from the HM' cement plant in Hannover, Germany to one of the potential storage sites in the German North Sea. Offshore storage sites were proposed by the Federal Institute for Geosciences and Natural Resources

Pumping tests and hydrogeological characteristics of the Cambrian aquifer in the Belgian Brabant provinces for geothermal potential

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Hydrogeological parameters of the Palaeozoic and overlying Paleogene-Neogene aquifers in the Flemish and Wallonian provinces of Brabant and Brussels Region are characterised to evaluate the geothermal potential of the Cambrian bedrock. Hydrogeological parameters are crucial in geothermal resource exploration, development, and management. Characterising them is also crucial in groundwater exploration and management. Thus, in this study, new pumping tests at different locations and calculations of specific well capacity from old well reports in the western part of Flemish Brabant region have been performed. Time series piezometry data of monitoring wells from the VMM network in Flemish Brabant were interpreted. Special attention was given to observation wells with screens in both the Palaeozoic basement and the overlying Paleogene-Neogene layers like the Landenian and Brusselian aquifers. Analytical models to check the fractional dimension of the groundwater flow (radial vs non-radial) have been applied before choosing a solution to interpret pumping test data. The specific well capacity (SWC) for 82 wells is estimated from drawdown data found in the old report archives. SWC ranging from 0.51 m^2/d to 248 m^2/d and with a mean of 7.41 m^2/d is observed, showing the high heterogeneous nature of the Cambrian aquifer in the region. The groundwater hydraulic head increases from the north to the south of the Flemish Brabant region due to the overexploitation effect in the north. Geophysical well logging was performed on 6 wells at Paul Henri Spaak building and Anderlecht Urbanités sites (3 wells at each site) to better understand the aquifer structure and properties. Fractured zones and weathered materials are identified and mapped from the interpretation of these log data. Existing pumping test results were compiled or test data were interpreted at several wells of Cambrian aquifers in the Brussels Region. Also, a step drawdown test and a geophysical well logging were performed at the Molenbeek case study well and pumping test data were interpreted with the method of Eden-Hazel, and, for the first pumping phase, also with the analytical solution of Barker (1988) using the concept of fractional flow dimension, based on which a software tool for the interpretation of pumping tests was developed for this study. More or less similar transmissivity values have been obtained, 15.51 m^2/d and 16.87 m^2/d, respectively by the former and the latter methods. In general, in all these new case studies and old data interpretation, the Cambrian formation is revealed to have highly heterogeneous properties and thus, variable and unpredictable geothermal potential.

Keywords: Cambrian; Brabant; pumping test; hydrogeological parameters; specific capacity; geophysical logging; aquifer

The subsurface hydrogen storage potential in Belgium

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In Europe's transition towards a sustainable and carbon-lean society, hydrogen has the potential to play a major role as energy carrier. There are several opportunities for hydrogen to replace or complement components for a more sustainable energy system. Hydrogen has a relatively high energy density, making it suitable for transport applications. So-called "green" hydrogen can be produced using electrolysis with renewable electricity. As-such, it can level out peaks in production demand. Seasonal fluctuations in energy demand can be tackled in a similar way as today's natural gas supply: using geological storage.

Following recent interest, as part of the EU H2020-funded HyStorIES project (HyStorIES, 2024) an EU-wide mapping of geological storage opportunities for hydrogen was created (consultable via BGS, 2024). Considering its expertise in mapping CO_2-storage opportunities, this task was completed by the CO_2GeoNet association. As one of its members, the RBINS-Geological Survey of Belgium delivered data for Belgium and Luxembourg.

Storage opportunities are categorized in three levels of knowledge and detail (from low to high): formation, storage unit, and trap or reservoir. Other boundary conditions include the reservoir type (aquifers and depleted oil or gas fields), depth (>500 m, but no hard limit), and the (potential) presence of sealing layers for containment.

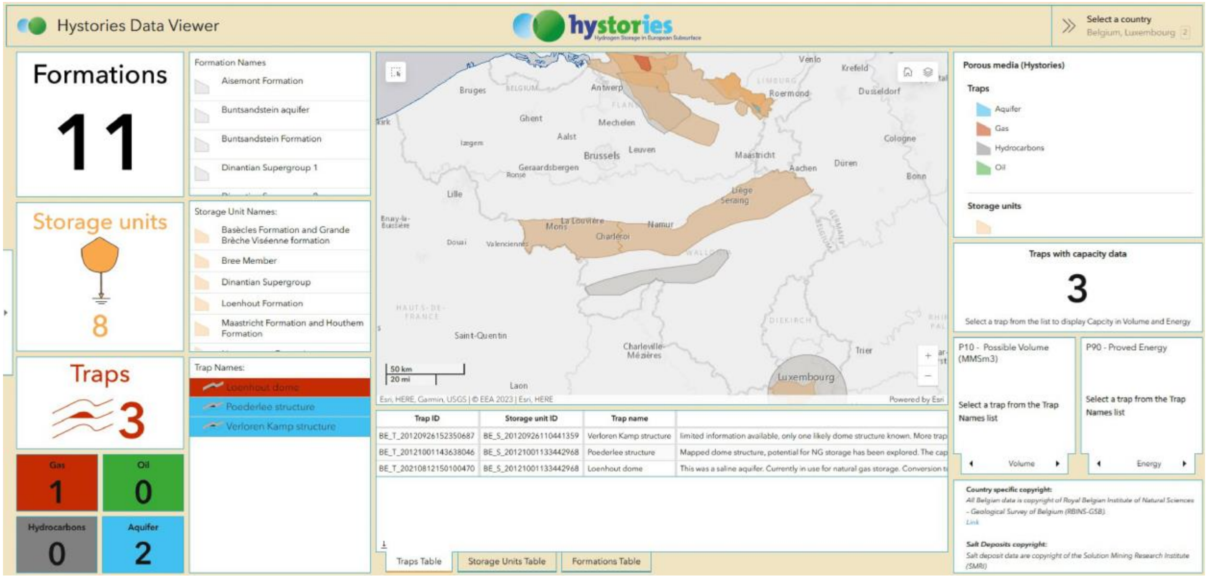
For Belgium, nine storage "formations" were mapped: the Devonian Aisemont Formation in the Campine Basin; the Givetian group and Frasnian group in the Dinant Synclinorium; the Dinantian Loenhout Formation in the Campine Basin; the Dinantian Basècles Formation and Grande Brèche Viséenne formation in the Mons Basin; the Dinantian supergroup in the Namur parautochtonous; the Neeroeteren Formation in the Campine Basin; the Neeroeteren Formation in the Roer Valley Graben; the Triassic Buntsandstein Formation in the Campine Basin; the Maastricht Formation and Houthem Formation in the Campine Basin.

For Luxembourg, two storage "formations" could be mapped: the Vogesensandstein Formation and Voltziensandstein Formation of the Buntsandstein; and the Rotliegend strata.

For a few of these formations, it was possible to define storage units or even traps. In some cases assumptions were made on the presence of the reservoir and sealing layers. This work presents the first mapping of geological storage opportunities for hydrogen in Belgium.

In the framework of the Geological Service for Europe (GSEU) EU Coordination and Support Action, the compiled HyStorIES database will be updated and extended with other EU countries for a further harmonization at EU level.

HyStorIES (2024) Hydrogen Storage in European Subsurface. https://hystories.eu BGS, 2024. Hystories Data Viewer. https://bgs.maps.arcgis.com/apps/dashboards/630ec7b3cbd54e39b4111e397315ae99



Screencapture of the HyStorIES data viewer, an interactive webGIS for the subsurface hydrogen storage potential in the EU, zoomed to Belgium and Luxembourg (BGS, 2024).

