21.-25. Sept. 2026

PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Abstractband
Abstract Volume

DOI: https://doi.org/10.3217/xxx

In Kooperation mit / In cooperation with

NAWI Graz Natural Sciences · TU Graz · UNI GRAZ

Träger der Veranstaltung / Event promoters

Österreichische Geologische Gesellschaft (ÖGG); Österreichische Geophysikalische Gesellschaft (AGS); Österreichische Mineralogische Gesellschaft (ÖMG); Österreichische Paläontologische Gesellschaft (ÖPG); Österreichische Vereinigung für Hydrogeologie (ÖVH)

Page intentionally left blank.

Wir danken unseren Sponsoren
We thank our sponsors

Wissenschaftliches Komitee:

Gerald Auer, Steffen Birk, Martin Dietzel, Martin Gross, Christoph Hauzenberger, Bernhard Hubmann, Christoph Iglseder, Markus Kaspar, Jürgen Konzett, Walter Kurz, Frank Melcher, Theresa Nohl, Barbara Schneider-Muntau, Christine Stumpp, Franz Tschuchnigg, Paul Unterlaß, Klaus Voit, Helmut Wannenmacher

Administratives Komitee:

Mirjana Bürger, Christine Gaster, Claudia Puschenjak, Daniela Sobian, Petra Stadlhofer, Georg Stegmüller, Christina Walcher

Editorial:

Gerald Auer, Christine Gaster, Tereza Kunkelova, Walter Kurz, Georg Stegmüller
Institut für Erdwissenschaften, NAWI Graz Geozentrum
Universität Graz, Heinrichstraße 26, A-8010 Graz, Österreich

Impressum:

Medieninhaber, Herausgeber und Verleger: Institut für Erdwissenschaften,
Universität Graz, homepage: www.uni-graz.at

Sessions & Field Trips

NAWI Graz
Natural Sciences

TU Graz

UNI GRAZ

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Session 01

Regionale Geologie von Österreich und Geologie der Ostalpen – Einblicke, Perspektiven und Trends

Regional geology of Austria and Geology of the Eastern Alps – insights, perspectives and trends

Conveners:
Christoph Iglseder & Walter Kurz

NAWI Graz
Natural Sciences

TU Graz

UNI GRAZ

Prä-Permische Paläogeographie und Beckenentwicklung der Alpen – eine Provenienzstudie in den fossilführenden Ostalpinen und Südalpinen Grundgebirgseinheiten

Marius Beck[1], Matthias Hinderer[1], Johannes Lukas[1], Armin Zeh[2], Laura Stutenbecker[3]

[1] TU Darmstadt, Schnittspahnstraße 9, 64287 Darmstadt
[2] KIT Karlsruhe, Adenauerring 20b, 76131 Karlsruhe
[3] Universität Münster, Corrensstraße 24, 48149 Münster

Correspondence to: mariusbeck74@gmail.com

Die paläogeographische Anordnung europäischer Terrane am Nordrand Gondwanas sowie deren Drift- und Entwicklungsgeschichte vor der variszischen Kollision sind weiterhin Gegenstand wissenschaftlicher Diskussionen. Die nicht- bis niedriggradig metamorphen vulkano-sedimentären Abfolgen des Ost- und Südalpins in der Grauwackenzone, des Gurktal-Deckenkomplexes, des Grazer Paläozoikums und der Karnischen Alpen haben aufgrund ihrer gut belegten biostratigraphischen Einstufungen ein hohes Potenzial zur Rekonstruktion der prä- bis syn-variszischen Entwicklung und sind besonders geeignet paläogeographische Bezüge zwischen Gondwana und dem außeralpinen Paläozoikum herzustellen. Dazu wird eine Multiparameter-Provenienzanalyse ausgewählter siliziklastischer Intervalle vom Ordovizium bis ins Unter-Karbon mittels Petrographie, Schwermineralanalyse, Granatgeochemie sowie U-Pb-Hf-Isotopenuntersuchungen an detritischen Zirkon- und Rutilpopulationen durchgeführt. Die neuen radiometrischen Daten sollen zudem dazu dienen bislang unzureichend datierte vulkanisch-siliziklastische Sequenzen in ihrem zeitlichen Umfang besser zu fassen und maximale Ablagerungsalter abzuleiten. Auf Basis dieser Daten soll ein geodynamisches Modell der prä- bis syn-variszischen Beckenentwicklung und Sedimentherkunft in der alpinen Region entwickelt werden. In diesem Beitrag werden erste geochronologische Ergebnisse aus dem Gebiet der Westlichen Grauwackenzone vorgestellt.

The Cu-Au-As bearing ore veins of Flatschach, Styria – A multi-stage Neogene mineralization?

Frederik Dunkel[1], M. Sophie Hollinetz[2], Jasmin Hiller[1], Reinhard F. Sachsenhofer[1], Phillip Gopon[1]

[1] Department Applied Geosciences and Geophysics, Montanuniversität Leoben, Peter-Tunner-Straße 5, A-8700 Leoben, Austria

[2] Department of Geology, University of Vienna, Josef-Holaubek-Platz 2, A-1090 Vienna, Austria

Correspondence to: frederik.dunkel@unileoben.ac.at

The historic mining district of Flatschach in the vicinity of Knittelfeld, Styria, is situated in a crystalline basement ridge alongside the northern edge of the Neogene Fohnsdorf pull-apart basin. Several ore-bearing veins crosscut the metamorphic host rocks (mainly gneisses and amphibolites) of the Silvretta-Seckau nappe in a NE-SW direction. Copper and gold were mined from the orogenic mineralization predominantly by the monastery of Seckau in the 18th century, leaving behind various small mine waste dumps. While recent research focused on the remaining raw material potential and environmental impact of those dumps, it revealed a strong spatial geochemical heterogeneity, raising questions on the formation of the mineralization.

By combining new analytical data (LA-ICP-MS, µXRF, Whole Rock assay) with structural measurements and regional studies on the Fohnsdorf basin, a new model for the development of the Flatschach Cu-Au-As ore veins was established. Not only hints the data towards a relatively young Neogene age, but also at multiple formation and overprinting stages in close relation to the complex, multi-staged evolution of the Fohnsdorf pull-apart basin at the intersection of the Pöls-Lavantthal and Mur-Mürz fault zones. The model indicates an overlapping formation age of the Flatschach mineralization with the Miocene Fohnsdorf coal seam, and provides an explanation for the heterogeneous distribution of critical and precious metals along the mineralization trend and the large variation of

minerals found at Flatschach. Finally, the model provides additional insight into the formation of other raw materials occurrences in the regional tectonic context.

The Meliaticum of the Eastern Alps - sourced from the East, displaced to the West

Harald Fritz[1], Josef Nievoll[2], Daniela Gallhofer[1], Christoph A. Hauzenberger[1], Kevin Karner-Rühl[1], Kurt Krenn[1], Walter Kurz[1], Gerhard W. Mandl[3], Franz Neubauer[4], Etienne Skrzypek[1]

[1] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Graz, Austria
[2] Gumpendorfer Straße 83–85/2/48, Wien, Austria
[3] Graf Starhemberggasse 26/19, Wien, Austria
[4] Department of Geography and Geology, Paris-Lodron-University of Salzburg, Salzburg, Austria

Correspondence to: harald.fritz@uni-graz.at

Remnants of ocean floor sediments of the Austroalpine Meliata Basin, as part of the Neo-Tethys, contain a variety of rocks interpreted as tectonic mélange. Oceanic crust developed from Middle Triassic on and was consumed by the Late Jurassic. Hence, the Meliaticum can be interpreted as the most distal oceanic unit of the Adriatic margin, which was thrust earliest on the uppermost parts of the Austroalpine – Western Carpathian nappe stack. Prior to this study, Meliata Groups sediments have been described only from two small localities in the easternmost part of the Northern Calcareous Alps, at Florianikogel and Ödenhof. Here we describe an occurrence at Ruthboden, next to Niederalpl. Laminated siltstone, mudstone, radiolarite, and intercalated sandstone represent Middle Triassic to Middle Jurassic deep-water deposits that contain shallow marine components derived from a carbonatic–clastic shelf. The relatively small fault bounded outcrops of Meliata Group sediments in the Eastern Alps have probably been laterally displaced hundreds of kilometres during the formation of the Alpine Nappe pile. Through an U/Pb detrital zircon provenance study we put constraints on their original paleogeographic position, the 'Home of Meliaticum'. The U/Pb detrital zircon age data from sandstones suggest the presence of different sources: (1) An Avalonian source delivered abundant Mesoproterozoic zircons from domains bordering Moesia and East European Platform. (2) A Galatian / Ligerian source, as part of the Armorican/Galatian/Ligerian continent, devoid of Mesoproterozoic zircons but with frequent Mississippian zircons (c. 350 Ma),

supplied the Meliata Basin with detritus from the ALCAPA super-terrane. (3) Serbo-Macedonia and/or Dacia delivered detritus devoid of Mesoproterozoic zircons, but prevalent Pennsylvanian zircons (c. 310 Ma). The original site of deposition, ';Home of Meliaticum', was a seaway extending at a high angle to the Neo-Tethys margin northwards between ALCAPA/Tisza and Dacia, connecting the Neo-Tethys Ocean with the evolving Piemont-Ligurian Ocean. During the Late Jurassic, when the Piemont-Ligurian Ocean (Alpine Tethys) widened and the Neo-Tethys closed, the Austroalpine Meliata units were displaced approximately 400 km westward along a transform fault system connecting both oceans and penetrating the thinned ALCAPA crust.

Geochemie von ausgewählten Metabasiten der Kitzbüheler und Gurktaler Alpen

Christopher Germautz[1], Matthias Hinderer[1], Henri Paul Meinaß[1], Dirk Scheuvens[1], Johannes Lukas[1], Marius Beck[1], Armin Zeh[2]

[1] Institut für Angewandte Geowissenschaften, Technische Universität Darmstadt, Schnittspahnstraße 9, 64287 Darmstadt
[2] Institut für Angewandte Geowissenschaften - Mineralogie and Petrologie, Karlsruher Institut für Technologie, Adenauerring 20b, 76131 Karlsruhe

Correspondence to: christopher.germautz@stud.tu-darmstadt.de

Bereits in den 1980er Jahren wurden in den Ostalpen umfangreiche geochemische Untersuchungen an paläozoischen Metabasiten durchgeführt. Durch eine wiederholte Beprobung einiger damals untersuchter Lokalitäten und mit neuen geochemischen Verfahren wurden die früheren Ergebnisse hinsichtlich Klassifizierung und plattentektonischer Implikationen überprüft. Dabei wurden Metabasit-Vorkommen ausgesucht, für die sich damals unterschiedliche geochemische Eigenschaften und unterschiedliche plattentektonische Interpretationen ergaben. Die ausgewählten Vorkommen gehören dem niedriggradig bis maximal grünschieferfaziell metamorphen Oberostalpin an. Insgesamt wurden 26 Proben genommen, denen ein Vergleichsdatensatz mit insgesamt 142 Proben vorwiegend aus den 1980er Jahren gegenübersteht. In der westlichen Grauwackenzone wurde am Marchbachjoch bei Wildschönau, sowie am Zwölferkogel und Ratzenstein im Saalachtal, in den Gurktaler Alpen an der Nockalmstraße im Bereich des Windebensees und an der Turracher Höhe beprobt. Die Proben wurden petrographisch untersucht und mit Hilfe von RFA und ICP-MS auf Haupt- und Spurenelemente analysiert. Insbesondere ICP-MS-Messungen liegen aus den 1980er Jahren nicht vor und es konnten dadurch damals keine Seltenen Erden-Muster und einige heute gängige Diskriminierungsverfahren mit in die Bewertung einbezogen werden. Ein weiterer Unterschied war die Auswertung mit heute zur Verfügung stehenden, großen Datenbanken und KI-generierten Verteilungsdiagrammen. Die meisten Ergebnisse der Literatur aus den 1980er Jahren ließen sich bestätigen. Trotz der Betrachtung zusätzlicher immobiler Elemente und einer größeren

Vergleichsbasis der verschiedenen plattentektonischen Positionen ergaben sich keine grundsätzlich abweichenden Interpretationen. Damit kann die Bildung der Metabasite der westlichen Grauwackenzone und der Turracher Höhe in einem kontinentalen Rift vom geochemischen Standpunkt aus bestätigt werden. Dies gilt umgekehrt auch für den Inselbogen-Charakter der Gesteine der Nockalmstraße. Der Kontext zur benachbarten Turracher Höhe ist damit allerdings weiter offen und nur durch geländegeologische Aufnahmen und Datierungen zu lösen. Unterschiede zu den älteren Ergebnissen zeigen sich vor allem bei Detailfragen wie dem subalkalinen Charakter einzelner Proben oder Gebieten. Hier zeigen einzelne der älteren Proben Abweichungen, die auf die Nutzung von Hauptelementen und deren Anfälligkeit für sekundäre Stoffverschiebungen zurückzuführen sind.

Lifting the orogenic lid – Assessing the European basement beneath the Alpine wedge by U-Pb zircon geochronology

Bianca Heberer[1], Elisabeth Holzner[1], Veronika Tenczer[1], Friedrich Finger[1], Bernhard Salcher[1], István Dunkl[2], Axel Gerdes[3], Hans Egger[4], Gertrude Friedl[1], Gabor Tari[5], Maria Parlea[6], Hubert Putz[7]

[1] Department of Environment and Biodiversity, University of Salzburg, Austria
[2] Geoscience Center, University of Göttingen, Germany
[3] FIERCE Goethe University Frankfurt, Germany
[4] Vienna, Austria
[5] OMV, Vienna, Austria
[6] Doctoral School of Geology, Faculty of Geology and Geophysics, University of Bucharest, Romania
[7] Salletmayr & Friedl Ziviltechniker GmbH, Vöcklabruck, Austria

Correspondence to: Bianca.Heberer@plus.ac.at

The distal European margin beneath the Eastern Alps was largely overridden during Alpine collision and is today widely concealed beneath the Alpine nappe stack. Consequently, the composition, architecture, and tectonic evolution of the underthrust European basement remain poorly constrained. This study uses U–Pb zircon geochronology from geological archives that provide rare access to these otherwise inaccessible crustal segments.

A total of 2,137 new LA-ICP-MS U–Pb zircon ages were obtained from 16 samples representing three complementary archives: (1) crystalline basement drill cores recovered from beneath the Alpine foreland and thrust belt, (2) granitoid and sedimentary exotic boulders preserved within Jurassic–Eocene Ultrahelvetic successions, and (3) Gresten Formation sandstones hosting these boulders. The latter two archives were derived from the Ultrahelvetic slope at the passive European margin, where coarse-grained rock fall and debris flow

material was deposited in pelagic sediments during opening and closure of the Penninic Ocean. During Alpine convergence, these Ultrahelvetic successions were incorporated into the basal part of the Alpine wedge and transported northward during nappe stacking. As a result, they escaped subduction and Alpine metamorphism, preserving a unique record of the southern European margin.

The drill-core samples reveal age patterns that closely resemble those of exposed units of the southern Bohemian Massif. Paleoproterozoic basement ages, Ordovician magmatism, and late Variscan granitoid emplacement allow correlation with the Drosendorf, Gföhl, and South Bohemian Batholith domains. These data demonstrate that major components of the Bohemian Massif continue southward beneath the Alpine foreland and provide new constraints on the subsurface architecture of the European basement.

The provenance of the Ultrahelvetic exotic boulders and sandstones is more complex. U–Pb zircon age spectra record several distinct magmatic episodes, including Ordovician (~467 Ma), Early Variscan (380–350 Ma), Late Variscan (350–310 Ma), and Permian (280–270 Ma) events. Carboniferous granitoids constitute a major component of the sampled basement and indicate that the concealed European margin was more heterogeneous than previously assumed. Contrary to earlier models emphasizing a predominantly Devonian basement source of exotic boulders, the new data reveal contributions from multiple crustal domains and magmatic episodes.

Comparison with published geochronological datasets from the Bohemian Massif and the Eastern Alps suggests that the dominant source region of the exotic boulders and associated sediments was similar to basement domains now exposed in the Tauern Window, while subordinate contributions likely originated from Austroalpine units for the Gresten formation samples. In particular, Ordovician and Permian age components provide important links to intra-Alpine basement provinces and support the existence of significant crustal variability along the southern European margin prior to Alpine convergence. The results refine current models of the distal European margin during the Penninic lifecycle by linking sedimentary archives to basement sources. More broadly, the study demonstrates that exotic boulders and sedimentary successions can preserve robust pre-collisional crustal signatures and provide a powerful means of reconstructing buried continental margins. These archives effectively "lift the orogenic lid", offering new insights into the geology of crustal domains that are otherwise largely inaccessible beneath collisional mountain belts.

A new interpretation of 3D in-depth structures of the western Northern Calcareous Alps, based on re-interpretation of seismic lines and balanced cross sections

Simon Hinterwirth[1], Hugo Ortner[1], Stefan Grießer[2]

[1] University of Innsbruck, Innrain 52f, 6020 Innsbruck
[2] Skava consulting ZT-GmbH, Grabenweg 68, 6020 Innsbruck

Correspondence to: simon.hinterwirth@student.uibk.ac.at

We present a new in-depth tectonic interpretation of the foreland fold and thrust belt between the Tauern Window and the Alpine front, in the western Eastern Alps. In this area, the external fold-and-thrust belt of is largely comprised of the Permo-Mesozoic sedimentary cover of the Austroalpine unit, the Northern Calcareous Alps (NCA), as well as their partly connected Variscan low-grade basement. Both the sedimentary cover and the basement were involved in nappe stacking, which started in the Early Cretaceous in the foreland of an intra-continental subduction zone in the Adriatic microplate. Late Cretaceous to Paleogene northwest-ward drift of the Adriatic plate subsequently led to the closure of the Penninic Ocean and into continent-continent collision in Eocene times, when European and Penninic units were incorporated into the thrust belt. Between Innsbruck and Kufstein in Tyrol, the complex history of deformation often hinders straightforward down-plunge projections and interpretations. Due to the limited existing seismic data, breaking down the resulting structure relies on tectonic modelling. This work presents an interpretation of the foreland fold and thrust belt above the Alpine basal thrust. This is based on new interpretations of deep seismic lines in the wider area, cross-section balancing and 3D modelling. The latter allows us to consider the lateral development of tectonic units along-strike of the orogen, a factor that has often been neglected in previous studies. The Retro-deformation of cross-sections acknowledges (1) the importance of Cretaceous in-sequence thrusting of the Austroalpine nappe stack, but (2) further shows a significant amount of shortening caused by younger out-of-sequence thrusting. This Paleogene deformation is expressed by significant thrusting, duplexing and folding, and accounts for up to 23% of the total

shortening restored in the sections through the NCA. This emphasises the importance of the Neo-Alpine/Eocene collisional phase of deformation, which caused crustal thickening and rearranged the existing nappe stack. (3) Subsequent Miocene orogen-parallel lateral extrusion created faults truncating and offsetting the older thrusts.