SESSION 13 - SUBSURFACE MANAGEMENT: METHODS, TOOLS AND INTERACTIONS

Conveners

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Koen Beerten, Belgian Nuclear Research Centre SCK•CEN, Mol (koen.beerten@sckcen.be)

In recent decades, the subsurface is gradually getting renewed attention as a key solutions for a variety of topics, such as, shallow and deep (mine water) geothermal projects, groundwater, different types of energy and gas storage, raw material extraction, or radioactive waste disposal. It is clear that subsurface planning is increasingly needed to combine the growing number of activities, avoiding adverse interactions, and optimizing the use of the subsurface. This session deals with the development of methods and tools, and with the subsequent application of these to study the (mutual) impact of subsurface activities on the short (years) and longer term (thousands of years). In its most basic form, a tool can be a geological model applied to assessing subsurface activities and planning, or a screening methodology to assess the vulnerability of a certain activity or project. We welcome contributions that demonstrate advancing insight into the geometry, structure and processes of the subsurface, as well as case studies in which subsurface management, interactions between activities, or policy and regulation play a central role.

Tectonics and Deformations of the Kortrijk Clay Formation in the Princess Elisabeth Zone, Belgian Continental Shelf

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A thorough investigation of the subsurface structure is required for planning and risk assessment of the future wind energy developments in the Princess Elisabeth Zone (PEZ) on the Belgian Continental Shelf. The PEZ is underlain by the Kortrijk Clay Formation, of Eocene age, which is characterised by the presence of a dense and complex intraformational fault system (i.e., clay tectonics; Henriet et al., 1988). A detailed understanding of the fault properties (e.g., geometry, orientation, displacement, distribution) is essential for project planning but this remains insufficiently understood. Gaining insights into this fault system would also provide important clues on its origin and on the processes that have led to the deformation of this formation and the broader Belgian Continental Shelf.

We use ultra-high-resolution seismic reflection surveys with dense grid spacing to investigate the subsurface structures in four carefully selected study areas within the PEZ (Block A, B, C, and D), as part of the Clay Tectonics project. Detailed mapping reveals distinct variations and structural styles featured in these blocks, despite their proximity (~10 km apart). Block A features densely spaced faults (30 to 160 m spacing), with a predominant orientation of N75°E-N85°E, a minimum fault length of 0.5 km, an apparent dip from 38° to 45°, and a displacement of up to 3.3 m. Block B exhibits wider spaced faults (90-580 m spacing), oriented N355°E-N25°E, with a larger fault length (at least 1.1 km), a shallower apparent dip (25°-28°), and a larger displacement (up to 5 m). Block B also features folding structures, comprising a syncline and anticline with fold axes parallel to the fault orientation. The properties of the fault system in Block C are generally similar to those of Block B but with denser fault spacing (90-280 m). Block C also features folding structures, although these folds are oriented obliquely (~N130°) to the faults (N355°E to N10°E). Additionally, Block C also includes a major fault with considerable displacement, up to 16 m. Significant changes in structural styles from Block A to C will be further investigated using more recently acquired data from Block D, where these changes are likely located.

The preferred orientations of the faults suggest the possible influence of far-field tectonic stresses, in contrast to the commonly accepted deformation model for clay tectonics, which are interpreted as diagenetic-related polygonal fault systems. The alignment between fold axes and fault orientation in Block B also indicates possible control of pre-existing structures in fault distribution. However, this control appears limited, as evidenced by the obliquity between fold axes and fault orientations in Block C. Accordingly, further investigation into the deeper structure under the clay formation and the basement is necessary to understand the main parameters in controlling the fault system. Moreover, the variability of structural styles observed in the PEZ underscores the importance of detailed subsurface investigation prior to wind farm development. Therefore, investigating the fault distributions, properties, and the controlling process in their development is crucial for quantifying the risk associated with wind farm construction in the PEZ.

Henriet JP, de Batist M, Vaerenbergh W, Verschuren M (1988) Seismic facies and clay tectonic features of the Ypresian clay in the southern North Sea. Bulletin van de Belgische Vereniging voor Geologie 97: 457-472.

Sustainability impact assessment of deep subsurface use in Flanders

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Given the urgent need to reduce greenhouse gas emissions to combat climate change, and an increasing demand for energy security, it is imperative for society to make an equitable transition to a carbon-neutral and circular economy. The deep subsurface plays an important role in this process. As part of a government assignment, the sustainability aspects of the use of the deep subsurface in Flanders were mapped.

Together with stakeholders with an interest in deep subsurface activities in Flanders, the principles, criteria and indicators for sustainable use of the subsurface were identified. To calculate the sustainability effects of deep subsurface use, detailed activity models are coupled with a regional reservoir model to simulate the regional effect of local subsurface activities. These detailed subsurface models are also coupled with the PSS V simulator to calculate for different policy scenarios the probability of a subsurface project becoming active, as well as its techno-economic feasibility (Welkenhuysen et al., 2024). Using these results, the social and environmental impacts of activated projects are also assessed.

Although not all sustainability indicators could be evaluated, we find that even under a zero-policy scenario, a significant part of the subsurface potential is used between 2025 and 2050, especially geothermal projects, resulting in environmental benefits. Policies that encourage subsurface use by supporting geothermal energy production and associated lithium mining result in higher economic benefits compared to a zero-policy scenario. However, the more subsurface projects become active, the more likely it becomes that these activities will interfere. This is evidenced by the increased changes in hydraulic head from regional pressure modelling (see also Rodriguez et al., 2024). While these incentive policies score relatively well on the sustainability principle of efficient allocation, they score less well on the sustainability principle of ‘resource conservation’. In contrast, policies that prevent extraction projects in areas that could be used for the storage of natural gas, hydrogen or CO_2 score well on the principle of 'resource conservation'. Furthermore, relatively more projects that become active under this policy scenario, are also socially justifiable.

Rodriguez, J., Piessens, K., Welkenhuysen, K., this volume. Building a regional telescoped model of the Campine Basin for subsurface management. Geologica Belgica Meeting 2024. Welkenhuysen, K., Meyvis, B., Rodriguez, J. & Piessens, K., this volume. PSS V, a modular techno-economic simulation tool for deep subsurface uses. Geologica Belgica Meeting 2024.

The Geotheek: the Flanders repository for soil and subsurface reference samples

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Geological and soil samples, collected in research and drilling campaigns or in (temporary) excavations inform us directly about the nature and structure of the (sub)soil. In order to valorise these samples as a base for sustainable subsurface management, the Department manages the 'Geotheek' since the end of 2018. It is the Flemish storage facility for subsoil and soil samples of reference value, and part of the Flanders Repository site in Vilvoorde. The depot management is linked to the online Soil and Subsoil Database Flanders (Databank Ondergrond Vlaanderen, DOV). The samples are stored for the long term in appropriate conditions. They are a valuable source for further (scientific) research by the government or third parties and they have an educational value. Currently there is no general legal obligation to preserve geological samples. They originate from: the Department's own research; mandatory storage under the environmental permit; outsourced or external projects; partial return from the federal repository; networking and collaboration with experts and drilling companies. Additionally, there is a collaboration with the partners within the government and the drinking water companies. The soil samples in the Geotheek originate from the Department's own soil research projects. Today, the Geotheek houses geological samples from the shallow and deep subsurface from more than 500 locations in Flanders, together accounting for several thousands of individual samples, mainly loose sediments from drillings and temporary outcrops, but also cored sediment and hard rock.

Focus is on high-quality, well-documented and examined samples to continuously complete the Geotheek reference collection. Geological descriptions, lithostratigraphical interpretations and microscope analyses of the samples are done in house and in collaboration with external experts. Samples are further analysed to support more qualitative geological 3D models in the future. A GIS-tool supports the evaluation of the intake of samples. The tool is based on the Geotheek database, geological data and information from the 'Geological Passport' (Verhaegen and De Nil, 2024) and DOV, and a supporting stratigraphy database. This latter relates the collection to the geological type sections and key stratigraphical locations, and defines preferred areas for sample collection. The geologists from the VITO-team, included in the reference task for the Flanders government (Vlaams Kenniscentrum Ondergrond, VLAKO), are partner for this knowledge development.

The Geotheek is an above-ground reference treasury of the Flanders (sub)soil. Knowledge of the soil and deeper subsurface is crucial to tackle our social challenges. Therefore, the repository, along with the network of experts, provides material, an expert network and knowledge for the soil and subsurface research projects, necessary to support the climate, energy, spatial and natural and mineral resources policy.

Verhaegen, J, De Nil, K (2024). A geological passport of the Flemish subsurface. Geologica Belgica Meeting 2024, Liège (this volume)

Modelling anthropogenic deposits in 3D geological models

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While geological models traditionally focus on the natural status of the underground, the shallow subsurface has been significantly altered by human activities over centuries. Particularly in urban contexts, ground has been raised, reworked, filled-in or disturbed in other ways. The rationale behind these alterations is as varied as the characteristics of the associated anthropogenic deposits: large-scale structures such as residential and industrial areas built on extensive sheets of filling materials or reclaimed lands are intertwined with smaller-scale features related, for example, to road and railway infrastructures, dikes or landfills. Their composition is equally diverse, ranging from displaced natural materials, such as crushed rocks, gravel, sand or clay, to artificial substances like recycled steel slags, concrete or rubble, or mixtures of these. Gaining knowledge on the presence and characteristics of such deposits is highly relevant, as their physical and chemical behaviour may differ significantly from those of natural deposits.

The significance of anthropogenic deposits is increasingly recognized in urban geology. Resolving the geometry and properties of the urban shallow subsurface is essential for anticipating associated risks, for example dealing with pollution, ground stability or distorted water infiltration patterns. Anthropogenic deposits are, however, often scantily archived in permit documentation or represented on (geological) maps. Within the GSEU (Geological Service for Europe) project, the GSB is contributing to the task to develop a common, international vocabulary to describe all aspects of anthropogenic deposits, allowing standardised representation and characterisation in geological models.

In parallel, VITO is developing shallow subsurface urban models for the Flemish government (VPO) within the VLAKO-framework, such as the published model of the Antwerp harbour and city. As the anthropogene inherently is part of these models, we are always aiming to better incorporate these deposits into the models. However, modelling the anthropogene presents unique challenges due to its high-resolution variability, scarcity of input data, and dynamic nature. It requires an approach that differs radically from traditional geological modelling techniques, in which depositional concepts related to the sedimentational or structural environment can be incorporated.

In this presentation we will outline how we integrate various 1D, 2D and 3D sources to identify and characterize anthropogenic deposits and incorporate these insights in a 3D geological model of the anthropogene. This methodology is applied to the urban periphery of Brussels, where a new 3D geological model is being developed to support infrastructure projects and urban planning with special focus on the ring road (R0) of Brussels. Secondly, we will evaluate current lithological standards, vocabulary and stratigraphic approaches to characterize anthropogenic deposits. We will discuss their applicability in Flanders with practical examples from the periphery of Brussels.

Ultimately, improving the representation of the anthropogene in geological models will significantly enhance their utility for urban planning, environmental management, and the sustainable utilization of the subsurface in urban areas.

Introducing the concept of sustainable scale to support the long-term use and management of geosystem services

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Increased exploitation of the subsurface requires proactive management that focuses on balancing resource utilization and long-term conservation of the various subsurface functions. Similar to ecosystem services, the term geosystem services is used to account for the plurality of services derived from the subsurface. Unlike ecosystem services, geosystem services are often overlooked and undervalued. Although the importance of these services and the need to manage them is increasingly being acknowledged, the current literature lacks a comprehensive discussion on the sustainable management of geosystem services. The objective of this paper is to systematically review the existing approaches for the management of geosystem services in literature and to propose a conceptual basis for the sustainable management of these services. The findings of the systematic literature review revealed: (1) multiple interpretations of geodiversity and geosystem services that do not fully capture the role of subsurface in delivering services, (2) under-representation of the role of geosystem functions in the delivery of geosystem services and (3) absence of operational principles that can guide decision making for sustainable management of geosystem services. To establish a conceptual scheme for the sustainable management of the geosystem services, we take an ecological economics approach. Central to the proposed conceptual scheme is to define the sustainable scale of subsurface utilization by connecting the subsurface characteristics (such as the replenishment rate) and the nature of benefits (economic, environmental, and social). We argue for an ecological economics approach that is informed by the sustainable development principles as put forward by Daly (1990). The goal is to maintain the resource rather than optimizing the economic viability of non-renewable resource extraction. We conclude with an objective understanding of what a sustainable scale for managing geosystem services involves by drawing upon insights from examples based on their geological limits, regenerative capacities and pace of exploitation.

Daly, H. E. (1990). Toward some operational principles of sustainable development. Ecological economics, 2(1), 1-6.

A vision for a responsible management of the deep subsurface in Flanders

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The deep subsurface nowadays gains a renewed interest for exploration and use for several applications. The challenges we deal with are wide: the need for green energy sources and security of supply, for reducing greenhouse gases, for critical raw materials, for strategic reserves of drinking water, among others. The subsurface can play a role in each of those and be part of sustainable solutions.

The potential for several activities in the deep subsurface (considering a depth larger than 500m TAW) is not equally distributed across Flanders, being dependent on the local geology. For most applications that need good reservoir characteristics, the potential is mainly present in the Campine Basin. But even there, not all geological layers and not all zones within a certain layer qualify for all applications. Useful “plays” are to be explored in an often heterogeneous geology. The best reservoir zones are limited in space, resulting in competition of subsurface targets for several potential applications.

Without a framework or vision for subsurface management, an arbitrary use and a waste of potential could result due to inefficient and scattered subsurface developments. The Flemish geology forces us to be even more efficient when it comes to subsurface management than larger countries, especially those that have more reservoir rocks.

Flanders has anchored the adoption of a structural vision for the deep subsurface in the deep subsurface decree. In the first place, this policy instrument that will be adopted by the Flemish Government should provide an overview of the relevant (theoretical) potential of all kinds of subsurface applications with their geographical distribution, determine the boundary conditions of such developments, and propose an assessment framework that gives a sound base for decision making. It is not legally binding, nor a subsurface registry that presents a plan with developments to be realized. Rather, it is meant to give insight into the subsurface opportunities and challenges and into the consequences of decisions in advance. Concrete projects will still need to apply for permits according to the legal requirements, but the evaluation of some criteria, such as efficient / sustainable use of the subsurface or interference with neighboring projects will be evaluated in view of the overall vision.

Being a region with limited useful subsurface volume and many future challenges, Flanders needs to focus on multiple and flexible valorization, efficient subsurface planning, protection of strategic reserves and functions, to allow present and future generations to answer their subsurface needs.

A vision document is in preparation and foresees already in the legal context for subsurface use, the geological potential, an overview of active permits, an inventory of theoretical applications with their boundary conditions, an overview of time and spatial aspects and provisional bibliography. Many flanking research (focusing on the 3D geometry of the deep layers, on the potential for geothermal and storage, on regional heat flux and on seismicity) has been carried out already to substantiate this draft document. Current research focuses on the development of an assessment framework for decision making in subsurface management.

Sensitivity study of parameters influencing benzene mobility in coal-waste dumps: implication for health risk assessment and for remediation work in Wallonia (Belgium)

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The benzene content commonly measured in the solid part of coal waste dumps (CWD) often exceeds the threshold permitted for residential use under the Soil Management Decree. The presence of benzene in CWD is therefore often considered incompatible with residential development projects. This potential incompatibility is determined under the Soil Management Decree by means of a risk assessment, without taking into account the specific nature of these CWDs and their residual coal content.

A total of 15 CWDs spread over the 4 major Belgian catchment areas were investigated: 6 CWDs showed exceedances of the SV of the Soil Decree for residential use for benzene. The maximum concentrations of benzene in the ambient air were observed in the vicinity of a burning CWD. Field observations and the results obtained confirm that the benzene measured in the solid part of the CWD is trapped, mainly in the deformed micropores of the coal, and that desorption is only possible when the coal is heated to higher temperatures. In addition, it appears that the benzene released in the combustion zones studied is not related to the benzene exceedance observed in the soil and would come from the pyrolysis of organic matter in the anoxic conditions inside the CWDs.

The risk assessment model used in the Soil Decree, which considers reversible sorption/desorption with an empirical Koc determined on natural soils, therefore incorrectly predicts the mobility of benzene trapped in coal. Taking this into account in risk management could reduce the cost of investigation and remediation in the event of a CWD occurrence.