The Geological Map Sheet Radenthein-East

Christoph Iglseder[1)]

[1)] Department Geological Mapping, GeoSphere Austria, Neulinggasse 38, 1030 Wien

Correspondence to: christoph.iglseder@geosphere.at

As part of the systematic, comprehensive national Geological Survey, the UTM sheet NL 33-04-06 Radenthein-East was produced at a scale of 1:25000. Now that the accompanying explanatory notes have been printed, a complete work can be presented that combines two UTM quarter sheets into a modern representation and is accessible both digitally in the GeoSphere Tethys research data repository and in print in the GeoSphere Austria library. The definitions of the geological units are available in the GeoSphere Austria Thesaurus.

The map sheet is located in the border region of the provinces of Styria, Carinthia, and Salzburg and covers the Gurktal Alps in the vicinity of the Turracher Höhe. It documents and provides essential data for understanding the complex structure of the Upper Austoalpine in this area. Using a structured concept, the tectonic and lithodemic units of this area are presented to illustrate a cross-section of the Upper Austoalpine nappe stack and characteristics of the Austroalpine Detachment System.

Through an interdisciplinary approach, a modern picture of the Quaternary geological situation and landscape development, as well as applied geoscientific content—particularly regarding raw materials and hydrogeology—can be presented. This provides the basis for future sustainable resilience and resource management.

Along with the proceedings of the 2019 workshop held by the Geological Survey in Murau and the geological walks “Fire and Ice – Turracher Höhe Adventure Geotrails,” an excursion guide is available for both the general public and experts, inviting readers to explore the content of the map sheet.

The Speik Complex as a Relic of a Devonian Oceanic Suture Zone in the Eastern Alps

Kevin Karner-Rühl[1)], Christoph A. Hauzenberger[1)], Walter Kurz[1)], Harald Fritz[1)], Daniela Gallhofer[1)], Ralf Schuster[2)], Heinrich Mali[3)]

[1)] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Graz, Austria
[2)] GeoSphere Austria, Vienna, Austria
[3)] Chair of Geology and Economic Geology, Montanuniversität Leoben, Leoben, Austria

Correspondence to: kevin.karner-ruehl@uni-graz.at

The Speik Complex is an ophiolitic assemblage within the Austroalpine Silvretta-Seckau Nappe System, composed predominantly of ultrabasic and basic lithologies. It preserves important evidence for the pre-Alpine evolution of the Austroalpine domain. This study integrates petrology, whole-rock geochemistry, geothermobarometry, thermodynamic modeling and geochronology to reconstruct its pressure-temperature-time (P-T-t) evolution and geodynamic significance.

The Speik Complex is exposed near the village of Traföß, in the Gleinalpe region, the southern Seckauer Tauern and at Hochgrößen mountain. It consists mainly of variably serpentinized ultramafic rocks associated with (garnet-)amphibolites, rare eclogites, and subordinate gneisses and marbles. Eclogites from two different localities contain garnet, clinopyroxene/omphacite, amphibole, zoisite, rutile and quartz. Garnets are generally homogeneous, but some record a second growth stage with elevated grossular (Grs28-36) and pyrope (Prp10-25) contents at their rims. Geothermobarometry, Zr-in-rutile thermometry and phase-equilibrium modeling indicate peak metamorphic conditions of ~ 650°C and 1.3-2.0 GPa. Whole-rock geochemistry of eclogites and (garnet-)amphibolites shows a tholeiitic differentiation trend derived from basaltic protoliths. Trace- and rare-earth-element patterns display MORB affinity, in particular N-MORB and E-MORB signatures, indicating an oceanic origin. U-Pb zircon dating of an eclogite (Gulsen) and garnet-amphibolites (Preg, Gmoaalm) yields Middle to Late

Devonian ages of 386.5 ± 1.7 Ma, 389 ± 2.1 Ma, and 381 ± 5.9 Ma, consistent with published data from Faryad et al. (2002) and Guan et al. (2025). Sm-Nd whole-rock-garnet isochrons from adjacent garnet-amphibolites give slightly older ages of 406 ± 4 Ma and 413 ± 5 Ma. Metagranitoids yield Late Cambrian zircon ages of 503.2 ± 1.6 Ma and 496.3 ± 2.1 Ma, linked to the Hochreichart Plutonic Suite, while middle to late Permian intrusions (272.3 ± 3.2 Ma and 256.9 ± 1.5 Ma) indicate later tectono-magmatic activity.

These data indicate that the Speik Complex represents fragments of oceanic lithosphere formed along the northern Gondwana margin (Neubauer et al., 2022; Finger and Riegler, 2023) that underwent Devonian high-pressure metamorphism. It is interpreted as an oceanic suture zone predating the Variscan collision, preserving a key record of pre-Variscan tectonic evolution in the Eastern Alps.

Polyphase Metamorphic and Magmatic Evolution of the Seckau Complex, Eastern Alps: Insights into the Pre-Alpine History of the Austroalpine Basement

Kevin Karner-Rühl[1], Walter Kurz[1], Christoph A. Hauzenberger[1], Harald Fritz[1]

[1] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Graz, Austria;

Correspondence to: kevin.karner-ruehl@uni-graz.at

Pre-Alpine basement units of the Eastern Alps preserve important records of the Paleozoic evolution of the northern Gondwana margin despite their incorporation into the Austroalpine Nappe System during Alpine orogeny. The Seckau Complex, part of the Silvretta-Seckau Nappe System, experienced greenschist- to amphibolite-facies Eo-Alpine metamorphism but locally retains evidence of older metamorphic and magmatic events. To constrain its tectono-metamorphic evolution, we combine petrological observations, whole-rock geochemistry, geothermobarometry, thermodynamic modeling and geochronological data from metapelitic and magmatic rocks of the Seckau Complex.

The Glaneck Metamorphic Suite, comprising predominantly garnet-bearing paragneiss and mica-schist records a polyphase metamorphic history. Garnet textures and compositional zoning reveal two distinct growth stages. Early garnet nucleation occurred at approximately 550°C and 0.4-0.5 GPa, whereas garnet rim growth developed under higher metamorphic conditions of ~ 570-620°C and 1.1-1.4 GPa. These conditions are characteristic of Eo-Alpine metamorphism and are supported by Zr-in-rutile temperatures of around 600°C. However, a migmatized paragneiss yielded a U-Pb zircon age of ~ 505 Ma, suggesting the preservation of a pre-Variscan metamorphic event (Mandl et al., 2018). In contrast, EPMA monazite ages of ~ 68-64 Ma from garnet-bearing mica-schists from the localities of Eisenpass and Roßbachkogel document Late Cretaceous metamorphic overprinting and may indicate a tectonic affinity of parts of the Seckau Complex with the adjacent Koralpe-Wölz Nappe System. Rocks of the Glaneck Metamorphic Suite are intruded by several generations of calc-alkaline,

predominantly peraluminous metagranitoids with I- to S-type affinities. U-Pb zircon geochronology identifies multiple magmatic episodes, including middle Cambrian-Early Ordovician intrusions of the Hochreichart Plutonic Suite (508 ± 3.9 Ma and 486.7 ± 2.2 Ma) and Early Carboniferous magmatism represented by the Hintertal Plutonic Suite (357.4 ± 1.2 Ma).

These results demonstrate that the Seckau Complex preserves a long-lived crustal evolution from the Cambrian to the Alpine orogeny. The combined record of Paleozoic magmatism, possible pre-Variscan metamorphism, and Late Cretaceous overprinting highlights the complex tectonic evolution of the Austroalpine basement and provides new constraints on the pre-Alpine history of the Eastern Alps.

New map, new insights: disentangling the Tauern Window's Matrei Zone

Chiara Költringer[1], Benjamin Huet[1], Manfred Linner[1], Michael Lotter[2)]

[1] Division of Basic Geological Services, Geosphere Austria, Hohe Warte 38, 1190, Vienna, Austria

[2] Division of Geophysical and Applied Geological Services, Geosphere Austria, Hohe Warte 38, 1190, Vienna, Austria

Correspondence to: Chiara.Koeltringer@geosphere.at

The Matrei Zone in the South of the Tauern Window is positioned in the contact zone of the Upper Penninic Nappes and the Austroalpine Unit in footwall and hanging wall positions respectively. It comprises a heterogeneous association of lithologies derived from the Piemont-Liguria Ocean and its southern continental margin, nowadays represented by the Lower Austroalpine Unit. Various genetic interpretations for the Matrei Zone exist. While its geodynamic setting as accretionary wedge in a subduction zone is widely agreed on, the presence of the Austroalpine lithologies within remains discussed. Their occurrence is explained either as olistoliths, elements scraped off the upper plate within a tectonic mélange, or as lenses formed by out-of-sequence thrusting. Also, clear markers are lacking to define the position of the lower boundary of the Matrei Zone. To unravel the debated tectonic situation, revisited geological mapping of key areas in the contact zone of the Tauern Window and the Austroalpine Unit is needed. Here, we reassess the lithological content and tectonic meaning of the Matrei Zone based on a newly established detailed geological map from the Upper Möll valley in Carinthia, Austria. New insights allow for discussion of its boundary to the Lower Penninic Nappes as well as the boundaries between the tectonic units within.

Our findings reveal that the basis of the Matrei Zone is marked by a phyllonitization front within the impure marbles of the Lower Penninic Nappes. A sharp lithological upward transition from thick impure marbles and massive greenschist to phyllite signals the boundary between two tectonic units. The Matrei Zone is formed of several lithological associations, which can be followed for several tens of kilometres. The lowermost unit contains of rare olistholiths and metaconglomerate of continental rocks within a matrix of graphitic phyllite and

carbonate phyllite. The central unit is made of greenish, chlorite rich phyllite and quartz phyllite. The uppermost unit is a tectonic mélange, framework-supported with little phyllitic matrix. It is composed of large olistholiths of triassic quarzite and carbonate, metamorphic debris-flow deposits, serpentinite, metaradiolarite and metamorphic Aptychus limestone. The unit is confined by a clearly tectonic contact at its top. Pristine coherent Lower Austroalpine Nappes occur as discontinuous elements above the uppermost tectonic mélange and in particular above the uppermost serpentinite.

Structure of the Graz Paleozoic Nappe Complex

Kurt Krenn[1], Harald Fritz[1], Bernhard Hubmann[1]
[1] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Austria

Correspondence to: kurt.krenn@uni-graz.at

The Graz Paleozoic Nappe Complex (GPNC) consists of a metasedimentary pile of facially diverse units that expands from the upper Silurian to the Carboniferous. The traditional view of the tectonic structure includes three major nappe complexes, from the structural base to the top, the Schöckl Group Nappes, Laufnitzdorf-Kalkschiefer Nappes and Rannach-Hochlantsch Nappes. The age of nappe stacking is considered to be Lower Cretaceous. Structural investigations show that the Schöckl Group Nappes formed by detachment- and fault-bend-folding creating a N- to NW-vergent antiform-synform duplex structure. Syn-tectonic temperatures range from c. 550°C in the highest units and c. 400°C in lower units. The structural style of the Hochlantsch and Kalkschiefer Nappes represents a thin-skinned fold-and-thrust belt with N- to NW-directed frontal thrusts and distributed S-directed back thrusts. Thrusting is predated by a prominent syn- to post-Gosauic fault system. The northwestern and southwestern boundaries represent Gosauic strike-slip and normal faults, respectively, associated with deposition of Gosau sediments. The northeastern fault system is represented by the discrete normal fault between the GPNC and its underlying Koralpe-Wölz Nappe System. The timing of shearing is linked to the Austroalpine detachment system. Internal faults of the GPNC, the sinistral Rabenstein Fault and the dextral Leber Fault, divide the GPNC into three domains with different structural styles. Domain 1 between both conjugate faults is characterized by NE-directed shearing and thrusting. Domain 2 between the Leber Fault and the easterly-located Gasen Nappe includes dominantly SE-directed structural elements that overprint earlier formed NW-directed thrust fabrics. Domain 3 between the northwestern boundary of the GPNC and the Rabenstein Fault is best characterized as a sinistral wrench corridor accompanied by coaxial vertical rock flow. Retro-deformation of all domains allows recognition of a simple Cretaceous duplex structure predating the Gosauic structures.

Provenance shift at the northern margin of Gondwana during the Ordovician and Silurian recorded by detrital U-Pb zircon dating from the Eastern Alps

Johannes Lukas[1], Laura Stutenbecker[2], Matthias Hinderer[3], Armin Zeh[4]

[1] Institut für Angewandte Geowissenschaften, Technische Universität Darmstadt, Schnittspahnstraße 9, 64287 Darmstadt, Deutschland
[2] Institut für Geologie und Paläontologie, Universität Münster, Corrensstraße 24, 48149 Münster, Deutschland
[3] Institut für Angewandte Geowissenschaften, Technische Universität Darmstadt, Schnittspahnstraße 9, 64287 Darmstadt, Deutschland
[4] Institut für Angewandte Geowissenschaften - Mineralogie und Petrologie, Karlsruher Institut für Technologie (KIT), Adenauerring 20b, 76131 Karlsruhe, Deutschland

Correspondence to: lukas@geo.tu-darmstadt.de

The paleogeographic position of the Alpine terrane with respect to (peri-)Gondwana during the Paleozoic is still a matter of debate. The Carnic Alps with its biostratigraphically well constrained siliciclastic deposits of Ordovician to Silurian age are specifically suited to shed new light on this question based on multi-proxy provenance analysis. These non- to low-grade metamorphic sediments allow the application of various provenance-sensitive methods such as petrology, heavy mineral distribution, bulk geochemistry, U-Pb and Lu-Hf zircon dating, rutile as well as garnet geochemistry.

Petrological and geochemical data indicate a predominantly felsic magmatic hinterland with subordinate sedimentary and metamorphic rocks. For most of the siliciclastic formations a high compositional maturity and zircon-tourmaline-rutile-dominated heavy mineral spectra suggest numerous reworking and recycling processes. The results of detrital U-Pb zircon dating (in total 1398 concordant ages) yield signatures typical for sedimentary rocks from the northeastern margin

of Gondwana and can be assigned to the East African-Arabian province. Most are Pan-African in age, but presence of Meso- to Paleoproterozoic and few Archean ages points to contributions from central Gondwana. Relatively young Cambro-Ordovician zircon ages are linked to local volcanism along the northern margin of Gondwana whose products are present in the western Carnic Alps. A stratigraphic trend upsection is marked by an increase of zircons with Stenian-Tonian ages (0.9-1.2 Ga) and a decrease of zircons with Pan-African ages (0.5-0.7 Ga). Notable is the increase of zircons with an age around 0.8 Ga in the Hirnantian.

This change is also observed in contemporaneous sediments on the Arabian Peninsula, thereby providing a spatial reference point. We interpret this punctuated shift around the Hirnatian glaciation in detrital zircon ages by enhanced sediment input from the center of Gondwana mainland and reduced input from the Cadomian crust and the Cambro-Ordovician magmatic arc of Northern Gondwana. Presumably, these rock suites became widely covered by glacial to proglacial detritus originating from the interior of Gondwana.

Timing and mode of initial marine flooding in the southern Pannonian Basin: new U-Pb age constraints from the Prnjavor and Tuzla basin

Oleg Mandic[1], Nevena Andrić-Tomašević[2], Robert Šamarija[2], Stjepan Ćorić[3], Ljupko Rundić[4], Armin Zeh[2], Davor Pavelić[5], Sejfudin Vrabac[6], Patrick Grunert[7]

[1] Geological-Paleontological Department, Natural History Museum Vienna, Burgring 7, 1010 Vienna, Austria
[2] Institute of Applied Geosciences, Karlsruhe Institute of Technology, Adenauerring 20a, 76131 Karlsruhe, Germany
[3] GeoSphere Austria, Neulinggasse 38, 1030 Vienna, Austria
[4] Department of Regional Geology, Faculty of Mining and Geology, University of Belgrade, Kamenička 6, 11000 Belgrade, Serbia
[5] Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva ul. 6, 10000 Zagreb, Croatia
[6] Faculty of Mining, Geology and Civil Engineering, University of Tuzla, Tuzla, Bosnia and Herzegovina
[7] Institute of Geology and Mineralogy, Faculty of Mathematics and Natural Sciences, University of Cologne, Otto-Luxemburger Straße 90, 50674 Cologne, Germany

Correspondence to: oleg.mandic@nhm.at

The Pannonian Basin in Central and Southeastern Europe is a huge landlocked basin delineated by Alpine-Carpathian-Dinarides chain. This extensional backarc basin originating by tectonic rifting at about 18 Ma, was successively flooded by the Central Paratethys Sea. The Slovenian Corridor along the Alpine-Dinarides junction enabled its communication with the Mediterranean Sea. Marine flooding along the southern margin of the Pannonian Basin - between the Styrian Basin in Austria and Velika Morava Basin in Serbia - is still poorly understood. While the conflicting biostratigraphic interpretations contribute to ongoing discussions on the timing and mode of this major environmental turnover, independent radiometric data are still rare.

The present study contributes three new U-Pb zircon ages which are the very first such data on the Miocene marine transgression in northern Bosnia and Herzegovina. Datings from primary volcaniclastic deposits prove the middle Badenian age for marine transgression uniformly, with a 0.5 Ma eastwards-younging trend of its onset, dated at 14.6 Ma in Prnjavor Basin and at 14.1 Ma in the Tuzla Basin. This trend stays in line with the literature data suggesting a steady eastwards propagation of extension along the Pannonian Basin southern margin.

Towards a better understanding of the interplay between tectonic and glacioeustatic forcing of the regional marine progression, a review of published stratigraphic data has been conducted, depicted correspondingly in four paleogeographic maps of ~1-Myr resolution. Building on these data, we bracket the initial gradual flooding interval to the late Burdigalian–early Serravallian (17 to 13.5 Ma) time interval, respectively, attaining up to 3.5 Myr overall duration in a step-wise manner.

We infer fault growth and linkage as mechanisms controlling the hydrological pathways and thereby the direction of the transgression. This implies a transgression direction oblique to the main regional extensional direction. In some cases, local stress changes may lead to formation of sea pathways/gates opposite to the direction of extension. Although the tectonic phases were the main drivers in the creation of accommodation space, along the NE Dinarides, glacioeustasy driven by the global climate suspended the landward propagation of the coastline during sea-level low-stands at long obliquity nodes.

The presently published study is available under https://doi.org/10.1016/j.gloplacha.2026.105532 (open access).

The Hasental porphyry, another type of Permian magmatic rock in the Austroalpine Unit (Eastern Alps)

Josef Nievoll[1], Harald Fritz[2], Daniela Gallhofer[2], Christoph Hauzenberger[2], Ralf Schuster[3], Etienne Skzypek[2]

[1] Gumpendorferstraße 83-85/2/48, 1060 Wien, Austria
[2] Department of Earth Sciences, NAWI Graz Geocenter, 8010 Graz, Austria
[3] Division of Geophysical and Applied Geological Services, Geosphere Austria, Neulinggasse 38, 1030 Vienna, Austria

Correspondence to: josef.nievoll@gmail.com

For the first time the Hasental porphyry appears in the geological map sheet Mürzzuschlag scale 1:75,000 (Cornelius, 1936) as two small occurrences about 10 km east of Mürzzuschlag. Shortly after, it was described by Cornelius (1938) as an eye-catching lithology with up to 60 mm large, idiomorphic K-feldspar and <15 mm-sized dark grey quartz porphyroclasts in a fine-grained, greyish matrix rich in serizite. It occurs within fine-grained, biotite rich paragneiss. Cornelius (1936) interprets it as a porphyry with a granitic composition, occurring in the form of one or more veins maybe following the regional strike.

Later on, the Hasental porphyry was shown in GK50 104 Mürzzuschlag (Mandl et al. 2001), mentioned in Nowotny and Rockenschaub (2001) as part of the Lower Austroalpine Stuhleck-Kirchberg Nappe and encountered in the new Semmering railway tunnel. It was recognized that its host rock is not monotonous, muscovite-rich, phyllonitic micaschist typical for the Stuhleck-Kirchberg nappe, but a more variegated rock association of biotite-rich and epidote bearing paragneiss, interlayered with banded amphibolite and greenschist. This association corresponds to that of the Waldbach Complex, and therefore, the unit was assigned to the Vorau nappe of the Silvretta-Seckau nappe system by Ranftl et al. (2025). Due to regional considerations, a Permian age of the Hasental porphyry was ventured.

We traced the Hasental porphyry by loose blocks over 1.5 km from SE to NW and sampled it for microscopic, geochemical and geochronological (U-Pb zircon) investigations. Close to its northwestern termination, it shows a thickness of about

5 m in an outcrop with a gently WNW dipping foliation. Brittle deformed and rotated K-feldspar porphyroclasts indicate top to the SSW sense of shear. The microscopic investigation confirms the findings of Cornelius (1938), who estimated an upper greenschist facies metamorphic overprint, due to the mineralogical composition of the matrix. This contrasts with the amphibolite facies overprint of the host rocks which is Variscan in age. Zircons in the Hasental porphyry form idiomorphic grains <200 μm with oscillatory zoning in BSE images. U-Pb dating by LA-ICP-MS is currently underway. If the Permian age of the Hasental porphyry can be confirmed, it would be another member of the Permian magmatic suite in the eastern part of the Silvretta-Seckau nappe system.

Permian age of hornblende gabbro of the Northern Calcareous Alps confirmed (GK50 Sheet 103 Kindberg)

Josef Nievoll[1], Harald Fritz[2], Daniela Gallhofer[2], Christoph Hauzenberger[2], Etienne Skrzypek[2]

[1] Gumpendorferstrasse 83-85/2/48, 1060 Wien, Austria
[2] NAWI Graz Geocenter - University of Graz. Institute of Earth Sciences, Universitätsplatz 2, 8010 Graz, Austria

Correspondence to: josef.nievoll@gmail.com

Hornblende gabbro near Hohe Veitsch was first described by Cornelius (1930). He provided a detailed description, a chemical analysis, and discussed the geological setting. In a later publication Cornelius (1936) suggested an early Triassic age of emplacement. Mandl (2016) reported a Permian age but provided no analysis data. Therefore, a resampling was carried out for another U-Pb zircon analysis, as well as for microscopic examination and geochemical analyses.

At Fadeneben the gabbro occurs together with rauwacke of probably Anisian age which typically occur along the Juvavic thrust plane (Mandl 2016, Bryda et al. 2020); the gabbro must, therefore, be considered as tectonically inserted at the thrust plane. Part of the gabbro has been displaced by the Almweg fault, an eo-Alpine dextral wrench fault (Nievoll et al. 2022) to the NW). Here, a very weak, brittle Alpine deformation can be observed. Another small gabbro occurrence was discovered at Lahnboden within sandstones of Werfen Formation about 50 m below the Juvavic thrust plane. In thin section the gabbro shows ophitic structure with <6 mm-sized, strongly altered hornblende and plagioclase grains, smaller ilmenite and titanite grains and secondary chlorite and epidote domains. In the TAS classification diagram, the data plot into the gabbro field; in diagrams discriminating geotectonic settings after Pearce and Cann (1973) the data plot into the areas of Within-Plate Basalts and Intraplate Tholeiites, respectively.

Conventional zircon preparation failed since very few grains >30 µm are present. Laser ablation inductively coupled mass spectroscopy was therefore carried out in thin section with a spot size of 10 µm. Out of a total of 17 grains, 4 were rejected as more than 6% discordant. The remaining 13 grains yielded 206Pb/238U ages between 306 and 250 Ma, with 9 spots in a cluster producing a weighted mean 206Pb/238U ages of 254.7 ± 0.9 Ma with MSWD = 5.1. We consider this age to be meaningful. It dates the magmatic emplacement of the gabbro during the latest Permian, when the Adriatic lithosphere thinned out predating the opening of the Meliata Ocean (e.g., Strauss et al., 2023; Leitner et al. 2025).

An alpine metamorphic T-max profile through the Western Tauern Window (Eastern Alps) using Raman spectroscopy on carbonaceous material (RSCM)

Mathias Oehlke[1], Walter Goetz[2]

[1] BGU-Büro für geologische Untersuchungen, 37154 Northeim, Germany

[2] Max-Planck-Institut für Sonnensystemforschung (MPS), 37077 Göttingen, Germany

Correspondence to: oehlke@gmx.de

Raman spectroscopy of carbonaceous material (CM) has been used to study a 50 km long profile across the Western Tauern Window from Gitsch and Pfunderer Tal in the South via Hochfeiler, Pfitscher Joch, Spannagelhaus, Tuxer Tal to Mayrhofen and Zell am Ziller in the North. Based on 77 samples from CM bearing, greenschist to amphibolite facies metasediments (schists, marbles, gneisses), applying the Raman geothermometer by BEYSSAC et al. (2002), we determined the maximum metamorphic temperature (T) during the ~30 Ma Tauern metamorphism. Each sample was analyzed in 20-30 points to obtain a stable mean value. All measurements have been performed on a WITec alpha300 Raman spectrometer at MPS, Göttingen, with a 532-nm Nd-YAG laser.

The profile starts in the South in the Austroalpine basement with temperatures of ~500°C and continues without any significant T jump at the tectonic border of the Tauern Window further into the penninic Glockner nappe. From Spannagelhaus (~525°C) along the Tuxer Tal, T decreases linearly towards the North with a gradient of 14-15 °C/km, and approaches ~320°C at the northern rim of the Tauern Window in Tuxer Tal and Zillertal.

Some samples showed bimodal T distributions within a given sample. Here, an older, likely variscan cluster could be separated from the alpidic one. These older T values from detrital CM grains that were incorporated into younger sediments, are 30-40°C higher (~560°C) than those of the alpidic part and have therefore been unchanged during the later alpidic event.
The new T values inferred from Raman spectra compare very well to those

inferred from oxygen-isotope data from HOERNES and FRIEDRICHSEN (1974) und SATIR and FRIEDRICHSEN (1986). For comparison, the isotope data have been recalculated using updated values of the fractionation coefficients (CHACKO et al., 2001), which lowered the original temperatures by 20-50°C.

In summary, we find a rectilinear temperature variation across our study area which suggests a block-like uplift of the Western Tauern Window along bordering fault zones rather than domal upwarp.

References

Beyssac, O. et al. (2002): J. Metam. Geol., 20 (9): 859-871

Hoernes, S. and Friedrichsen, H. (1974): Schweiz. Mineral. Petrogr. Mitt. 54 (2/3): 769-788

Satir, M. and Friedrichsen (1986): Neues Jahrb. Min., Abh. 154/3: 313–334

Chacko, T. et al. (2001) in: J.W. Valley and D. Cole (ed.), 2001, Rev. Min. Geochem. 43: 1-81

Keywords

Tauern Window, Raman spectroscopy, carbonaceous material, metamorphic temperature

New petrological, geochemical and geochronological data and a tectonic interpretation of the Wachau region (Lower Austria)

Eva-Maria Ranftl[1)], Ralf Schuster[1)], Christoph Hauzenberger[2)]

[1)] Division of Geophysical and Applied Geological Services, GeoSphere Austria, Neulinggasse 38, 1030 Vienna, Austria
[2)] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Graz, Austria

Correspondence to: eva-maria.ranftl@geosphere.at

As part of the project Terroir Wachau, the Wachau wine-growing region between Stein and Spitz is the focus of a multidisciplinary study including geological, geophysical, climatological, and meteorological investigations. This contribution presents results on bedrock geology, including mapping at the scale 1:10,000 as well as petrological, geochemical, and geochronological data. Geological mapping confirms the distribution of bedrock in previous maps, although the larger scale allows for greater detail. An additional feature is the tectonic subdivision, which attempts to assign the widespread paragneiss matrix and amphibolite layers to the Drosendorf nappe, Raabs unit and Gföhl nappe.

Geochemical analyses on metabasaltic rocks yielded results similar to those of earlier studies. Mostly they are subalkaline with MORB or WPT characteristics. Those from the Drosendorf nappe yield the highest Nb/Zr ratios (>1.3) suggesting a WPT origin. Some metabasalts from the Raabs unit also plot within the MORB and WPT fields, whereas others show VAB, CAB and IAT characteristics. Layers of diorite gneiss represent gabbro enriched in Ba, Rb, Cr and P, with a shoshonitic signature. Metabasalts from the base of the Gföhl nappe are relatively similar to those of the Drosendorf nappe but show lower Nb/Zr ratios. One sample from a metaeclogitic body within the Gföhl orthogneiss shows an OIB signature.

LA-ICP-MS U/Pb zircon dating was performed on four samples that were believed to be part of the Raabs unit. To determine the detrital spectrum of a paragneiss from the Mieslingbach valley, 85 zircons were analysed. The youngest concordant zircon is >1100 Ma and many concordant grains range from 1200 to

1850 Ma. For two diorite gneisses collected around Weißenkirchen magmatic crystallisation ages of 340 Ma were determined. Near one of those diorite gneisses, an undeformed granite forming a concordant layer within amphibolite was sampled. Few zircons indicate a crystallisation age <340 Ma, while mostly discordant ages measured on assimilated grains range from 350 to 600 Ma.

The new data allow the following conclusions: The depositional age of the paragneiss is most likely in the early Neoproterozoic and it is therefore not part of the Raabs unit but of the Drosendorf nappe. With respect to its age and geochemical characteristics, the diorite gneiss may represent an early member of the durbachitic plutonic suite, intruded in a deep crustal level and deformed during exhumation.

Rethinking the Silvretta Nappe: structural and thermal constraints reopen an old debate

Martin Reiser[1], Ben Huet[1], Alfred Gruber[1], Michael Zerlauth[1], Gerd Rantitsch[2]

[1] GeoSphere Austria, Neulinggasse 38, 1030 Wien, Österreich
[2] Lehrstuhl für Geologie und Lagerstättenlehre, Montanuniversität Leoben, Peter-Tunner Strasse 5, 8700 Leoben, Österreich

Correspondence to: martin.reiser@geosphere.at

In western Austria, the Phyllitgneiszone occupies a footwall position below the Silvretta Nappe, with both in the footwall of the Ötztal Nappe. The Phyllitgneiszone comprises pre-Variscan crystalline basement rocks, Carboniferous phyllites and a transgressive Permian to Mesozoic cover. It is currently regarded as an external part of the Silvretta Nappe that has been overthrust by internal parts along an out-of-sequence thrust.

This interpretation has been recently challenged by new correlations differentiating the Mesozoic covers of the Phyllitgneiszone and Silvretta Nappe. To address this, key outcrops in western, central and eastern parts of the contact were investigated through detailed geological mapping, structural analysis and Raman thermometry. Large mass movements, obscuring the tectonic contact between the Phyllitgneiszone, the Penninic Unit and the overlying Silvretta and Ötztal Nappes, led to the earlier misattribution of slid material as bedrock and its erroneous interpretation as folded Silvretta basement. Structural analysis shows a polyphase overprint of the contact with a first episode of top-to-the-WNW thrusting correlating with Cretaceous nappe stacking, followed by a top-to-the-N brittle overprint and NNW-directed thrusting of the Ötztal Nappe relative to the Silvretta Nappe, causing large-scale folding of the Phyllitgneiszone.

Raman thermometry of Carboniferous to Mesozoic cover rocks reveals an eastward-increasing metamorphic gradient, ranging from ca. 300 °C in the west to ca. 430 °C in the east, consistent with conditions recorded in a small sliver of Mesozoic rocks below the Ötztal Nappe and supporting its correlation with the Phyllitgneiszone cover.

The contact between the Phyllitgneiszone and the overlying nappes is a subhorizontal, polyphase structure rather than a steep out-of-sequence thrust. The Mesozoic cover acts as a nappe separator traceable over a length of at least 90 km, connecting with Mesozoic rocks framing the Penninic units in the Engadine Window and demonstrating that the Silvretta and Ötztal nappes shared the same tectonic position during Cretaceous nappe stacking. Only later, this coherent lid of crystalline basement was dissected by the Engadine fault, possibly as a precursor to the Oligocene–Miocene formation of the Engadine Window. These results question the separation of the Silvretta Nappe as an independent Eo-Alpine Unit and have significant implications for the tectonic architecture of the Eastern Alps.

ALPACA: A List of Published and georeferenced Ages Concerning Austrian geologic units

Gerald Schuberth[1], Manuel Werdenich[1], Christoph Iglseder[2]

[1] Department Mineral Resources and Geoenergy, GeoSphere Austria, Neulinggasse 38, 1030 Wien

[2] Department Geologic Mapping, GeoSphere Austria, Neulinggasse 38, 1030 Wien

Correspondence to: gerald.schuberth@geosphere.at

Despite extensive geochronological research on Austria's geological units, there is no central, easily accessible dataset of published age data. Currently, researchers have to manually scan decades of dispersed literature, often struggling with inconsistent rock nomenclature and missing spatial coordinates. To bridge this gap, we present ALPACA: A List of Published and georeferenced Ages Concerning Austrian geologic units.

The goal is to provide a straightforward, openly accessible collection of published ages that is lightweight, easy to handle, queryable and fully referenced without imposing subjective quality judgments on the basal studies. It provides an overview and is easily integratable into GIS applications. Consequently, the dataset exclusively focuses on specific geochronometric results reported as central values with associated uncertainties. It designedly omits stratigraphic or tectonic unit assignments, as this is made possible by cross-referencing with other datasets. Instead, ALPACA encourages users to consult original publications for full context and the raw data, while providing a snapshot of available data.

A key feature of the project is its systematic approach to obligatory spatial referencing. Older publications often lack sample coordinates. Where direct data was unavailable, the positions were deduced from sketches, textual descriptions or personal conversations. To communicate the reliability of these inferred locations transparently, we introduce the Estimated Quality of Georeferencing (EQOG) system. This system ranges from A (direct coordinates provided) to D (based on vague descriptions). All location data is harmonized into the EPSG:4326 reference system.

To address nomenclatural inconsistencies by local names, rock names are harmonized into standardized English terminology, while preserving original publication terms in a secondary field. Mineral abbreviations adhere to IMA conventions. The dataset compiles data from published works and provides BibTeX entries for citation. While not intended as an exhaustive repository or a replacement for a primary literature review, ALPACA serves as a starting point for research.

As the dataset grows over time, it is subject to versioning via a public repository. There will frequently be an official release via the Tethys RDR. The project actively invites contributions from the community to make accessing Austria';s complex geological history even simpler.