Stakeholder Perspectives on the Sustainable Management of the Subsurface in Flanders

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The subsurface has been recognized as a multifunctional resource that can host a variety of activities, ranging from the extraction of resources to the provision of sink capacity. The increasingly stringent climate objectives and the quest for (more) energy security, have sparked the interest in the use of the subsurface. With potential uses spanning from geothermal energy to the storage of CO_2, the subsurface could indeed be an important ally in achieving climate goals and supporting the energy transition.

While the range of potential uses of the subsurface is diverse, the available space to exploit these activities can be scarce, particularly in densely populated areas. In the region of Flanders, for example, the range of suitable locations for exploitation is limited, resulting in competition between different actors who want to perform activities in the subsurface. The limited number of suitable locations and the finiteness of resources make it essential that the space and the resources in the subsurface are used as efficiently and sustainably as possible. Policymakers are thus confronted with the challenge of governing the multifunctional use of the subsurface while recognizing the finiteness and scarcity of the subsurface as a natural resource. With a few exceptions, such as the Netherlands, most countries today lack a clear vision for the sustainable management of the subsurface. To develop such a vision, that is informed and supported by stakeholders, it is essential to consider the interests and perspectives of these stakeholders.

Therefore, this paper aims to identify stakeholders' perspectives on the multifunctional use of the subsurface, and how it can or should be managed sustainably. Taking a regional perspective, this study performs a stakeholder mapping for the subsurface in Flanders. In-depth interviews are performed with stakeholders from the public and private sectors.

In the first part of the interview, the aim is to understand the role and position of the stakeholders concerning the subsurface in Flanders. The second part of the interview is subdivided into five themes: activities in the subsurface, data management, the network of the stakeholders, policy, and sustainable management. Questions raised during the second part of the interview are aimed at identifying the present activities in the subsurface in Flanders, prioritizing activities depending on needs to be fulfilled in society, understanding the data needs and accessibility to data on the subsurface for the different stakeholders, mapping the stakeholder's network, and determining what stakeholders expect from a policy framework for sustainable subsurface management.

The results of the stakeholder mapping contribute to the development of a vision for the sustainable management of the subsurface in Flanders, which should recognize the finiteness and scarcity of the subsurface, and help prioritise critical activities for societal needs. The insights of this study are also applicable to other regions or countries, with limited subsurface space and a current lack of a clear policy framework.

METHAMINE - Refinement of the greenhouse gas (GHG) emissions balance in the Walloon Region for a better estimation of methane emissions from abandoned mines

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Climate change due to greenhouse gas (GHG) emissions has become a major environmental concern. Since 2018, GHG emissions at abandoned mines in Wallonia are included in the GHG reporting work for various international commitments (e.g. The Kyoto Protocol, the United Nations Framework Convention on Climate Change, ...).

The METHAMINE project aims to carry out a hazard study on the potential for methane emissions from former mining operations leading to the surface. This gas, which has a very high warming potential, is poorly documented in Wallonia regarding its emission from ancient mine fields. Methane migration from old mines through the surface can take the form of flow, gas transport by water and diffusion (Fig. 1). As methane slowly desorbs from coal and surrounding rock, it can migrate to the surface as a result of the pressure difference between the mining reservoir and the atmosphere. In the presence of water, the dissolved gas will be transported by the water and released into the air at emergence points. Lastly, diffusion is a very slow phenomenon, triggered by a concentration gradient between the underground environment and the surface. In this study, only flow migration will be investigated.

This project will enable us to expand the emissions database and draw up recommendations for reducing emissions on our territory. In order to build a regional model, a hazard mapping approach at local scale will be engaged first. The mapping of the methane gas emission hazard will be based on two parameters: (1) the intensity, which will be deduced on the basis of data on volumes extracted, firedamp class, mine water level, density of mined veins, etc. and (2) the predisposition to risk, which depends on the characteristics of the upper geological formations (thickness, permeability, damage), as well as on the presence of exposed structures (mine shafts, boreholes, access galleries, ...) and geologic permeability ways (faults, karstic features,...).

In situ data are also collected, to sustain the regional emission model. Surface gas concentration and flow measurements are compiled, in various meteorological conditions (wind, atmospheric pressure, temperature,...). The field surveys focus on potential emission zones, selected across Wallonia, related to former mines with historical firedamp class equal to 2 or 3 (3 being the maximum value for which explosive outbursts have occurred). A few former mines identified as "gas-free" have also been selected for blank measurements.

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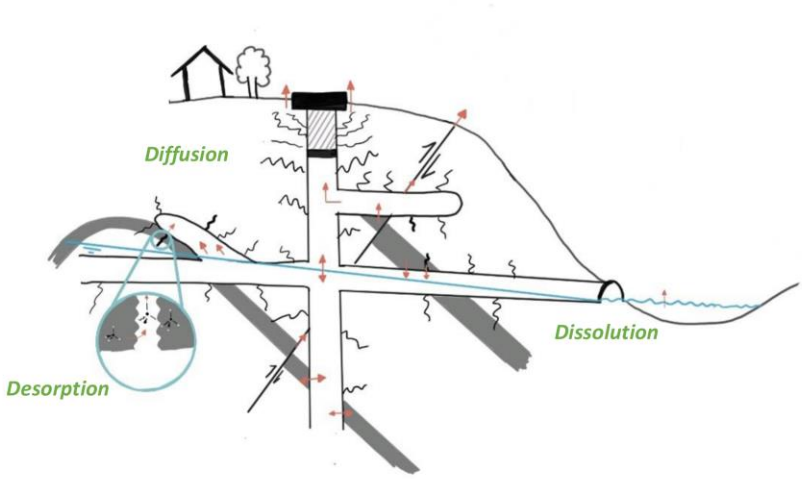

Fig.1 Various forms of underground mine gas migration that may be responsible for its emission to the surface

Optimizing mine water drainage management in Wallonia: Challenges and prospects in a context of climate change

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In the context of climate change, the pressure on water resources is leading to the exploration of alternatives to meet growing demand. Mine drainage water, hitherto neglected, is emerging as a potential solution, despite the challenges associated with its quality and variability (Seidl et al., 2019). In Wallonia, the increased frequency of drought episodes requires water management strategies to be adapted (Thibaut and Ozer, 2021).

This study presents quantitative and qualitative results based on the data available to us. The aim here is to assess the potential for recovery of mine drainage water in the Wandre-Cheratte region, using residual voids as an indicator of the potential volume of mine drainage water available, estimated by the ISSeP at 3.85×10^6 m^3 (Gardin et al., 2005). We based our analysis on hydrological data from the ISSeP piezometer network and on annual rainfall data over a reference period from 1991 to 2020 (data from the municipality of Visé according to the IRM). We also carried out physico-chemical analyses to assess their potability. The results of these analyses show sulphate concentrations averaging between 168-194 mg/L, with an average electrical conductivity of 1137 µS/cm.

Keywords : Drainage, Climate changes, Wandre-Cheratte, Alternative resources, Potability.

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Geomechanical modeling of the recent post-industrial uplift in Brussels and comparison with geodetic InSAR measurements

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Radar interferometry (InSAR) measurements have provided recent evidence of ground movements, particularly a slight uplift in north-western areas near the center of Brussels in response to changes in groundwater pumping and drainage linked to decreased industrial activities within the city.

Historical potentiometric head changes between 1970 and 2020 are translated in water pressures transmitted to 1D vertical models coupling the vertical flow (and subsequent water pressure variations) with geomechanical swelling/consolidation calculations. The discretization of the 1D model is refined in the most compressible layers to obtain an accurate transient propagation of the water pressure changes and thus a better estimation of the swelling/consolidation values. The total uplift (or subsidence) is compared to the estimations obtained from the InSAR data processing.

A detailed interpretation of such a comparison is not straightforward. Many factors and uncertainties can also play an important role in the estimated values from the processing of the InSAR measurements, as in the calculated values from the coupled hydrogeological-geotechnical models.

We acknowledge the support of the LASUGEO project—monitoring LAnd SUbsidence caused by Groundwater exploitation through gEOdetic measurements - LASUGEO has received funding from Brain-BE 2.0 research program – BELGIAN RESEARCH ACTION THROUGH INTERDISCIPLINARY NETWORKS (2018 -2024).