Crustal scale geological profiles through the southeastern part of the Bohemian Massif (Austria, Czech Republic)

Ralf Schuster[1)], Eva-Maria Ranftl[1)], Friedrich Finger[2)]

[1)] Division of Geophysical and Applied Geological Services, Geosphere Austria, Neulinggasse 38, 1030 Vienna, Austria
[2)] Department of Environment and Biodiversity, University of Salzburg, Hellbrunnerstrasse 34, 5020 Salzburg, Austria

Correspondence to: ralf.schuster@geosphere.at

While the paleogeographic framework for the Variscan orogenic belt in the southeastern part of the Bohemian Massif is quite clear, a controversial discussion about the tectonic subdivision and deep structure is ongoing. In most small-scale maps a suture of the Rheic oceanic realm is visible but it is missing in large-scale maps. This is because most authors strictly adhere to the classical tectonic subdivision into Moldanubicum and Moravicum even though it does not reflect the pre-Variscan paleogeography.

Two arguments have long been put forward in favor of a more flexible interpretation of the tectonic subdivision: 1) There is an oceanic suture zone of the Rheic Ocean, represented by the Raabs Unit. 2) The affiliation of the individual nappes with the formerly adjacent continents can be determined based on the age of the orthogneisses they contain. Nappes with Ordovician orthogneisses originate from the Armorican Terrane Assemblage (ATA, part of northern Gondwana margin), while those with Proterozoic orthogneisses originate from Brunia (Laurasia).

According to these assumptions and based on new field data, geologic maps and geophysical data sections through the area were constructed. They reach down to the lithospheric mantle and are E-W orientated. Geophysical data allow interpreting the MOHO depth and a thickened lower crust of Brunia. In the northeast Brunia derived rocks form the foreland of the Variscan orogen, and the overlying nappes. These include a fold and thrust belt of Silurian to Carboniferous sediments, and thick-skinned nappes with Neoproterozoic basement forming the

Brunovistulicum east and the Svratka Dome, Pulkau, Pleißing and Drosendorf nappes west of the Boskovice Graben and Diendorf shear zone respectively. In the hanging wall, the Raabs unit represents the oceanic suture. The ATA derived Gföhl, Dunkelstein and Ostrong nappes on top show east directed movement in the east, but westward-vergent folding further west. This argues for west-directed back folding with an overturned limb. Note, in this interpretation the Ostrong nappe is the uppermost tectonic element, instead as the lowermost as in the usual view!

For a nomenclature reflecting the paleogeographic framework we suggest to restrict the Moldanubian unit exclusively to nappes derived from the ATA, whereas the Moravian and Brunovistulian units should consist of rocks sheared off from Brunia. Remnants of the Rheic oceanic realm should be treated separately as 1st order Raabs unit.

Flysch or not flysch: An assessment of an old question regarding the geology of the Swiss Alps

Sophia Johanna Swaton[1], Guilherme Bozetti[2], Chantal L. Schmid[1], Jörg Hermann[1], Fritz Schlunegger[1]

[1] Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, 3012 Bern, Switzerland
[2] Institut Terre and Environnement, University of Strasbourg, 5 Rue René Descartes, 67084 Strasbourg, France

Correspondence to: sophia.swaton@unibe.ch

Foreland basin evolution is commonly divided into an underfilled ‘flysch’ and an overfilled ‘molasse’ stage, characterized by differences in basin fill and geodynamic processes. The flysch stage is initiated by the subduction of an oceanic plate beneath an active continental margin. Slab loading results in the downwarping of the foreland plate, creating accommodation space that is only partly filled by submarine hyperconcentrated and turbidity currents sourced from the hangingwall plate.

We investigated two Thanetian (c. 57–54 Ma) flysch outcrops of disputed paleogeographic position belonging to the Schlieren and Gurnigel nappes in the Central Alps of Switzerland. The Schlieren flysch, exposed c. 50 km to the northeast along strike, has been considered equivalent to the Gurnigel flysch based on their age and their tectonic position in the Alpine nappe stack. Both nappes are thrust onto the Helvetic and Ultrahelvetic and are overlain by nappes derived from the Briançonnais and Piemont-Liguria Ocean.

Our aim was to reconstruct a potential proximal-to-distal relationship between the two units.

We surveyed 50–70 m of Thanetian strata in the Gurnigel and Schlieren units, measured paleoflow directions using sole marks and cross-bedding, and documented the large-scale depositional architecture. Sediments of the Schlieren unit comprise several-metre-thick coarse-grained sandstone beds, likely deposited from (hyper)concentrated, friction-controlled flows that are

characteristic of underfilled basins in a geodynamically active foreland basin. The paleoflow directions indicate transport toward the E. However, the Gurnigel succession is dominated by fine-grained sandstone beds and mudstone interbeds, deposited from southward-directed turbidity currents in a more distal basin setting.

The differences in lithofacies, paleoflow directions, and depositional processes allow us to reject the interpretation that a proximal-to-distal relationship existed between the previously correlated Gurnigel and Schlieren basins, at least during the Thanetian. We propose the Valais Basin as a more plausible depositional centre given the nappes' position within the Alpine nappe stack. The sedimentary record suggests a heterochronous closure of the Alpine Tethys, with underfilled conditions established in the eastern Schlieren realm before affecting the western Gurnigel realm.

Coniacian through Santonian foraminiferal biostratigraphy and cooling signals along the northwestern Tethyan margin - new results from the Upper Gosau Subgroup, Austria

Erik Wolfgring[1], Xenia Hauser[1], Michael Wagreich[1]

[1] University of Vienna, Department of Geology, Josef-Holaubek Platz 2, 1090 Vienna

Correspondence to: erik.wolfgring@univie.ac.at

We revisit a Coniacian–Santonian succession of the Upper Gosau Subgroup (Austrian Northern Calcareous Alps) along the northwestern Tethyan margin to investigate biostratigraphy, palaeoecology, and possible cooling signals across shallow- to deeper-water settings.

The stratigraphic framework is established using calcareous nannofossil and planktonic foraminiferal biostratigraphy, while benthic foraminiferal assemblages and stable isotope data are employed to reconstruct ecological and palaeoceanographic change. Stable isotope records further suggest cooling trends across the studied palaeoenvironments, indicating that such signals are expressed in both shallow and deeper settings.

Particular emphasis is placed on benthic foraminiferal assemblages, which display distinctly different communities reflecting palaeoecological patterns (including taxa showing different habitat preferences). Together with other shallow-water indicators, benthic foraminifera document a clear bathymetric gradient, recording a progressive deepening from neritic environments to upper- and mid-slope settings. Among taxa indicative of shallower environments, we document miliolids such as Quinqueloculina sp. and large agglutinated forms (e.g., Haplophragmium sp.). A second assemblage, characterized by taxa such as Gavelinella spp. and Reussella sp., occurs alongside these forms but becomes more abundant in distal neritic, upper bathyal, and slope environments.

Together, these assemblage patterns provide insights into the organization of benthic ecosystems along the northwestern Tethyan margin. By integrating biostratigraphic, palaeoecological, and geochemical proxies, this study refines regional stratigraphic correlations across the basin';s full depth range and assesses how northwestern Tethyan palaeocommunities responded to environmental and climatic change during the Late Cretaceous.

„New Horizons in Geosciences and Geotechnics“

Session 02

Stratigraphie und Lithodemie in Österreich

Stratigraphy and lithodemy in Austria

Conveners:
Christoph Iglseder & Werner E. Piller

Sequence-Stratigraphic Interpretation of the Sarmatian Succession in the Eastern Styrian Basin Based on Integrated Well-Log Analysis

Arthur Borzi[1], Anna Arrigoni[1], Nikolaus Petschacher[2], Christina Neuhold[3], Gerald Auer[1], Gerfried Winkler[1], Mathias Harzhauser[4], Martin Gross[5], Werner E. Piller[1], Michael Ferstl[6]

[1] Institute of Earth Sciences, University of Graz, NAWI Graz Geocenter, Heinrichstrasse 26, 8010 Graz, Austria
[2] Hydro GmbH, Naglergasse 10, 8010 Graz, Austria
[3] Geo5 GmbH, Roseggerstraße 17, 8700 Leoben, Austria
[4] Museum of Natural History Vienna, Geological-Paleontological Department, Burgring 7, 1014 Vienna, Austria
[5] Universalmuseum Joanneum GmbH, Department for Geology and Paleontology, Weinzöttlstraße 16, 8045 Graz, Austria
[6] A14 – Wasserwirtschaftliche Planung, Wartingergasse 43, 8010 Graz, Austria

Correspondence to: arthur.borzi@uni-graz.at

Deep aquifer systems of the Styrian Basin represent an important resource for groundwater management and geothermal utilization. Their sustainable use requires a robust stratigraphic framework and improved understanding of basin evolution during the Sarmatian (Middle Miocene). The Styrian Basin is the westernmost part of the Pannonian Basin System and formed during Miocene back-arc extension. The investigated wells are located in the Fürstenfeld Subbasin. Geophysical well logs, borehole information, and stratigraphic constraints were compiled and correlated across four deep wells in the Fürstenfeld–Blumau area.

The presented study focuses on the sequence-stratigraphic interpretation of the Sarmatian succession using regional well-log correlations. Multiple stacked 4th-order depositional sequences were identified based on characteristic gamma-ray log patterns. The lower Sarmatian is characterized by two stacked highstand

successions separated by a flooding event and expressed by strongly serrated gamma-ray log patterns and stacked parasequences. These patterns reflect repeated shoreline shifts under fluctuating sediment supply and accommodation creation during continued basin subsidence.

A major 4th-order sequence boundary is identified at the top of the lower Sarmatian succession and is interpreted to reflect a relative sea-level fall and potential subaerial exposure event marking the transition to the upper Sarmatian. The overlying Carinthian Gravel is interpreted as a lowstand systems tract consisting of multiple stacked coarse-grained depositional pulses. Due to its erosive nature, the associated falling-stage systems tract is considered poorly preserved or entirely removed. Renewed transgressive deposition above the gravel succession culminates in the development of an upper Sarmatian highstand succession.

The results indicate that the established subdivision of the Sarmatian cannot always be reproduced using well-log correlations alone and suggest a more complex sequence-stratigraphic architecture. Integrated well-log and stratigraphic analyses improve regional stratigraphic and hydrogeological models and support deep groundwater management. Future biostratigraphic data will provide chronostratigraphic control and further refine regional correlations, sequence boundaries, and aquifer assessment.

Formationsbezeichnungen der Trias im Nordalpin und deren Validität – noch immer ein Problem?

Rainer Brandner[1)]

[1)] Institut für Geologie, Universität Innsbruck

Correspondence to: Rainer.Brandner@uibk.ac.at

Ja, leider ist das noch immer ein Problem. Im bestens erforschten Alpenraum mit zahlreichen Typlokalitäten werden seit langem unzulänglich definierte lithostratigraphische Bezeichnungen verwendet, die nach den geltenden Richtlinien zur stratigraphischen Nomenklatur nicht valide sind. Herkömmliche lithostratigraphische Begriffe werden gerne, vor allem in der englischsprachigen Literatur, unter Hinzufügung des Formationsbegriffes „pseudo“-formalisiert. Zumeist fehlt die Neubearbeitung eines Typprofiles. Das ist bei vielen lithostratigraphischen Begriffen, die in der Stratigraphischen Tabelle von Österreich, 2004 eingetragen sind, der Fall. Ähnlich verhält es sich auch bei der nicht nachvollziehbaren neuen Gruppengliederung im bayerischen Alpenanteil mit ebenso nicht validierten Formationsbezeichnungen (Teipel and Hornung, 2022, Geol. Bavarica 123).

Zwei besondere Probleme seien hervorgehoben: „Werfener Schichten“ und „Nordalpine Raibler Schichten“. Bei beiden Bezeichnungen sind schon früh Fehler bei der Übertragung der Begriffe vom Südalpin auf das Nordalpin und umgekehrt passiert. Für die Werfener Schichten in den Nördlichen Kalkalpen (NKA) liegen detailliert beschriebene Profile in der Typregion Werfen vor, die allerdings bisher nicht definiert wurden. Der Begriff wurde auf die Südalpen übertragen und dort als Werfen-Formation mit zahlreichen Subformationen definiert (Bosellini, 1968, Broglio-Loriga et al.,1990). Die Werfen-Fm. der Südalpen liegt jedoch in einer völlig anderen lithologischen Ausbildung und Fazies vor als in den Nordalpen. Eine mögliche Lösung wäre die Einführung einer „Werfen-Gruppe“, wobei die bisherigen Subformationen zu Formationen gehoben werden sollten. In den Nordalpen kann damit die „Werfen-Formation“ als Teil der Werfen-Gruppe definiert werden. Allerdings würde hier der geographische Name zweimal verwendet werden, was nicht den Richtlinien entsprechen würde.

In den westlichen NKA ist schon lange der Begriff der „Nordalpine Raibler Schichten“ gebräuchlich. Hier wurde nun wiederrum ein Begriff der Südalpen auf die Nordalpen übertragen, der weder in der faziellen Ausbildung noch im zeitlichen Umfang jenem der Südalpen entspricht. Die Bezeichnung sollte daher in den NKA nicht mehr verwendet werden. Stattdessen sollten neudefinierte Begriffe wie Reingraben-Fm. und Opponitz-Fm. der östlichen NKA auch im Westen angewendet werden.

EAGLE: die Erstellung einer einheitlichen Generallegende für Österreich

Esther Hintersberger[1], Isabella Bayer[1], Gerhard Bryda[1], Stjepan Coric[1], Diego Garcia-Ramos[1], Holger Gebhard[1], Gerit Griesmeier[1], Alfred Gruber[1], Margareta Harbich[2], Diana Hatzenbühler[1], Monika Hölzel[2], Felix Hofmayer[3], Benjamin Huet[1], Christoph Iglseder[1], Christoph Kettler[1], Chiara Költringer[1], Otto Kreuss[1], Manfred Linner[1], Michael Lotter[2], Eva-Maria Ranftl[2], Martin Reiser[1], Jürgen M. Reitner[1], Mathias Steinbichler[1], Michael Zerlauth[1]

[1] Bereich Geologische Landesaufnahme, Geosphere Austria, Neulinggasse 38, 1030 Wien

[2] Bereich Geophysik und Angewandte Geologie, Geosphere Austria, Neulinggasse 38, 1030 Wien

[3] GWU Geologie-Wasser-Umwelt GmbH, Bayerhamerstraße 57, 5020 Salzburg

Correspondence to: esther.hintersberger@geosphere.at

Das Projekt EAGLe (Erstellung der Allgemeinen Geologischen Legende) hat das Ziel, bis 2026 einen österreichweiten Gesamtdatensatz mit einheitlicher Generallegende im Maßstab 1:50.000 basierend auf publizierten Daten zu erstellen. Diese erste Version des Gesamtdatensatzes mit der implementierten ersten Version der Generallegende soll Ende 2026 auf dem Tethys-Datenrepositorium (www.tethys.at) publiziert und über www.maps.geosphere.at öffentlich einsehbar gemacht werden.

Die Datengrundlage bilden über 25.000 Legendeneinträge aus zahlreichen verschiedenen Datensätzen, die auf publizierten geologischen Karten, GeoFAST-Karten und Gebietskarten im Maßstab 1:50.000/1:25.0000 basieren. Wir stellen hier den Arbeitsfortschritt vor und thematisieren Lösungsansätze für Probleme, denen wir auf unserem Weg dorthin begegnet sind.

Die Ausgangsdatensätze für die Kompilation des Gesamtdatensatzes hatten sehr unterschiedliche Datenstrukturen. Teilweise waren nur analoge Karten verfügbar, die zunächst digitalisiert werden mussten. Seit Jänner 2026 werden die aufbereiteten Quelldaten kompiliert und schrittweise mit der Generallegende verknüpft. Mittlerweile wurde auch eine erste Visualisierung basierend auf den vorhandenen Kartensymboliken erarbeitet. Eine geometrische Überarbeitung des Datensatzes, also die Anpassung von Polygonen, Linien oder Punkten (z.B. „Blattrandstörungen") wurde nicht vorgenommen.

Die Generallegende besteht aus einer hierarchisch strukturierten Liste mit über 3200 lithostratigraphischer und lithodemischer Legendenbegriffen, die für die jeweiligen tektonischen Großeinheiten von entsprechenden regionalen Expertenteams bearbeitet wurden. Einige dieser Teams konnten auf vorhandene moderne Übersichtsarbeiten aufbauen, in vielen anderen Gebieten waren jedoch intensive Literaturrecherchen und -studien notwendig. In Kristallingebieten bestand zusätzlich die Herausforderung, schlüssige Konzepte für eine lithodemische Gliederung zu erarbeiten. Oft bestand auch die einzige Information zu einer geologischen Einheit aus veralteten, wenig aussagekräftigen Legendeneinträgen auf älteren Karten. Ohne Geländebegehungen konnten diese nur sehr generellen Begriffen zugeordnet werden. Da eine detaillierte Aufarbeitung aller Legendenbegriffe daher nicht überall möglich war, werden die Originallegendeneinträge zur Nachvollziehbarkeit im Gesamtdatensatz mitgeführt.

Lithodemic Classification of Paleozoic Rocks in Austria: Challenges and Correlation

Christoph Iglseder[1), Martin Reiser[1), Benjamin, Huet[1), Chiara Költringer[1)

[1) Department Geological Mapping, GeoSphere Austria, Neulinggasse 38, 1030 Wien

Correspondence to: christoph.iglseder@geosphere.at

The precise characterization and mapping of pre-Mesozoic geological units in Austria often presents fundamental methodological challenges for mapping geologists. While established lithostratigraphic units and formations dominate in the classic, low-grade, fossil-bearing sediments of the Paleozoic, fundamental stratigraphic principles such as the principle of superposition do not hold in most metamorphic areas of the Eastern Alps and the Bohemian Massif. There, geologic units are sometimes fragmented, have intrusive contacts or experienced intense overprinting by metamorphism and deformation. To overcome this challenge, the use of lithodemic classification following guidelines such as the North American Stratigraphic Code (NASC) has proved effective to structure and subdivide metamorphic units. Within the EAGLe project, lithodemic units were implemented wherever possible to classify metamorphic units in a database-compatible way.

This work presents the application of lithodemic units in Paleozoic rocks of Austria. The focus is on polymetamorphic crystalline basements, magmatic intrusions, and heavily deformed areas of the Eastern Alps and the Bohemian Massif. By delineating lithodemes, suites, and complexes based on rock-specific characteristics, it is possible to bring order to tectonically highly overprinted rock associations whose original stratigraphic sequence has often been lost.

The results show that lithodemic classifications can provide crucial links for regional and supraregional correlation. Particularly for rocks formed and overprinted during the Permian, Variscan, and Ordovician periods, this approach allows the structuring of legends and databases, supported by modern geochemical, geochronological, and thermochronological methods. The introduction of formal lithodemes replaces heterogeneous, informal working designations and creates a consistent, spatial structural model for the Austrian

crystalline rocks. This forms the indispensable basis for future geological mapping, the exploration of mineral resources, and a fundamental understanding of Paleozoic geodynamics in the Variscan and Alpine orogens.

Biostratigraphy revisited

Werner E. Piller[1)]
[1)] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Heinrichstrasse 26, 8010 Graz, Austria

Correspondence to: werner.piller@uni-graz.at

Biostratigraphy is one of the most important methods in stratigraphy and is therefore a main component in the various versions of the International Stratigraphic Guide (ISG). From time to time, the principles of biostratigraphy have to be evaluated and, if necessary, updated by the Subcommission of Stratigraphic Classification of the International Commission on Stratigraphy. The latest update 2026 considered these principles generally valid as described in the ISG. The basic unit is the biozone which can be subdivided into Range Zones (Taxon Range Z., Concurrent Range Z.), Interval Zones (Base Z., Top Z., Base-Top Z., Partial Range Z.), Acme Zones and Assemblage Zones. A special biozone is the Lineage Zone which is based on phylogenetic relationships of species. Biozones are bounded by biohorizons which may be defined by the lowest occurrence and highest occurrence of a taxon. In contrast to frequent use the lowest occurrence should be named Base (B) and highest occurrence Top (T) to avoid confusion with other definitions/abbreviations. First Occurrence Datum (FOD) and Last Occurrence Datum (LOD) have to be rejected because these are temporal terms. First Appearance Datum (FAD) and Last Appearance Datum (LAD) are reserved for Lineage Zones but should be used with caution. The sequence of biozones represents a biozonation which is together with the biohorizons the most important correlation tool. The strong influence of several parameters such as phylogeny, paleoecology, paleobiogeography and paleogeography clearly explains that no global biozonation can exist. As pragmatic but insufficient option ‘standard biozonations’ are established which represent, however, only a fraction of existing biozonations. Correlation of biohorizons and biozones can and should be supported by numerical methods to gain geochronologic results. The step from biostratigraphy to biochronology reflects different approaches and has to be considered very important. For biochronology numerical age dating is required for which several methods exist but basically dating by radiogenic elements or by astrochronology and (as indirect method) by magnetochronology is applied. The final step is to interrelate biostratigraphy/biochronology with other stratigraphic methods to end up with a well based high-resolution integrative stratigraphy. Biostratigraphy plays an

important role for chronostratigraphy because 80% of the defined GSSPs are based on bioevents.

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Session 03

Die Rolle der Paläontologie in der Erdsystemforschung –
Methoden, Innovationen und integrierte Forschungsansätze

The Role of Paleontology in Earth System Research –
Methods, Innovations, and Integrated Research Approaches

Conveners:
Gerald Auer, Theresa Nohl & Anna Arrigoni

NAWI Graz Natural Sciences

TU Graz

UNI GRAZ

Evaluating foraminifera-based paleodepth proxies across temporal and spatial scales: insights from the Early-Middle Pleistocene Transition

Anna Arrigoni[1)], Werner E. Piller[1)], Matthias Kranner[2)], Briony Mamo[3)], Gerald Auer[1)]

[1)] Department of Earth Sciences, University of Graz, NAWI Graz Geocenter; Graz, 8010, Heinrichstraße 26, Austria.
[2)] Bavarian Environment Agency – Geological Mapping, Geohazard Assessment; Hof/Saale, 95030, Hans-Högn-Straße 12, Germany.
[3)] School of Natural Sciences, Faculty of Science and Engineering, Macquarie University; NSW, 2109, Australia.

Correspondence to: anna.arrigoni@uni-graz.at

Paleobathymetric reconstructions are crucial in understanding sedimentary basin evolution, oceanographic circulation, marine basins´ connectivity and spatial dynamics of past marine ecosystems. Foraminiferal abundances and assemblage composition are valuable tools for resolving the paleodepth evolution of a given location. Here, we compare different widely applied foraminifera-derived paleodepth proxies –the planktic to benthic foraminiferal ratio (%P) and the depth habitat ranges of benthic foraminiferal taxa– by applying the corresponding transfer functions to ~100 m-thick sedimentary succession recovered at International Ocean Discovery Program Site U1460. This site is located at the shelf edge of the western Australian continental shelf and encompasses ~450 kyr of glacial-interglacial sea-level variability across the Early-Middle Pleistocene Transition (EMPT; 1.25-0.6 Ma). The EMPT represents a fundamental interval in the Pleistocene, as it marks the shift from a 41-kyr to a 100-kyr dominant glacial-interglacial cyclicity with associated amplified glacio-eustatic oscillations, making it an ideal time frame for: i) tracking the paleodepth evolution of the continental shelf; ii) evaluating temporal and spatial sensitivity of the examined paleodepth proxies to the glacial-interglacial forcing. Together, both proxies document an initial deepening of the shelf prior to Marine Isotope Stage 24, followed by a gradual shallowing through the remaining record. This study clarifies both strengths and limitations of foraminifera-based paleobathymetric reconstructions in shallow-water environments, where

ecological processes strongly modulate foraminiferal assemblage composition. The %P and its derived paleodepth estimates reliably capture pattern and trends of global glacial-interglacial sea-level variability. However, the paleodepth values resulted anomalously elevated for a continental shelf setting, suggesting that ecological imprint might control in part the %P and mask the bathymetric information. In contrast, paleodepths solely derived from the benthic foraminiferal depth ranges led to a more plausible depth reconstruction for a carbonate ramp, although it lacked the resolution needed to distinguish glacial-interglacial depth fluctuations due to the broad depth zonation characterizing the benthic assemblage. Achieving a higher bathymetric resolution will require the targeted use of depth-sensitive benthic taxa rather than relying on the full assemblage.

Tracing the Messinian Salinity Crisis into the Indian Ocean: Bulk Carbonate and Bulk Organic Matter Isotope Records from the Maldives (IODP Site U1467)

Gerald Auer[1], Tereza Kunkelova[1], Or M. Bialik[2]

[1] University of Graz, Department of Earth Sciences, NAWI Graz Geocenter, Heinrichstrasse 26, 8010 Graz

[2] National Institute of Oceanography, Israel Oceanographic and Limnological Research, Haifa 310800, Israel

Correspondence to: gerald.auer@uni-graz.at

The Messinian Salinity Crisis (MSC) was a major hydrological event in the Mediterranean Sea during which salinity increased dramatically, resulting in extensive evaporite deposition across much of the basin. The tectonic restriction that initiated the MSC began at 5.97 Ma, significantly reducing connectivity between the Mediterranean and the Atlantic by closing and restricting the Mediterranean-Atlantic seaways between Africa and Iberia.

In the Mediterranean, the MSC can be subdivided into three distinct stages of restriction, each associated with different evaporite emplacement within the restricted basin. During MSC Stage 1 (5.97–5.60 Ma), large gypsum deposits accumulated in circum-Mediterranean shallow-marine settings (< 800 m water depth). During MSC Stage 2 (5.60–5.55 Ma), hydrological restriction further intensified, and up to 3 km of halite precipitated. Finally, during MSC Stage 3 (5.55–5.33 Ma), restriction of the remaining seaway (i.e., the Strait of Gibraltar) lessened, reconnecting the Mediterranean basin to the North Atlantic and resulting in the deposition of a final evaporitic gypsum sequence in the deeper basin.

The MSC thus represents a catastrophic, tectonically driven reorganisation of the land–ocean configuration in the Tethyan realm. However, modelling studies remain inconclusive about how this localised sea-level anomaly, together with the expansion of a regional high-pressure zone, affected atmospheric circulation patterns. Consequently, the potential global impacts of the MSC, particularly changes in oceanic and atmospheric circulation, are currently debated.

Here we present new bulk-sediment isotope data from International Ocean Discovery Program (IODP) Site U1467, located within the Inner Sea of the Maldives. We place the data in temporal context using a combined chemo-, bio-, and magnetostratigraphic age model. Using combined $\delta^{13}C$ and $\delta^{18}O$ records in bulk carbonate, as well as $\delta^{13}C$, $\delta^{15}N$, and $\delta^{34}S$ data in bulk organic matter, we observe patterns reminiscent of the three stages of the MSC in our data from the Maldives. Changes in the isotopic composition of both carbonates and organic matter indicate significant shifts in water-column mixing, productivity and sedimentary redox cycling during the MSC. These results provide first-order evidence for the global impact of Mediterranean sea-level fall during the Messinian.

From collections to computation: building structured paleontological datasets for AI-ready workflows

Davide Di Franco[1), Daniela Festi[1), Florian Hödl[1), Katharina Danis[1), Holger Gebhardt[1)

[1) Paleontology and Collections, GeoSphere Austria, Neulinggasse 38, 1030 Vienna, Austria

Correspondence to: davide_di_franco@hotmail.it

The use of Artificial Intelligence (AI) in palaeontology is limited by the availability of structured, accessible, and annotated datasets, as well as the incomplete and biased nature of the fossil record (Yu et al., 2023). Natural history collections represent a vast but underused resource that could help address these limitations.

Here, we present our ongoing efforts to digitize and standardize a major paleontological collection within the framework of the GeoSphere Austria initiative, comprising over one million specimens, and over 128,000 database records, including over 25,000 type specimens across vertebrates, invertebrates, microfossils and plants.

Our work focuses on transforming heterogeneous data into standardized, machine-readable formats, following methods such as Darwin Core. In doing so, we address key challenges such as inconsistent metadata, data completeness, and the need for standardized taxonomic and stratigraphic information. We also focus on visual documentation, including images of specimens and labels. Once openly accessible with structured metadata, these resources can support research and serve as training data for AI methods, especially for image classification and label information extraction. Tools such as Transkribus are also explored to support the transcription of historical collection data.

The broader aim is to prepare these data for publication through infrastructures such as the Open Scientific Collections Austria (OSCA), GBIF and a planned GeoSphere Austria collection portal, improving access and reuse. Although machine learning applications have not yet been implemented, this work provides a basis for future AI-driven analyses, while underlining the importance of

taxonomic expertise, since the quality and consistency of both metadata and training data ultimately rely on expert identification and curation.

References

Yu, C., Qin, F., Watanabe, A., Yao, W., Li, Y., Qin, Z., ... & Xu, X. (2023). AI in paleontology. bioRxiv, 2023-08.

Paleoecological changes based on micro- and nannofossil assemblages during the Badenian-Sarmatian transition in the eastern Vienna Basin.

Holger Gebhardt[1], Stjepan Ćorić[1], Werner Schwarzhans[2]

[1] Geosphere Austria, Neulinggasse 38, A-1030 Wien
[2] Natural History Museum of Denmark, Øster Voldgade 5–7, 1350 Copenhagen K

Correspondence to: holger.gebhardt@geosphere.at

Micro- and Nannofossil assemblages represent the paleoenvironmental changes in the Central Paratethys around 12,65 Ma. We present records from 41 shallow drill-cores along the Stempfelbach in Lower Austria. The *Spirorutilus*-, *Bulimina-Bolivina*-, "Verarmungs"- (Badenian) and *Anomalinoides dividens*-Zones (Sarmatian) were identified by foraminiferal assemblages. All samples can be attributed to the NN6-Nannoplankton Zone and are dominated by reticulofenestrids and *Coccolithus pelagicus*. High percentages of *H. walbersdorfensis* occur in the uppermost part of the Badenian. A short bloom of large morphotype of *R. pseudoumbilicus* in the lower part of the Sarmatian points to the Mediterranean nannofossil Zone MNN6b. Otolith findings show the presence of mostly Clupeidae, Callionymidae, juvenile Gadidae, and Gobiidae.

Results from foraminiferal proxies show: 1. High numbers of epiphytic species (*Asterigerinata*, *Elphidium*, *Lobatula*) are characteristic for the base of the succession, followed by an increase of *Amphistegina*. 2. High contents of planktic foraminifera indicate a normal marine ingression (highstand systems tract) coeval to predominance of infaunal, marine species (mass-occurences of *Bolivina*) near the end of the Badenian. 3. Planktic foraminifera disappear and infaunal species drop significantly at the Badenian-Sarmatian boundary. Reworked Badenian benthic and planktic foraminifera become frequent (up to 75%) in the Sarmatian. 4. The assemblages point to normal marine conditions for the base of the Sarmatian. 5. Presumably brackish conditions start not until c. 12 m above the Base of the Sarmatian. Epiphytic species dominate the entire section except

during the *Bolivina* bloom and at the base of the Sarmatian (*Anomalinoides dividens* mass-occurrence). Sarmatian assemblages show distinctly impoverished faunas (species numbers and diversity). Vegetated seafloor at least in the vicinity of the depositional area (sea gras meadows or kelp forests) and muddy lagoons and basins are indicated.

The Miocene Climate Transition as tipping point for the tropical marine biodiversity hotspot of the Central Paratethys Sea

Mathias Harzhauser[1], Thomas A. Neubauer[2], Oleg Mandic[1]

[1] Natural History Museum Vienna, Burgring 7, 1010 Vienna, Austria

[2] SNSB – Bavarian State Collection for Paleontology and Geology, Richard-Wagner-Straße 10, 80333 Munich, Germany

Correspondence to: mathias.harzhauser@nhm.at

The Miocene Climate Optimum was a period of exceptional marine biodiversity in the Circum-Mediterranean region. This biodiversity peak is best documented in the deposits of the now-vanished Central Paratethys Sea, which once covered large parts of Central and Southeastern Europe. The sea hosted extraordinarily diverse tropical to subtropical ecosystems. However, its biodiversity has long been underestimated due to the fragmentary and outdated state of taxonomic research.

Comprehensive revisions of more than 1,000 gastropod species have revealed levels of diversity in many families that greatly exceed those of the modern Mediterranean Sea and are comparable to those of the tropical eastern Atlantic and the present-day Red Sea. Although Middle Miocene faunas appear highly endemic, this pattern is likely an artefact of insufficient comparative data from the Mediterranean region rather than a genuine biogeographic signal. In contrast, the overall faunal structure, characterized by radiations of particular genera and families, carries significant biogeographic information. Owing to different geodynamic histories, modern eastern Atlantic molluscan faunas differ markedly from those of the Indo-West Pacific. Our analyses demonstrate strong faunal affinities between the Central Paratethys Sea and the tropical eastern Atlantic.

The subsequent cooling associated with the Middle Miocene Climate Transition resulted in a dramatic biodiversity decline of approximately 67% of all gastropod species. Corallivorous gastropods were among the most severely affected groups, reflecting the widespread collapse of coral reef ecosystems. Deep-water faunas suffered a species loss of approximately 57%, likely driven by changes in ocean circulation patterns. The northern distribution limits of many taxa shifted southward into the proto-Mediterranean and ultimately toward the tropical coasts of West Africa.

These observations indicate that Central Paratethyan ecosystems were highly sensitive to climatic changes during the Miocene Climate Transition. This vulnerability was probably related to the region's position near the northern margin of the tropical reef belt during the Miocene Climate Optimum.

The Middle Miocene Central Paratethys Sea represents an ideal natural laboratory for investigating how large marine ecosystems respond to and ultimately cross major climate-driven tipping points.

Middle to Late Miocene bottom-water temperature variability in the southern Indian Ocean (ODP Site 752) based on single-chamber LA-ICP-MS analyses of benthic foraminifera

Tamara Hechemer[1)], Jassin Petersen[1,2)], Christoph A. Hauzenberger[1)], Werner E. Piller[1)], Arianna V. Del Gaudio[3)], Xabier Puentes-Jorge[1)], Gerald Auer[1)]

[1)] Department of Earth Sciences, University of Graz, NAWI Graz Geocenter, Graz, Austria
[2)] Institute of Geology and Mineralogy, University of Cologne, Cologne, Germany
[3)] Institute of Geology and Paleontology, University of Münster, Münster, Germany

Correspondence to: tamara.hechemer@uni-graz.at

The Middle to Late Miocene was a period of major climatic and oceanographic change in the Indian Ocean (IO), following the Miocene Climatic Optimum (MCO), a period characterized by global temperatures 3–4°C warmer than today and reduced sea-ice volumes, and was marked by the establishment of a near-modern monsoonal wind system and major climatic changes associated with the Middle Miocene Climatic Transition (MMCT). Subantarctic Mode Water and Antarctic Intermediate Water (AAIW) form major components of cool, low-salinity intermediate waters (IW) in the IO, transporting deep waters northward at intermediate depths. To investigate IW dynamics in past warm climate analogues, we focus on ODP Site 752, located in the southeastern IO on Broken Ridge at a water depth of 1086.3 m, as a key site for reconstructing changes in IW conditions during the Middle to Late Miocene (15-8 Ma).

In this study, a robust cleaning protocol was developed for Miocene IO samples, for which no standardized cleaning procedure currently exists. Single-chamber LA-ICP-MS analyses of the benthic foraminifer Cibicidoides mundulus from ODP

Site 752 were used to reconstruct bottom-water temperatures (BWTs) from Mg/Ca ratios. Other trace element-to-calcium ratios, including Sr/Ca, Ba/Ca, and Mn/Ca, were employed to provide further paleoenvironmental context and aid in the interpretation of the reconstructed temperature variability.