Building a regional telescoped model of the Campine Basin for subsurface management

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Effective subsurface management is crucial for optimizing subsurface activities, particularly in the context of transitioning to sustainable energy and resource management. As the demand for raw materials, cleaner energy sources and secure storage solutions increases, innovative approaches like telescoped reservoir modeling are becoming important. This methodology aims to introduce a new way for managing complex subsurface interactions by using modular simulations adapted to each specific activity. These individual simulations are then integrated into a regional model, making it easier to identify and address interferences, especially through analyzing pressure changes in groundwater and deeper reservoir systems.

This methodology enhances flexibility in spatio-temporal analysis for managing subsurface activities on a regional scale. Having the possibility of using independent simulation of each activity, it becomes feasible to use a variety of modeling software, methods or data. This flexibility further facilitates continuous updates and refinements of individual modelling modules without needing to completely redesign and rebuild the entire regional model. As a result, the traditionally complex and resource-intensive supermodel is replaced by a more adaptable and efficient telescoped modeling framework.

The Campine Basin in Belgium provides an excellent case study for this method. This region has the potential for multiple underground activities such as gas storage, hydrogen storage, CO_2 storage, nuclear waste disposal, and geothermal systems, extraction of raw materials, and others in a limited space, making it ideal for testing to which degree telescoped reservoir modeling allow integrating such a variation of activities into a regional model. Through ad hoc simulations of each activity, the method integrates activity-specific datasets into a cohesive regional model, facilitating the analysis of interactions and interferences between these activities.

The study highlights several key benefits of the telescoped reservoir modeling approach. Firstly, it conceptualizes the subsurface activities to be managed by breaking them down into manageable modules. This modularity can be used to reduce computational demands, or alternatively to improve the precision of simulations by enabling the use of specialized modeling techniques tailored to an activity. Secondly, the method's flexibility ensures that the regional model can evolve with the inclusion of new data, improved models or new simulation techniques, or the addition of new activity models. In that way the relevance and accuracy of the regional model is maintained over time. In certain cases, it allows to make predictions with extended time horizons or cope with a larger diversity of scenarios. The telescoped approach can be used as a framework for regulatory compliance and risk assessment, because the framework is able to show the interactions between various underground projects, allowing to predict the probability on potential conflicts and environmental impacts, and as such mitigate them.

By offering a more flexible and efficient way to integrate diverse simulation inputs into a unified regional model, it paves the way for improved optimization and management of subsurface activities. The positive application in the Campine Basin showcases its potential for wider adoption, promising enhanced management of subsurface resources essential for a sustainable future.

Developing a qualitative model of subsurface activities in the Belgian Campine basin using stakeholder input and a multi-method qualitative approach

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The effects of climate change are becoming more visible year by year. To mitigate this threat, governmental interventions usually focus on above-ground solutions, while the potential of the subsurface is mostly looked over. Seasonal gas storage, generation of energy both in the form of heat and electricity, carbon capture and storage are just some examples of the possible activities that can aid in achieving climate goals put forward by the European Union. Current ad-hoc planning of subsurface activities could lead to suboptimal and counterproductive decisions due to possible interferences between activities happening concurrently and with regards to intergenerational welfare. As the use of subsurface space and resources is expected to increase, the need for an overarching policy strategy increases. A crucial knowledge gap in discussing and designing such a strategy is linking geological dynamics with social, economic and environmental systems at local and regional levels.

In this context, this study aims to create a qualitative framework of subsurface systems as a starting point for building a quantitative model to evaluate policy scenarios. To capture all the key characteristics of the subsurface system, the participation of relevant stakeholders is key. Representatives from each stakeholder role as defined during the stakeholder analysis are included in this study. Bringing together people with very diverse backgrounds, requires an intuitive and visual tool to streamline the discussions. Therefore, the concept of creating causal loop diagrams (CLD) in a collaborative way with stakeholders was selected. This method has a number of strengths: it increases understanding of the studied system by the stakeholders (Coletta et al., 2024; Inam et al., 2015; Perrone et al., 2020), highlights the system boundaries perception of different stakeholders and in what ways they differ amongst stakeholders (Pluchinotta et al., 2022), it improves decision making outcomes by policy makers (Perrone et al., 2020), and policies developed using the outputs of the collaborative model are supported by a higher number of stakeholders (Perrone et al., 2020).

The methodology chosen to design a collaborative CLD consists of the following steps: problem definition, stakeholder analysis, creation of CLDs in small groups of up to five people (in contrast to one-on-one interviews done in the original study), digitization of created CLDs and merging of the created CLDs (Inam et al., 2015). Primary data gathering is done in different ways, to suit the comfort of the heterogeneous groups of stakeholders. Two large stakeholders groups are recognized: geotechnical (GT) stakeholders and socio-ecological (SE) stakeholders. A sequence of workshops is organized to gradually enrich the causal loop diagrams up to the point of data saturation and consensus amongst stakeholders. During the workshops predefined case studies are discussed with the stakeholders, which is methodologically justified in this situation (Priya, 2021). Data processing is done afterwards by the researcher. When complete, the stakeholders receive these results and are open to give feedback. This cycle is repeated iteratively. The final CLD is expected to form a common ground for stakeholders and policy makers to discuss activities in the subsurface while taking into account the effects on the social, economic, geological and environmental systems.

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Developing tools for a better incorporation of geoscientific knowledge in policy making

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The need for a more efficient use of the subsurface in tackling a variety of issues is becoming more apparent, certainly in densely populated regions. For a better incorporation of geological knowledge into policy making, e.g. related to underground space use, raw materials management and (deep) subsurface planning for technologies such as geothermal energy, it is essential to develop user-friendly tools. These can translate geological information to field applications, which can be understood by policy officers, engineers, architects, etc. In Flanders (Belgium), such tools are developed and published on an open platform. Even though many tools are already available based on extensive 3D geological models, advances can still be made towards voxel models and 2D maps combining information for specific purposes.

Geological maps, models and tools for Flanders are publicly available on the website and map viewer of the database of the subsurface of Flanders (DOV, dov.vlaanderen.be). Geological 3D models include both classic layer cake models covering the whole region up to a depth of several kilometers as well as regional or local voxel models with a limited depth. The voxel models consist of thousands of cubes, in which each cube contains values for certain parameters such as stratigraphic unit, lithological composition, glauconite content, carbon content, etc. These models can have a more targeted purpose such as the models of raw material potential in the loam belt in the south and the coarse sand and gravel area in the east of Flanders. Voxel models of urban areas can be used for many applied questions relating to geotechnics, hydrogeology, raw material potential and subsurface land use. These 3D models allow for the creation of many useful tools such as virtual cores, virtual geological profiles and volume calculations in specific project areas.

Applied 2D maps remain an important tool for efficient communication. For example, with regard to underground space use, maps are being created which highlight the subsurface potential for underground space use based on many different factors. Similarly, hazard maps with regard to the risk of swelling clays in the subsurface have been constructed.

In the deep subsurface, conscious planning is even more imperative as multiple high value applications vie for rather limited useful space. Detailed 3D models of the deep subsurface and public information on the current active permits will allow for a responsible deployment of these applications, such as deep geothermal energy, in Flanders.

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Nuclear waste characteristics and geological disposal system requirements

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In Belgium, radioactive waste primarily arises from nuclear energy production, medical applications and research activities. Another part stems from historical mining and refinement activities. Such waste needs to be managed safely on the long term, which is the responsibility of the Belgian waste management organization ONDRAF/NIRAS. The European directive 2011/70/Euratom demands that member states work towards final disposal solutions of radioactive waste, including the spent nuclear fuel if considered as waste. Indeed, to protect man and environment from the hazards of ionizing radiation, containment and isolation of the waste needs to be guaranteed for thousands to hundreds of thousands of years, depending on the nature of the waste. This can be realized by the combination of a robust multi-barrier disposal facility, an appropriate host formation and a stable site. One governing principle in disposal facility development is the so-called graded approach, which states that protection measures need to be proportional to the risk posed by the waste. This not only refers to the number and type of containment barriers but also to the considered disposal depth. Indeed, one of the basic objectives of the disposal is to isolate radioactive waste from the accessible biosphere and to significantly reduce the likelihood and consequences of unintentional intrusion into the disposal facility and the waste contained therein.