Here, we present the first Middle to Late Miocene BWT record from the southeastern IO at ODP Site 752 based on single-chamber LA-ICP-MS analyses. Following the MCO and during the MMCT, BWTs ranged between 5 and 8°C. Subsequently, temperatures increased to approximately 8–10°C toward the end of the MMCT. Around 12 Ma, coinciding with the expansion of Antarctic Sea ice and a northward migration of the Subtropical Front, BWTs decreased by up to 3°C, as inferred from Mg/Ca ratios. This cooling was followed by a return to warmer conditions, potentially linked to a strengthening of the Indonesian Throughflow. During the Late Miocene, BWTs generally ranged between 10 and 12°C and exhibited a warming trend beginning around 9 Ma. A southward shift and intensification of the Westerlies reduced the influence of AAIW at Broken Ridge, resulting in warmer BWTs. In contrast to previous studies that suggest a Late Miocene cooling, our C. mundulus-based BWT record indicates progressively warmer IW conditions in the southeastern IO.

Big and bizarre: Giant ooids in tidal Neoproterozoic seas

Brennan O'Connell[1,2], Malcolm W. Wallace[2], Ashleigh v.S Hood[2]

[1] Department of Geology, University of Vienna, Josef Holaubek-Platz 2 1090 Vienna
[2] School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Vic., Australia

Correspondence to: bo295@cam.ac.uk

Ooids are concentrically laminated, abiotic, shallow-marine carbonate grains. They are useful indicators of water depth, pH, temperature, and depositional energy. Most modern and ancient ooids are small (<1–2 mm), but the Neoproterozoic Era has an enigmatic abundance of giant ooids (>2 mm). How giant ooids form, how fast they grow, and how they relate to ocean chemistry all remain poorly understood. We investigated giant ooids from the Cryogenian Trezona Formation, South Australia, using sedimentological observation and trace-element geochemistry (iron; rare earth elements + yttrium, REE+Y) to propose a model for their growth.

Trezona Formation giant ooids have strange non-spherical forms, including elongate, triangular, and capsule-like shapes. Strange shapes are interpreted as caused by frictional abrasion via sliding and rolling during bedload transport. Some giant ooid laminae show thin-thick couplets of iron-oxide-rich and iron-oxide-poor laminae which progressively thicken and thin outward. These couplets may represent tidal rhythmites(?). If so, ooids precipitate rapidly during tidal cycles. Such rapid growth rates likely require extremely carbonate-supersaturated conditions. Intervals of rapid(?) growth are interrupted by erosional surfaces/unconformities, corresponding to intervals of ooid erosion, abrasion, and/or non-deposition.

Giant ooids are commonly associated with stromatolites, occurring in the intercolumnar space. This association may control their growth both physically and chemically: tidal currents are funnelled through the stromatolite columns, and the stromatolites may locally elevate carbonate saturation.

Shale-normalized REE+Y profiles of giant ooids show middle-REE enrichment, a conspicuous europium peak, and heavy-REE depletion. Averaged profiles show no negative cerium anomaly, unlike the strong negative anomaly in ooids that precipitate from modern oxic seawater. These patterns suggest giant ooids formed in low-oxygen Cryogenian oceans. Ocean anoxia is associated with extreme carbonate supersaturation, which may also help explain the rapid growth and unusual abundance of giant ooids in the Neoproterozoic.

Reconstructions of monsoonal activity in a deglacial context

Jassin Petersen[1], Tamara Hechemer[1], Gerald Auer[1], Christoph A. Hauzenberger[1], Werner E. Piller[1], Patrick Grunert[2]

[1] Department of Earth Sciences – NAWI Graz Geocenter, University of Graz, Heinrichstraße 26, 8010 Graz, Austria
[2] Institute for Geology and Mineralogy, University of Cologne, Luxemburger Straße 90, 50939 Cologne, Germany

Correspondence to: jassin.petersen@uni-graz.at

Ooids are concentrically laminated, abiotic, shallow-marine carbonate grains. They are useful indicators of water depth, pH, temperature, and depositional energy. Most modern and ancient ooids are small (<1–2 mm), but the Neoproterozoic Era has an enigmatic abundance of giant ooids (>2 mm). How giant ooids form, how fast they grow, and how they relate to ocean chemistry all remain poorly understood. We investigated giant ooids from the Cryogenian Trezona Formation, South Australia, using sedimentological observation and trace-element geochemistry (iron; rare earth elements + yttrium, REE+Y) to propose a model for their growth.

Trezona Formation giant ooids have strange non-spherical forms, including elongate, triangular, and capsule-like shapes. Strange shapes are interpreted as caused by frictional abrasion via sliding and rolling during bedload transport. Some giant ooid laminae show thin-thick couplets of iron-oxide-rich and iron-oxide-poor laminae which progressively thicken and thin outward. These couplets may represent tidal rhythmites(?). If so, ooids precipitate rapidly during tidal cycles. Such rapid growth rates likely require extremely carbonate-supersaturated conditions. Intervals of rapid(?) growth are interrupted by erosional surfaces/unconformities, corresponding to intervals of ooid erosion, abrasion, and/or non-deposition.

Giant ooids are commonly associated with stromatolites, occurring in the intercolumnar space. This association may control their growth both physically and chemically: tidal currents are funnelled through the stromatolite columns, and the stromatolites may locally elevate carbonate saturation.

Shale-normalized REE+Y profiles of giant ooids show middle-REE enrichment, a conspicuous europium peak, and heavy-REE depletion. Averaged profiles show no negative cerium anomaly, unlike the strong negative anomaly in ooids that precipitate from modern oxic seawater. These patterns suggest giant ooids formed in low-oxygen Cryogenian oceans. Ocean anoxia is associated with extreme carbonate supersaturation, which may also help explain the rapid growth and unusual abundance of giant ooids in the Neoproterozoic.

Giant Triassic Amphibians of Bavaria – Cyclotosaurus and Metoposaurus

Matthias Kranner[1], Frederik Spindler[2]
[1] **Bavarian Environment Agency, Geological Department, Hans-Högn-Straße 12, 95030 Hof, Germany**
[2] **Palaeonavix, Kipfenberg, Germany**

Correspondence to: matthias.kranner@lfu.bayern.de

In 2021, fossil remains were discovered in a quarry in Lower Franconia, Bavaria, Germany. Following notification by quarry workers, several large sandstone blocks containing numerous bone fragments were recovered. Ongoing preparation and study indicate the presence of at least ten individuals. First analyses indicated that the bones belong to the temnospondyl amphibian *Cyclotosaurus ebrachensis*.

Among the most remarkable specimens are a lower jaw measuring approximately 71 cm in length with preserved teeth.

This specimen is more than twice the size of the approximately 34 cm long skull described in 1933 by Kuhn and demonstrates that *C. ebrachensis* reached substantially larger body dimensions than previously assumed.

Preparation is complicated by the limited structural contrast between the bones and the surrounding sandstone matrix. High-resolution three-dimensional computed tomography (CT) scans are therefore being performed by the Fraunhofer Institut in Fürth and were used alongside mechanical preparation. Initial results allow concealed bone fragments to be located and provide the basis for digital reconstructions, facilitating the scientific investigation of large and difficult-to-handle blocks.

Due to the CT-Scans another genus of temnospondyl amphibian was discovered in the same block as the large *C. ebrachensis* lower jaw. After 3D reconstruction the remains could be identified as a well preserved half skull roof of *Metoposaurus diagnosticus* with about approximately 75 cm length.

The finding of these two large carnivorous amphibian predators only centimeters apart were the basis of paleoecological discussion.

Associated micro- and macrofossils provide additional information on the paleoenvironment. *Cyclotosaurus ebrachensis* and *Metoposaurus diagnosticus* probably inhabited freshwater swamps, slow-flowing rivers, and ponds. The new material therefore improves our understanding of the species' morphology and maximum size, while also contributing to the reconstruction of continental ecosystems during the Late Triassic of Bavaria.

Causes and evolution of the Middle to Late Miocene Carbonate Crash

Xabier Puentes-Jorge[1], David De Vleeschouwer[2], Werner E. Piller[1], Tamara Hechemer[1], Gerald Auer[1]

[1] Department of Earth Sciences, University of Graz, NAWI Graz Geocenter, Graz, Austria
[2] Institute of Geology and Paleontology, University of Münster, Münster, Germany

Correspondence to: xabier.puentes-jorge@uni-graz.at

The Miocene Carbonate Crash (CC) corresponds to a global decrease in the sediment carbonate content that spans from ~13.5 – 7 Ma, with a minimum around 12 – 9 Ma. However, despite being a global event, the onset of the carbonate crash does not occur at the same time in every ocean basin. In this regard, multiple hypotheses have been proposed in order to explain the diachronous nature of this event (e.g., productivity, constriction of rain belts, deep ocean circulation). Here, we provide a data compilation from 10 ODP/IODP sites, together with new carbonate content data from ODP Site 752, to track the evolution and test the plausibility of the hypotheses formulated in order to explain the diachronous origin of the CC. The comparison of our $CaCO_3$eq (%) data for Site 752 and the compilation from the other site locations revealed that the oldest records of the CC were documented in the Indian Ocean and central Pacific Ocean at ~13.5 – 13 Ma, coinciding with the increase in Antarctica sea ice cover. Meanwhile, the easternmost sector of the equatorial Pacific Ocean, the equatorial Atlantic Ocean and the Caribbean Sea sites only recorded the decrease in carbonate content in the sediment after 12 Ma, concomitantly with the formation of permanent artic ice. We therefore interpret that the diachronous onset of the CC was caused by an acceleration of the Antarctic Bottom Water (AABW) due to the increase in sea ice coverage. This event only affected areas where the AABW was dominant. However, by ~12 Ma, also the north hemispheric deep waters went through an acceleration, caused by the permanent formation of the artic sea ice, which caused the enhancement of carbonate dissolution of the ocean floor and led to the minimum in carbonate content occurred between 12 – 9 Ma.

Elasmobranch diversity and faunal response across the Cretaceous-Paleogene boundary in southern Germany

Mara Reichenberg[1], Jürgen Pollerspöck[2], Bernhard Beaury[3], Thomas Nichterl[3], Guillaume Guinot[4,5], Stjepan Ćorić[6], Michael Wagreich[1], Iris Feichtinger[3]

[1]Department of Geology, Faculty of Earth Sciences, Geography and Astronomy, University of Vienna, Vienna, Austria
[2] Bavarian State Collection of Zoology, Munich, Germany
[3] Department of Geology and Paleontology, Natural History Museum Vienna, Austria
[4] ISEM, University of Montpellier, CNRS, IRD, Montpellier, France
[5] Institut universitaire de France (IUF)
[6] Sedimentary Geology, GeoSphere Austria Vienna, Vienna, Austria

Correspondence to: a12544639@unet.univie.ac.at

The end-Cretaceous (K-Pg) mass extinction event was one of the most severe biotic crises in Earth's history, leading to the extinction of numerous marine and terrestrial taxa, including non-avian dinosaurs. Despite extensive research on the ecological consequences of this event, the response of elasmobranchs (sharks, rays, and skates), a highly resilient vertebrate lineage that has survived multiple mass extinctions over the past 400 million years, remains insufficiently understood. This knowledge gap is largely attributable to the rarity of accessible, fossiliferous sedimentary successions that continuously span the K-Pg boundary and preserve abundant elasmobranch remains. To address this issue, recent international collaborative efforts have focused on identifying suitable K-Pg sections and applying standardised bulk-sampling techniques to recover elasmobranch teeth. These investigations have considerably improved our understanding of elasmobranch extinction and recovery patterns within the Tethyan Realm.

Here, we present preliminary results from a newly discovered K-Pg boundary section in Bavaria (Germany), which has yielded an exceptionally rich assemblage of elasmobranch remains. Initial bulk sampling of more than 1.000 kg of sediment produced approximately 5.000 ichthyoliths, demonstrating the remarkable potential of the locality. Taxonomic assessment reveals a highly diverse elasmobranch fauna dominated by squaliform sharks, indicating the presence of a complex neritic environment immediately before the extinction event. The pre-extinction assemblage exhibits strong similarities to coeval assemblages documented from the well-studied Waidach section in Austria, suggesting broad regional consistency in late Maastrichtian elasmobranch communities across the southern Helvetic Shelf.

In contrast, post-extinction assemblages from the Bavarian section differ markedly from those recorded at Waidach, pointing to significant spatial variation in ecological restructuring and recovery following the K-Pg event. These differences may reflect local environmental conditions, habitat heterogeneity, or varying responses of elasmobranch communities to ecosystem disruption after the extinction. The exceptional abundance and diversity of material recovered from the Bavarian locality provide a rare opportunity to investigate extinction selectivity and survivorship among elasmobranchs at high taxonomic resolution.

Constraining the effects of diagenesis on the isotopic and trace element composition of the non-marine ostracod Cyprideis torosa: An experimental approach

Lena Werber[1], Madhura Ghosh[2], Claudia Wrozyna[2], Martin Dietzel[1], Andre Baldermann[1], Laurence Warr[2]

[1] Institute of Applied Geosciences, Graz University of Technology, Rechbauerstraße 12, A-8010 Graz, Austria
[2] Institute of Geography and Geology, University of Greifswald, Friedrich-Ludwig-Jahn-Str. 17A, D-17487 Greifswald, Germany

Correspondence to: lena.werber@student.tugraz.at

Lacustrine carbonates are important but yet underexplored sedimentary archives in paleoenvironmental research, especially with respect to early diagenetic processes that operate at the sediment–water interface. The low-Mg calcite valves of non-marine ostracods provide a primary source of authigenic biogenic carbonate. However, because these valves are formed and deposited directly above or within surface sediments, they are highly susceptible to syn- and early post-depositional alteration that can potentially overprint original environmental signals. Even though they are widely used in paleolimnological reconstructions, the extent to which early diagenesis impacts the geochemistry of ostracod calcite remains poorly constrained.

In this study, we experimentally assess sedimentary and mineralogical controls on the preservation of primary geochemical and stable isotope signatures in non-marine ostracod valves. Therefore, valves of Cyprideis torosa collected from the Achterwasser lagoon in Northern Germany were exposed to 0.01 M NaCl or 0.01 M $MgCl_2$ solutions at 25, 50 and 90 °C to simulate early diagenesis. Additionally, for burial simulations, valves were placed in dialysis tubes within kaolinite and smectite clay buffers at 50 and 90 °C to isolate distinct substrate effects. Subsets were sampled over a period of several months for subsequent trace element and stable isotope ($\delta^{18}O$, $\delta^{13}C$) analyses. Terminal samples are additionally examined by scanning electron microscopy to document microstructural alteration of the

reacted valves. All treatments are compared with the unaltered valves from the same population to quantify parameter-specific diagenetic effects. By identifying the parameters that drive alteration, this study refines screening criteria and improves the reliability of ostracod calcite as a paleolimnological archive.

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Session 04

Dynamics of Earth’s Spheres – Petrology, Geochronology, Tectonic, Analytical Techniques

Dynamics of Earth’s Spheres – Petrology, Geochronology, Tectonic, Analytical Techniques,

Conveners:
Daniela Gallhofer & Jesse Walters

NAWI Graz Natural Sciences

TU Graz

UNI GRAZ

Biological hot spots on a dynamic Earth: disentangling geo-bio pathways

Nicolas Villamizar-Escalante[1], Anna Götz[1], Stefan Dötterl[1,2], Christoph von Hagke[1,2], and the AlpsChange Consortium;

[1] Department of Environment and Biodiversity, University of Salzburg, 5020 Salzburg, Austria

[2] Center for Climate Change Resilience (CC:R), University of Salzburg, 5020 Salzburg, Austria

Correspondence to: nicolas.villamizarescalante@plus.ac.at

Feedback loops between biodiversity and geodiversity are widely recognized, with biological activity influencing soil formation, rock weathering, sediment stabilization, hydrology and nutrient cycling, while geodiversity shapes the physical and chemical conditions in which biodiversity develops. Several studies have attempted to identify the mechanisms linking abiotic heterogeneity to biodiversity, emphasizing geo-bio pathways related to habitat heterogeneity, refugia and persistence, dispersal and connectivity, isolation and divergence, and evolutionary adaptation. Yet, the specific geo-to-bio pathways that produce and maintain biological hotspots remain difficult to isolate. However, these pathways are often treated as separate explanatory mechanisms or conditions, whereas their combined effects, scape dependence and temporal dynamics remain challenging to evaluate.

Here, we synthesize existing evidence to evaluate how these geo-bio pathways contribute to biological hotspots and increasing biodiversity. We focus on how abiotic heterogeneity can generate habitat diversity, buffer populations through refugia, regulate dispersal and connectivity, promote isolation and divergence, and create the environmental contrasts that favor evolutionary adaptation.

We investigate these pathways within the context of the AlpsChange Doctoral School, in which 10 PhD students focus on examining the links between geodiversity and biodiversity in Alpine landscapes. These landscapes serve as ideal laboratories, as hotspots of geo- and biodiversity coincide with strong gradients in climate, topography, hydrology, and land use. This allows us to assess how physical landscape properties trigger biological responses across different spatial scales and through time.

New insights into the U-Pb zircon data of northern Gondwana fragments from the basement of the southern Pannonian Basin

Dražen Balen[1)], Petra Schneider[1)], Daniela Gallhofer[2)], Etienne Skrzypek[2)], Christoph A. Hauzenberger[2)]

[1)] Department of Geology, Faculty of Science, University of Zagreb, Horvatovac 102a, 10000 Zagreb, Croatia
[2)] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Universitätsplatz 2, 8010 Graz, Austria

Correspondence to: drbalen@geol.pmf.unizg.hr

The study examines LA-ICP-MS U-Pb age spectra of zircons from granitoids and metamorphic rocks of Mt. Papuk (Croatia). Small bodies of “I-granitoids” near Kutjevo are associated with pre-Variscan metamorphic rocks, while larger bodies of “S-granitoids” (Zvečevo) are associated with Variscan metamorphic rocks.

For the Kutjevo granitoid, the U-Pb age spectrum displays a prominent cluster at ~535 Ma (Ediacaran–Cambrian) and a skewed cluster towards ~500 Ma (Cambrian–Ordovician). Xenocrystic zircon cores yield minor age groups and single dates within a Pan-African cluster at ~0.65–0.8 Ga and the Mesoproterozoic, along with clusters from detrital sources between 1.6 and 3.0 Ga, covering Palaeoproterozoic and Archean ages. The associated metamorphic rocks, which host several decametre-thick, foliation-parallel granitoid bodies, contain zircon grains characterised by a prominent Lower Palaeozoic to Ediacaran age peak at ~550 Ma, scarce individual ages in the Neoproterozoic and Mesoproterozoic, and a diverse Palaeoproterozoic and Archean age distribution.

The Zvečevo granitoid contains zircon grains that display Variscan crystallisation ages (~350 Ma) and an inherited Lower Palaeozoic population at 500 Ma, practically without Proterozoic record. Besides a prominent Lower Palaeozoic narrow cluster (~540 Ma) and a Pan-African cluster, zircon grains from the associated metamorphic rocks show rare Mesoproterozoic ages at 1.2 Ga and a

diverse Palaeoproterozoic record from 1.6 to 2.5 Ga, with a gap between ~2.2 and ~2.4 Ga.

Among the collected data, the Kutjevo granitoid crystallisation age of 535.3 ± 0.9 I 7.1 Ma represents the “oldest dated rock” in Croatia, while a xenocrystic zircon core with a 207Pb/206Pb date of 3061 ± 27 Ma (Mesoarchean) represents the “oldest zircon” in Croatia measured so far. The age spectra, analysed by the frequency ratios of Proterozoic to Archean zircon ages, the shapes of the kernel density estimate curves and multidimensional scaling plots, in addition to the ages related to the Variscan, Cenerian and Cadomian events, indicate a provenance of zircon grains (mainly their inherited xenocrystic cores) typical of northern Gondwana, particularly the Saharan Metacraton, with traceable contributions from the Arabian-Nubian Shield and the West African Craton, where transport to the distant northern Gondwana margin occurred from their hinterland. These data further strengthen Precambrian palaeogeographic connections between Europe and Africa.

Expanding the geochronological toolbox of the epidote supergroup

Marko Bermanec[1)], Jesse B. Walters[1,2,3)], Christoph Hauzenberger[1)], Axel Gerdes[2,3)], Andreas Karlsson[4)], Horst Marschall[2,3)]

[1)] Department of Earth Sciences, University of Graz, Universitätsplatz 2, 8010 Graz, Austria
[2)] Department of Geosciences, Goethe University Frankfurt, Altenhöferallee 1, 60438 Frankfurt am Main, Germany
[3)] Frankfurt Isotope and Element Research Center (FIERCE), Goethe University Frankfurt, Altenhöferallee 1, 60438 Frankfurt am Main, Germany
[4)] Department of Geosciences, Swedish Museum of Natural History, P.O., Frescativägen 40, 10405 Stockholm, Sweden

Correspondence to: marko.bermanec@uni-graz.at

Epidote-supergroup minerals (ESM) are common rock-forming phases that crystallize in a wide range of magmatic, metamorphic, and hydrothermal environments. To date, U-Th-Pb petrochronology within the ESM has focused almost exclusively on allanite, with limited at-tempts to date the epidote-clinozoisite solid solution. Consequently, it remains unclear whether other epidote-supergroup minerals can be dated and which crystal-chemical or geochemical factors control their suitability for U–Th–Pb petrochronology. Because ESMs commonly par-ticipate directly in major mineral-forming reactions and fluid–rock interaction processes, ex-panding geochronology to additional endmembers could provide new opportunities to directly date metamorphic, metasomatic and particularly fluid-mediated alteration reactions in systems which cannot be dated by other conventional chronometers.

We address under what analytical and geological conditions meaningful U–Th–Pb dates can be obtained. We have assembled a globally sourced collection of approximately 100 sam-ples representing at least 15 ESMs spanning diverse tectonic settings and metamorphic condi-tions, providing an unprecedented framework for systematic evaluation. This dataset provides an initial framework for assessing how mineral chemistry, REE substitution mechanisms, and bulk-rock composition influence actinide incorporation and Pb systematics in the epidote su-pergroup. Major- and trace-element compositions were characterized

by electron microprobe and LA–ICP–MS to evaluate the intra-grain distribution of U, Th, and Pb.

Dissakisite-(Ce) from the Trimouns quarry, France contains less than 5 µg/g of U, Th and Pb. Nevertheless, the obtained age of 106.5 ± 2.9 Ma (2s) is consistent with the xenotime ages between 112 and 97 Ma from the same quarry. Dollaseite-(Ce) from Norberg, Sweden yields a concordia intercept age of 1720 ± 30 Ma (2s), consistent with the zircon ages between 1720 and 1650 Ma from the regional granite intrusions. Uranium, Th, and Pb concentrations in the dollaseite-(Ce) reach up to 2.5, 1.5, and 1.4 µg/g, respectively.

Our results demonstrate that the petrochronological potential of ESMs extends beyond the traditionally studied allanite and epidote. Expanding U–Th–Pb dating to additional ESMs opens new opportunities to directly date mineral growth, metamorphic reactions, and fluid–rock interaction processes in geological environments where conventional accessory mineral chronometers are absent or rare.

A deeply eroded Neo-Tethys derived ophiolitic unit above metamorphosed Late Triassic – Jurassic limestones and below a non-metamorphosed Tithonian and younger turbiditic overstep sequence in the Gjilan Area (SE Kosovo)

Bujar Bilalli[1], Hans-Jürgen Gawlick[2], Mensi Prela[3], George Pleş[4], Andrea Uta[3]

[1] Faculty of Geology and Mining, Polytechnic University of Tirana, Albania
[2] Department of Applied Geosciences and Geophysics, Energy Geosciences, Montanuniversitat Leoben, Peter-Tuner Strasse 5, 8700 Leoben, Austria
[3] Polytechnic University of Tirana, Earth Science Department, Rruga e Elbasanit, Tirana, Albania
[4] Department of Geology and Research Centre for Integrated Geological Studies, Babeş-Bolyai University, M. Kogãlniceanu 1, 400084 Cluj-Napoca, Romania

Correspondence to: bilallibujar@gmail.com

A tectonically stacked succession exposed north of Parallova village in the Gjilan area (SE Kosovo) provides new insights into the post-obduction evolution of the Neo-Tethyan realm. The studied succession comprising two tectonic units.

The lower unit consists of metamorphosed Late Triassic-Jurassic carbonates. The succession starts with shallow-water Dachstein reefal to fore-reefal limestones carbonates. Near the top, they are highly recrystallized and karstified, with reddish siliciclastic infillings. Above the karst unconformity, non-recrystallized shallow-water limestones indicate a depositional gap between the Dachstein carbonates and the overlying Early Jurassic succession. Their microfacies correspond to transitional facies between the Lithiotis Ramp and the drowned Dachstein Platform. The succession is similar to the Pelagonian domain of the Hellenides.

The upper unit consists of non-metamorphosed ophiolites with ophiolitic mélanges at the base and an overlying Tithonian overstep sequence. The ophiolitic unit starts with a few-meter-thick OM3-type mélange and is overlain by an OM2-type mélange. The ophiolitic unit is rather thin compared to other ophiolite units in the Dinarides-Albanides-Hellenides, indicating deep erosion.

The overstep sequence starts with a basal conglomerate and is followed by a turbiditic succession. The carbonate beds contain shallow-water bioclastic material derived from the Kurbnesh Carbonate Platform. The shallow-water fossil assemblage, including Mohlerina basiliensis, Neokilianina rahonensis and Labyrinthina mirabilis, indicates a Kimmeridgian-Tithonian age, whereas the upper part of the succession passes into organic-rich marls of probable Berriasian-Valanginian age.

The overlying sequence above the ophiolitic unit resembles the Tithonian/Berriasian-Valanginian Firza Formation in Albania, sealing the obducted ophiolites, and corresponds to the “Paraflysch sequence”, comparable to successions from the Axios Zone and Vardar Gorge, deposited above the eastward downgliding and younger uplift and unroofing. The deeply eroded ophiolites received material from a growing carbonate platform. Continued unroofing is reflected by the fining-upward trend of the turbiditic siliciclastic influenced succession. These relationships indicate that the deeply eroded ophiolitic unit represents Neo-Tethyan ophiolites obducted during the Middle-Late Jurassic.

Keywords

Neo-Tethys, ophiolite obduction, East Vardar, Albanides, sealing sequence

Optimizing sample preparation methods for REE analysis in geological samples: 3-acid versus ammonium bifluoride digestion methods

Dina Isabel Guerreiro Cabrita[1)], Catherine Beltran[1)], Benjamin Huet[1)], Tanja Knoll[2)], Thomas Angerer[2)]

[1)] Division of Basic Geological Services, Geosphere Austria, Neulinggasse 38, 1030, Vienna
[2)] Division of Geophysical and Applied Geological Services, Geosphere Austria, Neulinggasse 38, 1030, Vienna

Correspondence to: dina.cabrita@geosphere.at

Sample preparation is essential for accurate geochemical analysis. Conventional sample preparation methods for geological samples use acid reagents for digestion. These methods typically employ a combination of acids such as nitric acid (HNO_3), hydrochloric acid (HCl), perchloric acid ($HClO_4$), and hydrofluoric acid (HF). While acid digestion works well for geological materials (most carbonates or mafic rocks) with insignificant contributions from refractory minerals, it can be challenging for felsic rocks containing resistant minerals as the main hosts for rare earth elements (REEs). The goal of this study is to compare the recovery and analytical reproducibility of 15 REEs using two digestion methods: 3-acids (HF, HNO_3, and HCl) and ammonium bifluoride (NH_4HF_2 and HNO_3). The latter method offers a faster and safer alternative to the HF-based method. For a comprehensive evaluation, seven certified reference materials were selected to represent diverse geological samples: diorite gneiss (SY-4), granite (GM), basalt (BM), soil (SO^{-3}), Tibet sediment (NCSDC 70314), and two pegmatites (OREAS 750 and OREAS 751). All samples underwent both digestion methods using the same sample weight and standardized preparation procedures to minimize the preparation-related variability. In both methods, 100 mg of material was used, and each method consisted of a two-step process. REEs were quantified using an ICP-MS instrument in the laboratory of the Geoanalytics Competence Unit of GeoSphere Austria. The results indicate comparable recoveries for both digestion methods, generally exceeding 80% for

all sample types, except the sediment NCSDC 70314. Yb shows the poorer recoveries in both methods for granite GM (~ 70 %). Tm also shows poor recoveries in both methods for soil SO-3 (~ 70 %), and for the ammonium bifluoride method in pegmatite OREAS 751 (~ 70 %). Overall, both digestion methods are comparable for most samples with recoveries mostly >80% and equal primitive mantle normalised spider diagram patterns, but neither is universally quantitative, flagging specific low recoveries for some elements (Yb and Tm), and problematic for sediment sample NCSDC 70314. This study highlights the necessity of selecting appropriate samples for each digestion method, as recovery vary depending on the sample type. Careful consideration of sample composition is essential to optimize accuracy and reproducibility in REE analysis using either the 3-acids or ammonium bifluoride methods.

Variation of intraplate stresses within oceanic crust along the South Atlantic Transect: Implications from calcite vein microstructures

Lucien Eckstein[1)], Walter Kurz[1)], Gerald Auer[1)], Terezia Kunkelova[1)], Thomas Müller[2)], Jochen Gätjen[2)]

[1)] Department of Earth Sciences, University of Graz, Heinrichstrasse 26, A-8010 Graz
[2)] Department of Mineralogy, University of Göttingen, Goldschmidtstrasse 1, D-37077 Göttingen

Correspondence to: walter.kurz@uni-graz.at

The South Atlantic Transect (SAT) is a multidisciplinary scientific ocean drilling experiment designed to investigate the evolution of the ocean crust and overlying sediments across the western flank of the Mid-Atlantic Ridge (Coggon et al., 2024). The SAT comprises International Ocean Discovery Program (IODP) Expeditions 390 and 393It targeted six sites on 7, 15, 31, 49, and 61 Ma ocean crust.

This contribution focuses on the internal microstructure of hydrothermal veins in drill cores sampled during IODP Expeditions 390 and 393. Microstructures, preferably in calcite, were analyzed using Electron Backscatter Diffraction (EBSD). Here, data on the density and misorientation of calcite sub-grains potentially allow the assessment of intraplate stresses and stress variations with depth and distance from the Mid-Atlantic Ridge, related to the increasing density of crust with cooling and age.

Microstructures in vein calcite are characterized by the formation of sub-grains, indicating that calcite deformation is mainly characterized by dislocation glide. The evaluated misorientation axes between the calcite sub-grains indicate that basal and prism planes are the main intracrystalline gliding planes. The activation of these slip planes requires relatively high differential stresses, which are far above the critical stresses for twinning. Analysis of average calcite sub-grain sizes shows a general trend characterized by a continuous decrease in sub-grain size with decreasing distance from the mid-ocean ridge.

Oxygen stable isotope data from vein calcite indicate low precipitation temperatures in the range of 2° to 10 °C, without a correlation between precipitation temperature and the age of the oceanic host rock, and with a very minor influence of magmatic fluids. Therefore, we assume that vein calcite precipitated from seawater.

The microstructures, particularly the calcite sub-grain sizes, seem to indicate that the related differential stresses decrease with increasing distance from the Mid-Atlantic Ridge. This can be related to the higher cooling rates of the oceanic host rocks situated closer to the Mid-Atlantic Ridge; higher cooling rates presumably generate higher internal stresses due to higher rates of density increase and volume loss with cooling. Alternatively, it may also be related to the fact that the ridge-push forces, and therefore the related intraplate stresses, decrease with increasing distance to the Mid-Atlantic Ridge.

Continental tectonic mélanges in the Tauern Window

Benjamin Huet[1)], Chiara Költringer[1)], Alessia Tagliaferri[2)], Anna Rogowitz[2)]

[1)] Division of Basic Geological Services, Geosphere Austria, Hohe Warte 38, 1190, Vienna, Austria
[2)] Department of Geology, University of Innsbruck, Innrain 52, 6020, Innsbruck, Austria

Correspondence to: benjamin.huet@geosphere.at

In contrast to oceanic mélanges, mélanges formed of continental rocks are poorly documented. We present a geometric and lithological characterization of tectonic mélanges formed of continental rocks mapped in the Rauris and Zirknitz valleys of the Tauern Window. They comprise mostly well identifiable cover and basement units formed prior to the opening of the Alpine Tethys, juxtaposed without lithostratigraphic coherence. They are strongly deformed and show systematic top-to-the-N shearing consistent with the subduction and collision kinematics. Four mélange types are distinguished based on thickness, degree of continuity, tectonic position as well as occurrence and nature of a matrix.

Type 1 mélanges are continuous, hundreds of meters thick and located directly above coherent continental nappes. The matrix is composed of Carboniferous and Jurassic-Cretaceous schists. Within it are found lenses of metasediments from all known Permo-Triassic lithostratigraphic units and rare orthogneiss. A Type 2 mélange occurs as a single 100-200 m thick continuous unit between oceanic nappes. The matrix is composed of Jurassic-Cretaceous schists containing smaller lenses of the same lithologies as described for type 1. In contrast, type 3 mélanges are characterized by the absence of a matrix and a thickness of less than 20 m. They are built of slivers composed of a single lithostratigraphic unit. Type 4 mélanges correspond to strings of 1-5 m thick boudins of Triassic marble found within oceanic nappes.

We interpret the four identified mélange types as a mixture of cover and basement units scraped off the down going plate during continental subduction. The evolution from mélange type 1 to type 4 corresponds to an increase of strain. The occurrence of up to three mélanges sandwiched between oceanic nappes on each investigated profile, indicate out-of-sequence thrusts within the hanging wall oceanic unit active during collision subsequent to continental subduction.

The units described here are not an exception in the Tauern Window, yielding several questions: Are mélanges formed of continental rocks widespread in the Alpine-Mediterranean orogenic system? Why are continental elements scraped off whereas deformation is expected to localize in weak oceanic metasediments or serpentinite? Why are oceanic rocks barely found in the mélanges? Why did thickening compartmentalize independently within continental and oceanic units during collision?

Sediment Provenance and Paleoenvironmental Evolution of the Majala and Chacarilla Formations (Late Jurassic–Early Cretaceous), Northern Chile

Nejla Tutnjevic[1], Daniela Gallhofer[2], Christian Andreas Meyer[3], Vincenzo Gesualdi[4], Matteo Belvedere[4], Dorothee Hippler[1]

[1] Graz University of Technology, Institute of Applied Geosciences, Rechbauerstrasse 12, 8010 Graz, Austria
[2] University Graz, Institute of Earth Sciences, Univeritätsplattz 2, 8010 Graz, Austria
[3] Department of Environmental Sciences, University of Basel, 4056 Basel, Switzerland
[4] Dipartimento di Scienze della Terra, Università degli Studi di Firenze, 50121 Firenze, Italy

Correspondence to: dorothee.hippler@tugraz.at

The Mesozoic sedimentary record of the northern Atacama and Tarapacá region in Chile is still to be fully explored. Mineralogical and geochemical studies as well as dating methods have never been carried out in this region, even though numerous and well-preserved Late Jurassic to Early Cretaceous dinosaur tracksites have been found recently. Two field campaigns were therefore carried out in the Quebrada de Huatacondo in 2022 and in the Quebrada de Arcas in 2023. At both sites, Late Jurassic to Early Cretaceous sedimentary rocks of the Majala and Chacarilla Formations are well-exposed and constitute a promising geological archive. A total of 65 sedimentary rocks, mainly fine-grained sandstones and siltstones were sampled along the lithological sections. The samples were analyzed using mineralogical (XRD), geochemical (XRF) and detrital zircon U-Pb dating methods in order to investigate the depositional and paleo-environmental conditions, provenance and tectonic setting as well as climate-related paleo-weathering of the study area.