The questions we would like to address here are the following. What are the characteristics that make a geological layer a possibly suitable host formation (if needed), in terms of the physico-chemical properties, geometry, depth? What are the time scales associated to the isolation and containment requirements of the disposal system for a particular type of waste? How can safety be guaranteed over such timescales and which are the relevant geodynamic processes to be evaluated? These questions will be framed within the current disposal plans that ONDRAF/NIRAS is developing for high-level and long-lived waste (category B&C waste) arising from the Belgian nuclear fuel cycle, and legacy radium-bearing waste stemming from historical radium production activities at the former Union Minière (now Umicore) site at Olen. The topics will be discussed from the perspective of R&D and impact studies performed at SCK CEN, and will be discussed at methodological level, as no site(s) or host formation(s) have been selected yet for these types of waste.

PSS V, a modular techno-economic simulation tool for deep subsurface uses

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In the transition towards a more sustainable society and a responsible use of natural resources, our subsurface holds a large potential. However, this potential is not unlimited, nor is it equally distributed. The use of this common good therefore requires careful management and planning to avoid inefficient or over-exploitation and a proper integration in policy (see e.g. Eswaran et al., 2024).

Techno-economic simulation is a method often applied to determine economic impacts and viability of activities. An integration of this method for subsurface activities can help in developing effective policies for the (sustainable) management of the subsurface. However, working with subsurface data and its use for evaluating the performance of activities is challenging. Large and difficult-to-quantify uncertainties need to be considered, together with the managerial flexibility that is needed to tackle these. In addition, every type of subsurface application requires its own modelling.

A geo-techno-economic simulation tool that is able to deal with uncertainties and flexibility on activity and regional scale was developed for investigating the implementation of geological CO_2 storage: PSS (Policy Support System, Welkenhuysen et al., 2013). In essence, investment decisions are simulated considering several sources of uncertainty (economic, technical, geological). Through the application of Real Options analysis in a nested Monte Carlo approach, the development of subsurface activities over time can be simulated.

Until now, such analyses have always been applied to single activities, such as CO_2 storage or geothermal energy production. In its latest version, PSS V, two major and simultaneous developments have been successfully integrated. Firstly, the activity modelling (reservoir and techno-economic) has been made fully modular. Apart from economic and performance parameters, a set of 40 user-assignable stochastic in- and output parameters is available for reservoir simulations. New activities or reservoir simulations can be added or connected with reduced effort. Secondly, multiple activities can be simulated at the same time. For example, potential deep geothermal and CO_2-storage projects can be evaluated not only within a single simulation. They can influence each other's development by excluding the other at a certain location. Geological impacts at regional scale, such as pressure interferences, can be evaluated by connecting to a regional pressure model (see Rodriguez et al., 2024).

This newly developed tool allows for an all-encompassing geo-techno-economic analysis of deep subsurface activities at regional scale, with conclusions that can be drawn at project, sector or regional level.

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UNFC as a tool to manage and develop natural resources in Belgium: A case study for critical raw materials

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The process of estimating and classifying resources inherently requires scientific methodologies and high-level techno-economic analyses, making it a complex, costly task. Yet, such tasks are essential to determine the global outlook for resource supply. For decades, different countries and global organizations have worked on establishing definitions and principles that enable the assessment and classification of resources within a consistent framework. An example of this is the UNFC (United Nations Framework for Resource Classification). It is globally applicable and can be used for various natural resources including geothermal energy, raw materials, water, hydrocarbons, among others (UNFC Update 2019). UNFC provides the principles to assess projects that aim to develop resources, more specifically on their environmental-socio-economic viability, technical feasibility, and (geological) uncertainties. Government resource management policies, industrial process planning, and financial capital allocation can benefit from the use of this framework.

Europe is currently undergoing a digital and energy transition, which simultaneously corresponds with a transition in natural resources. To facilitate new technologies and enlarge capacity the demand of certain raw materials will increase. Additionally, not all of these are available in the European subsurface, which makes Europe dependent of third countries. To counter the emerging criticality of some raw materials, the European Commission recently approved the European Critical Raw Materials Act (CRMA, EU 2024/1252), in which a strategy is drafted concerning the extraction, processing and recycling of critical raw materials (CRM) in Europe. In the CRMA, the European Commission has selected UNFC as key tool for the evaluation of strategic projects, monitoring, national or regional exploration plans and the recovery of CRM from extractive waste. The importance of UNFC for natural resources, especially the CRM, is thus only growing.

The GSEU-project (Geological Service for Europe, Horizon Europe 101075609), supported by the European Commission, gave priority to the urgent need of UNFC-trained CRM-experts and organized a training on applying UNFC for Strategic raw material projects, as well as to equip the trainees for training other experts within their respective national context. This training was conducted in the framework of the International Centre of Excellence for Strategic Raw Materials that will be developed as part of GSEU. Its focus was 1) the basics of UNFC, 2) its application with own case studies and 3) working out a national training plan. Two Belgian partners of the GSEU-project, GSB and VPO, participated in this initiative. Everyone who wants to learn the application of UNFC on potential CRM-related projects is invited to express their interest to the authors.

UNECE (2020) United Nations Framework Classification for Resources. Update 2019. UN. ECE Energy Series, no. 61, 28 pages.

SESSION 14 - GEOSCIENCE EDUCATION AND OUTREACH

Convener

Manuel Sintubin, KU Leuven (manuel.sintubin@kuleuven.be)

Geoscience education is confronted with a lot of challenges to remain relevant in both higher and secondary education. This is though in stark contrast to the ever-increasing societal relevance of the geosciences tackling the global challenges of the 21st Century. Several questions require an answer. How can we reverse the rather negative perception about geosciences? How do we convince young people to choose to study geosciences? How do we adapt our programs to appeal to young people?

This session is intended to make up a state-of-the-art of our geoscience programs, to present and discuss recent changes to our programs, to highlight good practices in geoscience education and outreach, to discuss the future of geoscience education in Belgian universities and high schools.

Invited Speaker

Connecting Science with Society: Essential Tools for Effective Research Communication

Julie LOUIS*

Communication Department, University of Liège, Belgium

Effective communication of scientific research to the public is increasingly recognized as essential for fostering a scientifically literate society, promoting informed decision-making, and garnering support for scientific endeavors. This presentation explores the critical need for scientists to engage with the public about their research and examines the tools and strategies that can enhance these communication efforts. Social networks, press interactions, and the collaboration with communication officers are highlighted as key resources for amplifying outreach and ensuring clarity and accessibility of scientific information. By adopting these tools, scientists can bridge the gap between complex research and public understanding, dispel misinformation, and inspire a culture of curiosity and critical thinking. This presentation will provide practical guidance on utilizing these platforms effectively, addressing common challenges, and leveraging professional support to optimize the impact of scientific communication. Through these efforts, scientists can ensure their work not only advances knowledge but also contributes meaningfully to societal progress.

A new Bachelor program in Geosciences at ULiege

Bernard CHARLIER*

Department of Geology, University of Liege, Belgium

Our Earth is composed of the envelopes that are the solid Earth, the hydrosphere, the cryosphere, the atmosphere, and the biosphere. Geosciences gather the disciplines that study these different layers and their interactions. The aim, through a multidisciplinary approach, is to reconstruct the history of the Earth and understand its current functioning. In addition to deciphering the fundamental processes that control the composition, structure, and dynamics of the Earth, the goal of Geosciences is to address the major challenges of our planet on a global and local scale, related to resources and their sustainable management, climate, natural hazards, and the impact of humans. Geosciences thus aim to understand the Earth, its past, and its current behavior in order to work towards its future.

Geosciences aspire to be naturalistic through the observation and description of the processes that shape the Earth, but also quantitative through various measurements and modeling of the Earth's evolution and its components. The specific disciplines of Geosciences are numerous and aim to understand the various reservoirs from the inner core to the limits of its stratosphere. The University of Liege is recognized for its expertise in diverse fields such as Geology, Climatology and Paleoclimatology, Meteorology, Oceanography, Geomorphology, Mineralogy, Igneous Petrology, Paleontology, Geomatics, Natural Hazards, Geophysics, and Environmental Sciences. These disciplines are currently taught in different programs by different Departments. The evolution of Geosciences, its multidisciplinary, the progresses in quantitative methods, and the absence of boundaries between the different reservoirs of the Earth, imposes to rethink our educational programs.

The new Bachelor program at ULiege will be based on solid learning in physics, chemistry, mathematics, and biology complemented by general knowledges in the specific disciplines of geosciences. At the end of the program, students will master the fundamentals about the Earth and will be able to apply this knowledge to complex problems where there is an intersection between natural sciences and quantitative methods. The new Bachelor program in Geosciences at ULiege offers numerous opportunities for specialization in Master's degrees: Global Change, Geomatics, Geology, Oceanography, Environmental Sciences (Arlon), and Space Sciences. A link to the Master’s degrees in Mining and Geological Engineering and Bioengineering Sciences and Technology of the Environment would also be obvious.

Modernising the Geosciences programme at ULB

Karen FONTIJN*, Sandra ARNDT, Frank PATTYN + Faculty members DGES-IGEOS ULB

Institute of Geosciences (IGEOS), Department of Geosciences Environment and Society (DGES), Université libre de Bruxelles, Belgium

The past years have seen a growing public and political awareness of the significant environmental and resulting socio-economic challenges that our societies face in the coming decades. European societies are beginning to take leadership in tackling these challenges. However, responding to the climate emergency and global environmental issues, reducing the impact of natural hazards, and living up to the ambitions of the sustainable development goals requires a better understanding of the Earth System and translating that knowledge into actionable solutions for society. A new generation of well-trained geoscientists is thus essential for guiding the path to a more sustainable and healthy future.

The modern geoscientist is interested in the formation and evolution of planets; the complex physical, chemical, and biological interactions within the Earth system, their evolution and response to perturbations; understanding natural hazards and mitigating their destructive potential; and understanding the formation and optimal exploitation of natural resources. To tackle these research questions, the modern geoscientist develops and applies advanced observation and analytical methods, information technology, remote sensing, and complex numerical modeling tools. Consequently, geosciences have become increasingly interdisciplinary (including social sciences) and quantitative. Geoscience courses should thus reflect this ongoing transformation of research interests and methods.

Geoscience research and teaching activities at ULB are highly complementary as evidenced by already existing (in)formal collaborative activities in the form of common research projects, student supervision, excursions, punctual contributions to the respective teaching programs. The creation of a new Master in Geosciences program helps close strategic gaps and streamline our educational programs to a unique and modern teaching program that covers some of the most important, international strategic development areas. Our new program, of which more than a quarter will be taught in English, maintains its focus on natural science while integrating and highlighting socio-economic aspects. We target the development of a comprehensive interdisciplinary and multi-methodological technical skill set, as well as transferable and general skill training which prepares the students for careers in the academic, private or public sector.

"Matinées « Les Changements climatiques »" at ULiège – An Innovative Combination of Public Outreach and Geoscience Teaching

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In the framework of the course on "Climate Change and Impacts", which is part of the programmes of the Master in Geography, Global Change, the Master in Geology and the Master in Space Sciences at the university of Liège, students have to carry out a personal project which consists in a practical, full-size, live, public-outreach exercise in climate communication, on a subject of their own choice. That subject only has to be directly related to the climate system in the broad sense (which includes biogeochemical cycles, atmospheric chemistry, etc.), or to climate change. It may cover any aspect related to these two broad fields, encompassing

- Scientific foundations ("How does the climate system work?");
- Past, present, future;
- Policy (national, international);
- Social impacts (health effects, food security, water security, livelihood security, migration, etc.);
- Economic impacts: damages to infrastructure, reduced reliability of infrastructure due to extreme events, wildfires, etc.

The primary target audience are 5th and 6th year secondary school classes. Accordingly, projects have to be realized in French by default. Students with insufficient proficiency in French may realize their project in English, and they have to present it to one of the classes of the English courses of the first years' science bachelors' students (geography, chemistry, geology, physics).

The preparation follows a multi-stage process. First, students have to select appropriate publications from the scientific literature to cover the chosen subject. During the course tutorials, we assess the quality and pertinence of the references, and students then frame their subject, formulate an appealing title and produce a 4–5 line abstract, in the style of the lead of a newspaper article. These leads are used produce the programme to be announced to the secondary schools of the greater Liège area. In a second stage, students must submit a 3–4 page summary report that is going to be copy-edited, typeset and included in the educational kit posted for class usage by the participating schools. Writing this summary report is one of the major challenges for the project: it has to be written in the style of a newspaper article, without references to scientific literature, although it has to be based upon the scientific literature; it has to respect the level of understanding of the target audience and it must include a final section entitled "To find out more…" where the students have to provide 3–4 quality references to freely accessible resources (web or print) for readers who want to learn more about the subject. Finally, students prepare (with two mandatory rehearsals at least) and give a 25–30 minute oral presentation to school classes. The different outcomes are assessed with regard to their scientific and pedagogic qualities.

In my talk, I present in detail the different challenges and learning outcomes that we aim at: to select, define and delimit a scientific subject, to popularize without caricature, to simplify, with rigour, to inform without exaggeration or dramatization, and the importance of using precise language.

TPA in Belgium - achievements and courses proposals

Pascal PETTEAU

TPA (TotalEnergies Professeurs Associés)

The history of TPA (TotalEnergies Professeurs Associés) consists of 23 years of activity worldwide with presently 256 teachers, including 25 in Belgium. The main objective is "sharing experience" with students.

Conferences are given to secondary schools via Aptaskill and their program « JCSV » (les jeunes, la chimie et les sciences de la vie) to highlight the career opportunities in scientific domains to last year students.

The main courses of interest for geosciences students proposed by TPA for Universities and High Schools are the following:

- « Les hydrocarbures et la transition énergétique » (Hydrocarbons and Energy Transition) given to the faculty of sciences in ULiège.
- « Climate Change and Energy Transition » (up to 15 hours of course to cover the subject broadly).
- "Geoscience for CCS (Carbon Capture and Storage)".

Note that other courses are proposed (see website prof.totalenergies.com) like "Intercultural Management" a preparation for an immersion in a foreign environment.

Ik Doorgrond Vlaanderen: an educational website on the Flemish soil and subsurface for secondary schools

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The soil and subsurface are literally and figuratively the foundation of our living environment. With the renewed website ‘Ik Doorgrond Vlaanderen’, the Flemish Environment Department wants to enhance knowledge and raise awareness about the importance of the soil and subsurface, specifically in relation to the different social challenges of today. The website is aimed at secondary school teachers and their students. Revision of the former website ‘IkDoorgrondVlaanderen.be’ was required, because of a technical update and in order to expand the scope to both soil and subsurface and their role and importance for our society.

‘Ik Doorgrond Vlaanderen’ was developed in collaboration with the Department of Earth and Environmental Sciences at the KU Leuven. Earth science and educational experts from Flemish administrations, geography teachers and secondary school students provided input, guidance and feedback. The website contains multiple modules that elaborate on the Flemish soil and subsurface, its possible applications, such as extraction of raw materials and geothermal energy, and the links between soil, subsurface and themes as the “above ground” environment, sustainability, future scenarios and research. The website can be explored both by subject and by region. An introduction to the Geotheek, Flanders repository for soil and subsurface samples (De Nil et. al, 2024) and a walkthrough, practical exercise to use the Databank Ondergrond Vlaanderen (DOV) are included as well.

Special attention was paid to arousing student interest, for example by taking their everyday life and environment as a starting point via ‘virtual excursions’. The content of the website is in line with the current Flemish educational goals, and explicitly goes beyond them as well, to provide additional inspiration for teachers who want to present extra-curriculum material to their students or for curious students. In addition, this will make the content more durable on the long term. The website is in line with the Flemish IT and communication standards and will continue to be updated and expanded in the coming years.

De Nil, K., Verhaegen, J., De Koninck, R. and Deckers, J. 2024. The Geotheek: the Flanders repository for soil and subsurface reference samples. Geologica Belgica Meeting 2024, Liège (this volume)

Bachelor in Geosciences at the KU Leuven (Belgium), a new curriculum of and for the future

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Starting in the academic year 2024-2025, the new Bachelor's programme in Geosciences (*Bachelor in de Geowetenschappen*) will be organized at the KU Leuven (Belgium), replacing the two existing Bachelor's programmes in Geography and Geology. This new programme is not just a merger of the two existing programmes, but aspires to form a future-oriented programme.

Today's key global challenges are particularly complex, and require a holistic, interdisciplinary approach. Geologists and geographers share that holistic view of socio-ecological issues, and place emphasis on understanding complex systemic interactions between human societies and Planet Earth. By combining the expertise of both disciplines in one programme, we can offer students a unique, exceptionally broad and integrated view of global sustainability issues. The unique holistic nature of the programme is expressed in a rich spectrum of courses from the natural and social sciences. Moreover, the programme focusses on the epistemological and methodological diversity from the social and natural sciences, which is rather unique in the educational landscape. Thinking in space and time is also a crucial skill here: it calls attention to the multi-scale and time-space dimension of sustainability issues, and highlights the past (historical or geological) as key to the future, in the short, medium and long term. With the combination of holistic and 4-dimensional (time-space) thinking, we distinguish ourselves from existing programmes where either the holistic, integrated view or the multi-scale, 4-dimensional perspective is missing.

Stewart et al. (2013) use the '3 horizons' framework of Sharpe (2013) to develop a future perspective for geosciences. This framework is often used to think strategically about major transitions. While horizon 1 represents 'business as usual' practices, horizon 3 starts from a visionary view of the future. If we wish to continue fulfilling our societal role, we need a paradigm shift from the first to the third horizon. Notwithstanding that the first horizon, in the form of the basic courses, remains a necessary foundation, both existing bachelor's programmes, Geography and Geology, already tried to translate the second horizon into their educational practice. With the Bachelor in Geosciences, we are now resolutely opting for the third horizon, ensuring that our geoscience graduates will play a key role in the transition to a sustainable world.

Stewart, I., Capello, M.A., Mouri, H., Mhopjeni, K., Raji, M. 2023. Three Horizons for Future Geoscience. Earth Science, Systems and Society, 3. DOI:10.3389/esss.2023.10079.

Sharpe, B. 2013. *Three Horizons: The Patterning of Hope*. Charmouth, Triarchy Press.

Exploring the Virunga Volcanoes: from Digital Elevation Models to 3D geomorphological maps for inclusive education of visually impaired students

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Understanding geomorphology, tectonics, and volcanism is crucial for comprehending the processes and events that shape and influence our planet (Carrión-Mero et al., 2020). However, geography classes present a significant challenge for secondary school pupils with visual impairments due to their reliance on visual aids such as maps, graphs, and images, making it difficult for these students to grasp complex earth science concepts (Kizilaslan et al., 2021; Rule, 2011). Drawing on a geomorphological map of the Virunga volcanoes we drafted (De Cock et al., 2024), we wanted to investigate how 3D models and geomorphological maps that incorporate 3D features, can help overcome these difficulties and foster inclusive education.

Educational aids in the form of 3D models were printed using a digital elevation model with a 12.5 m spatial resolution based on ALOS PALSAR data. Additionally, a tactile version of the geomorphologic map, including braille codes and a legend, as well as a 3D model incorporating a tactile legend, were prepared (Fig. 1). The strengths and limitations of these visual aids were tested during lectures in the 5th and 6th years of secondary school, with students with typical vision and those with impaired vision.

The integration of 3D models and tactile geomorphological maps effectively addressed the challenges faced by visually impaired students in understanding complex earth science concepts. During the lectures, both visually impaired and typically sighted students interacted with these educational aids. The tactile maps provided visually impaired students with a tangible means of exploring the complex geomorphological features of the Virunga volcanoes, enabling them to gain a deeper understanding of geomorphic features and their spatial relation, covering shield and stratovolcanoes, rift formation, hilly country derived from pre-Cambrian rocks. Furthermore, the use of 3D models enhanced engagement and participation among all students, promoting inclusivity.

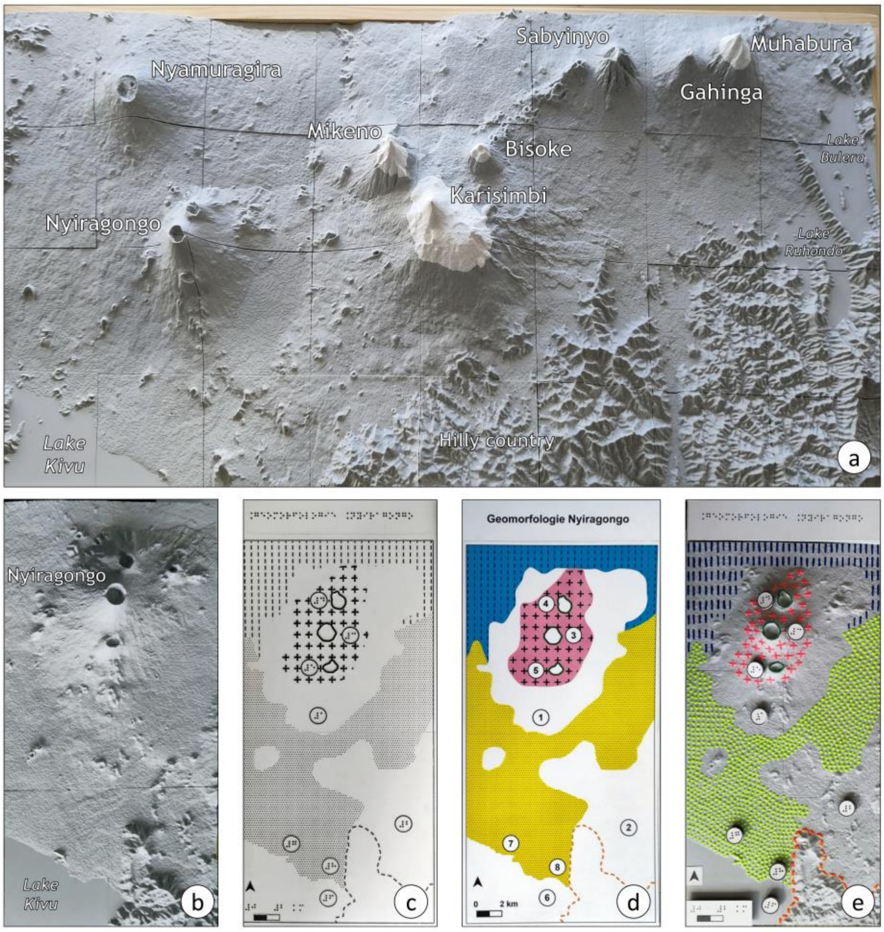
However, challenges in preparing and utilizing tactile materials were encountered, necessitating attention to detail and additional educator training. These findings underscore the potential of 3D models and tactile maps in overcoming learning barriers and fostering inclusive education in earth sciences. Further research is needed to refine and expand these educational tools for broader implementation in secondary school curricula.

Carrión-Mero P, Montalván-Burbano N, Paz-Salas N, Morante-Carballo F. 2020. Volcanic Geomorphology: A Review of Worldwide Research. Geosciences 10: 347. DOI: 10.3390/geosciences10090347

De Cock H, Timmermans E, Goossens R, Dondeyne S. 2024. Comparing modern remote sensing data to aerial photography for geomorphological mapping of the Virunga volcanoes. paper submitted to be presented at the 8th International Geologica Belgica Meeting 2024. Liège, Belgium

Kizilaslan A, Zorluoglu SL, Sozbilir M. 2021. Improve learning with hands-on classroom activities: science instruction for students with visual impairments. European Journal of Special Needs Education 36: 371–392. DOI: 10.1080/08856257.2020.1732110

Rule AC. 2011. Tactile Earth and Space Science Materials for Students with Visual Impairments: Contours, Craters, Asteroids, and Features of Mars. Journal of Geoscience Education 59: 205–218. DOI: 10.5408/1.3651404



Visual aids derived from a digital elevation model, based on 12.5m resolution ALOS PALSAR data, of the Virunga volcanoes and surroundings.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