Mineralogical analyses revealed predominantly siliciclastic compositions characterized by quartz, feldspars (albite and orthoclase), muscovite/illite, and

chlorite that validate the evolution from a mixed carbonate-siliciclastic into a pure terrestrial depositional system. Geochemical classifications indicate mainly litharenitic to feldspathic sandstone compositions sourced from predominantly felsic continental rocks. Geochemical discrimination diagrams and palaeo-weathering indices further suggest variable sediment maturity, differing degrees of sediment recycling and severe climatic changes between the two formations. Detrital zircon U-Pb geochronology identified dominant Paleozoic zircon populations between ~450 and 560 Ma related to the Famatinian Orogeny, indicating sediment supply predominantly from northeastern to eastern continental source regions associated with the Famatinian arc and older crustal provinces presently exposed in northwestern Argentina. Additional Permian-Triassic zircon populations around ~250 Ma indicate subordinate Gondwanide-Choiyoi contributions, whereas the absence of Jurassic zircon populations suggests no input from the Jurassic Andean volcanic arc.

The integrated mineralogical, geochemical and provenance data thus provide a refined multi-proxy reconstruction of continental sedimentation within the Tarapacá Basin during Late Jurassic to Early Cretaceous times and contribute to a better understanding of the tectono-sedimentary evolution and paleoenvironmental conditions of the Majala and Chacarilla Formations in northern Chile.

Geometry of growth strata in wrench-dominated transpression: Trattberg, Northern Calcareous Alps, Austria, and Prelitoral Ranges, Catalan Coastal Ranges, Spain

Hugo Ortner[1], Oscar Fernandez[2]
[1] Department of Geology, University of Innsbruck, Innrain 52f, 6020 Innsbruck
[2] Department of Geology, University of Vienna, Josef Holaubek-Platz 2, 1090 Wien

Correspondence to: hugo.ortner@uibk.ac.at

Growth strata are sediments that are deposited during structural growth. They record incremental strain that can be reconstructed by removing younger increments progressively. Here we investigate growth strata geometry of sediment wedges attached to transpressive fault systems.

In the forelimb of anticlines, growth wedges are expected to thin towards the fold hinge. Here we investigate the geometry of growth strata that are related to transpressional wrench fault systems. In such cases, fault propagation will cause monoclinal folding above the tip of a steep but not vertical fault, until the fault breaks across the fold. Subsequently, the structure will grow by increasing fault throw, which increases topography across the fault zone.

In the Trattberg case study, Upper Jurassic growth strata are attached to a 20 km long wrench fault system. Stratal architecture in the footwall of the Trattberg thrust records bedding attitudes from subvertical overturned to subhorizontal. Growth strata show that the system initially developed like a fold, until the fault breached the seafloor. Syntectonic sediments then draped the growing topography, resulting in wedges alternatively thickening and thinning towards the fault.

In the Prelitoral Ranges of the Catalan Coastal Range, Eocene growth strata are found along a 230 km long transcurrent fault system. The eastern part of the fault system is associated with basement nappe emplaced northwards onto growth strata. A growth syncline in the footwall of the faults has overturned to horizontal bedding in its southern limb.

In both cases, growth strata feature alternating wedges tapering toward and away from the growing structure. We interpret wedges tapering away from the growing structure as event beds sourced from the fault's hanging wall, when deposition rate was elevated. Alternatively, such beds may document time intervals in which the structure only grew by increasing fault throw and the wedges are akin to fault-scarp deposits.

We argue that the alternation of the tapering direction in growth wedges is indicative of faults in wrench-dominated transpression. The following reasons can be given for this correlation:

(1) A fold hinge cannot be the sole sediment source for sediment wedges. Only fault growth can exhume large areas and thus mobilize large amounts of sediment that can then drape the growing topography.

(2) Wedges tapering away from the growing structure have not yet been observed in fold-related growth strata.

Deciphering a Billion-Year Metamorphic Record: Polyphase Evolution of the Isua Supracrustal Belt from Coupled Garnet-Monazite Geochronology

Dominik Sorger[1,2], Julian Wolf[2], Thomas Mueller[2], A. Alex. G. Webb[3], Matthias Willbold[2], Christoph A. Hauzenberger[1]

[1] Department of Earth Sciences – NAWI Graz Geocenter, University of Graz, Graz, Austria
[2] Geoscience Center, University of Göttingen, Göttingen, Germany
[3] Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany

Correspondence to: dominik.sorger@uni-graz.at

The tectono-thermal history of the Eoarchean Isua Supracrustal Belt (ISB) remains a subject of intense debate, particularly concerning the chronology and number of metamorphic events that have shaped its crustal architecture. While earlier models proposed a dominant Eoarchean event, more recent investigations have emphasized a pervasive Neoarchean overprint. We resolve this controversy by integrating texturally controlled Sm-Nd garnet geochronology with in situ U-Pb monazite dating on rare metapelites.

Detailed petrographic investigation reveals polyphase garnet growth comprising three compositionally distinct domains: an inclusion-rich core (Grt I), a Ca-rich mantle (Grt II), and an inclusion-poor rim (Grt III). Sm-Nd isochron analyses of microdrilled garnet fractions yield Paleoarchean ages for the core (~3550 Ma) and mantle (~3200 Ma), whereas the rim records a Neoarchean age (~2710 Ga). Despite this protracted growth history spanning nearly one billion years, phase equilibrium modelling indicates that all garnet domains formed under comparable amphibolite-facies conditions of approximately 0.5–0.6 GPa and 500–600 °C. This polyphase evolution is independently corroborated by monazite geochronology, which identifies two distinct generations: ancient grains occurring

as inclusions within the garnet core, yielding ages of 3576 ± 10 Ma, and a younger population situated in the garnet rim and the matrix, with an age of 2686 ± 14 Ma.

These findings confirm a complex metamorphic evolution for the ISB, characterized by at least three discrete tectonothermal events. The ~3600 Ma monazite generation, representing one of the oldest terrestrial occurrences, demonstrates that crustal lithologies capable of stabilizing this phase were already established during the early Archean. Additionally, supervised machine learning analysis identifies specific bulk chemical discriminants, such as Al_2O_3/CaO ratios, that distinguish these unique monazite-bearing metapelites from typical Archean crust. Consequently, the ISB preserves a long-lived record in which Neoarchean metamorphism overprinted, but did not obliterate, the evidence of earlier Archean tectonothermal events.

Uplift and Exhumation of the Alpine Foreland and Fold-Thrust Belt

Christoph von Hagke[1,2], Laura Mora Rojas[1], Bernhard Salcher[1]

[1] Department of Environment and Biodiversity,University of Salzburg, 5020 Salzburg, Austria

[2] Centre for Climate Change Resilience (CC:R), University of Salzburg, 5020 Salzburg, Austria

Correspondence to: christoph.vonhagke@plus.ac.at

The North Alpine foreland basin and its fold–thrust belt provide a key archive of Miocene to recent Alpine uplift and exhumation. Previous studies demonstrate late-stage uplift and erosion. However, the timing and magnitude of exhumation is heterogeneous along strike and the underlying driving mechanisms are still debated. In particular, it remains unclear whether an observed eastward decrease of the amount of shortening in the Subalpine Molasse is due to less convergence, possibly associated with lateral extrusion of the Tauern Window. Alternatively, strain may be partitioned differently along strike between Subalpine Molasse and Flysch units, with a larger proportion of deformation accommodated within the Flysch units. These competing hypotheses exist because of the lack of thermochronological data in the Flysch and east of the Lech River (Bavaria), age dispersion in existing data sets, as well as geometric uncertainty of the structures at depth. Furthermore, the driver of the eastward decrease in exhumation of the foreland basin itself and its link to fold-thrust belt tectonics remains poorly understood.

Here we focus on the basin, Subalpine Molasse and Flysch between the Bregenzarach and the Krems River, Austria. We present a compilation of previously published and new low-temperature thermochronological data, showing strain partitioning along strike the deformation front of the Alps as well as variability of basin exhumation. We combine this with uncertainty models of the subsurface and their influence on exhumation estimates. We conclude that climate-induced exhumation is limited. Instead, plate convergence in combination with slab-related processes are responsible for the observed heterogeneity of the exhumation signal.

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Session 05

Magmatische und metamorphe Petrologie

Igneous and Metamorphic Petrology

Conveners:
Dominik Sorger & Christoph Hauzenberger

NAWI Graz Natural Sciences

TU Graz

UNI GRAZ

The record of assimilation, magmatic crystallization and metamorphic overprint in deep crustal gabbros: a case study from the Mafic Complex of the Ivrea-Verbano Zone, Italy

Matteo Del Rio[1)], Luca Ziberna[1)], Ana Černok[1)], Christoph Hauzenberger[2)], Othmar Müntener[3)]

[1)] Department of Mathematics, Informatics and Geosciences, University of Trieste, Trieste, Via Weiss 2, 34128, Italy
[2)] Department of Earth Sciences, NAWI Graz Geocenter, Universitat of Graz, 8010 Graz, Austria
[3)] Institute of Earth Sciences, University of Lausanne, Géopolis, CH-1015 Lausanne, Switzerland

Correspondence to: matteo.delrio@phd.units.it

We present a new investigation of gabbroic lithologies from the Upper Zone of the Mafic Complex within the Ivrea–Verbano Zone [Sesia Valley, Italy], representing the deep-seated roots of a Permian magmatic system [Quick et al., 2009]. Detailed petrography, textural analysis, mineralogical mapping, and Electron Probe Micro-Analysis were integrated to reconstruct the multistage evolution of mafic assemblages under lower-crustal conditions. The studied sequence includes hornblende gabbronorites, olivine–garnet gabbros, olivine–garnet melagabbros, olivine gabbros, and garnet hornblendites displaying granoblastic–polygonal to coronitic textures and marked variations in garnet abundance. Primary magmatic layering and modal banding are variably overprinted by granulite-facies recrystallization [Rivalenti et al., 1984]. Al-rich pyroxenes [up to 8.1 wt% Al_2O_3], fayalitic olivine [Fo49.5–61.5], abundant apatite, hercynite-rich spinel, titanomagnetite, and rutile-bearing orthopyroxene indicate crystallization from evolved melts affected by crustal assimilation of metapelitic material during magma differentiation. Textural, mineral-chemistry, and thermobarometric data based on olivine–clinopyroxene equilibria [Loucks, 1996] and the COIP geobarometer [Ziberna et al., 2017] indicate that the primary assemblage [plagioclase + clinopyroxene + orthopyroxene ± olivine + Fe–Ti oxides + hercynite-rich spinel + apatite ± garnet] crystallized at ~1100 °C and ~8 kbar. Clinopyroxene–orthopyroxene coronas around olivine are interpreted as

products of late-stage peritectic melt–mineral reactions involving evolved residual melts. Hornblende crystallized subsequently at near-solidus conditions [~900 °C] from hydrous residual melts. We also investigate a second generation of coronitic garnet, previously documented in the literature [Mazzucchelli et al., 1992], formed during subsolidus re-equilibration through diffusion-controlled reactions involving olivine, pyroxenes, plagioclase, and hercynite-rich spinel. The reactions responsible for garnet formation are identified and their petrological significance discussed. Geothermometric estimates for garnet coronas associated with symplectitic clinopyroxene yield temperatures of ~630–675 °C, lower than those obtained from two-pyroxene Fe–Mg exchange thermometry of the primary assemblages [731–863 °C], suggesting that these coronas record cooling from granulite- to amphibolite-facies conditions, likely during Triassic–Jurassic extension.

Preliminary results of a new thermometer based on tourmaline

Andreas Ertl[1,2)]

[1)] Mineralogisch-Petrographische Abt, Naturhistorisches Museum, Burgring 7, Wien 1010, Austria
[2)] Institut für Mineralogie und Kristallographie, Universität Wien, Josef- Holaubek-Platz 2, Wien 1090, Austria

Correspondence to: andreas.ertl@a1.net

Over the last 15 years, several excellent linear correlations between X-site charge and F content have been observed in zoned tourmalines from various pegmatites. These correlations are independent of the Li, Fe, Mn, Al content, if these zones are crystallized at the same temperature in a closed system. A geothermometer was calibrated by using 10 different data sets with excellent linear correlations. This correlation yields a preliminary tourmaline thermometer with: T [°C] = (k + 1.144)/0.0034\) [Eq. 1], where k is the slope of the linear correlation between X-site charge and F content in zoned crystals. Bermanec et al. (2026) conducted Ti-in-quartz thermometry on quartz crystals from miarolitic cavities within the well-studied Rosina aplite–pegmatite dike, Monte Capanne pluton, Elba, Italy. The largest quartz crystals grew at temperatures of ~590 °C within large miarolitic cavities. As the cooling process progressed, an influx of fluid caused the dissolution of garnets and the subsequent growth of smaller quartz crystals in smaller cavities. Thermometric data indicate that this event took place at ~330 °C. Tourmalines developed into similar pockets from this pegmatite, were investigated by Ertl et al. (2025). When the F contents are plotted against the X-site charge for the examined tourmaline crystals, all zones except for the termination show a positive linear correlation (tourmaline #1: slope k = 1.038, r^2 = 0.997; tourmaline #2: k = 0.846, r^2 = 0.999). The fact that the tourmaline cap lies outside of this function in both cases was interpreted as evidence that they grew during a different event than the preceding crystals. The calculated growth temperature for the investigated tourmaline crystals is ~600 °C [Eq. 1]. This is consistent, within error, with the Ti-inquartz-derived temperatures for the large quartz crystals from similar cavities. Interestingly, all investigated tourmaline caps from Ertl et al. (2025) also lie on a linear correlation with a slope of k = -0.174 (r^2 = 0.972). The calculated growth temperature for these caps would be ~300 °C [Eq. 1]. This would also be consistent with the Ti-in-quartz thermometric data. The present study was funded in whole by the Austrian Science Fund (FWF) project P 35585.

References

Bermanec, M., Gies, N.B., Pettke, T. and Hermann, J. (2026): Eur. J. Mineral., 38, in press.

Ertl, A., Pezzotta, F., Hughes, J.M., Meyer, H.-P., Ludwig, T., Dyar, M.D., Giester, G. and Rossman, G.R. (2025): Geol. Carpath., 76, 301–309.

Lower crustal differentiation and transient shallow assembly of the Laacher See magma system

Michael W. Förster[1], Dejan Prelević[2], Chunfei Chen[3], Svyatoslav S. Shcheka[4,5]

[1] Research School of Earth Sciences, The Australian National University, Canberra, Australia
[2] Faculty of Mining and Geology, University of Belgrade, Belgrade, Serbia
[3] School of Earth and Planetary Sciences, China University of Geosciences, Wuhan, China
[4] Centre for Exploration Targeting, School of Earth Sciences, The University of Western Australia, Perth, Australia
[5] School of Natural Sciences, Macquarie University, Sydney, Australia

Correspondence to: michael.forster@anu.edu.au

The depth, longevity, and architecture of the phonolitic magma system beneath the Laacher See volcano, Germany (e.g., Wörner and Schmincke, 1984), remain debated, especially regarding whether a long-lived shallow magma chamber existed prior to the ~13 ka BP VEI 6 eruption that produced ~20 km^3 phonolitic tephra.

We performed high-pressure experiments on basanite and tephrite compositions to simulate fractional crystallization of stalled mafic magmas in the lower crust of the East Eifel Volcanic Field. Experimental melts produced at 0.5–1.0 GPa (~13–28 km depth) evolve toward phonolitic compositions closely matching the Lower- and Middle Laacher See Tephra (LLST, MLST), reproducing their major-element trends and silica undersaturation. This demonstrates that phonolite formation can occur efficiently in the lower crust rather than requiring long-term shallow storage of ~20-50 ka at ~5 km depth as proposed earlier (e.g., Schmitt et al., 2022). Further, mass-balance calculations indicate that a magma supply rate of ~4 × 10^{-4} km^3 a^{-1} (~0.4 km^3/ka) over ~200 kyr is sufficient to generate the erupted volumes of the East Eifel basanite–phonolite suite. This relatively low magma flux is more consistent with incremental magma addition and argues against the long-term stability of large magma chambers in the upper crust.

We propose a transcrustal system in which long-term phonolite differentiation occured primarily in the lower crust (>15 km), while extracted phonolitic melts formed a saucer- or sill-like reservoir at the top of a crystal-rich mush near the brittle-ductile transition (BDT) at ~12-15 km depth. A small, eruptible shallow reservoir formed only briefly at ~5 km depth just months to years before eruption. This shallow body likely contained only the most evolved LLST-type phonolite, while MLST and Upper Laacher See Tephra units were mainly sourced from deeper levels at the BDT.

This model resolves the “low heat flux paradox” of Laacher See Volcano by placing most differentiation at depth, limiting shallow thermal anomalies despite active CO_2 degassing.

References

Wörner, G., Schmincke, H.-U., 1984. Petrogenesis of the Zoned Laacher See Tephra. Journal of Petrology 25, 836–851. 10.1093/petrology/25.4.836.

Schmitt, F.H., Schmitt, A.K., Gerdes, A., Harvey, J.C., 2022. Magma accumulation underneath Laacher See volcano from detrital zircon in modern streams. Journal of the Geological Society 180. 10.1144/jgs2022-064

How zircon survives and monazite dissolves during partial melting of orthogneiss – a case study from Mt. Papuk, Croatia

Daniela Gallhofer[1)], Etienne Skrzypek[1)], Petra Schneider[2)], Dražen Balen[2)], Christoph A. Hauzenberger[1)]

[1)] Department of Earth Sciences, University of Graz, Universitätsplatz 2, 8010 Graz, Austria
[2)] Department of Geology, University of Zagreb, Horvatovac 102a, 10000 Zagreb, Croatia

Correspondence to: daniela.gallhofer@uni-graz.at

Partial melting is a ubiquitous process during the tectono-metamorphic evolution of collisional orogens. It is commonly recorded by the formation of migmatites or granitoids and particularly by their accessory phases zircon and monazite. While in many cases both minerals newly crystallize from partial melt, they can also show contrasting degrees of preservation/dissolution. This study presents an example of nearly full zircon preservation but completely new monazite growth during partial melting of a mildly peraluminous orthogneiss from Mt. Papuk, Croatia. We combine U-Pb zircon and monazite dating, zircon trace element and whole rock geochemical data with phase equilibria modelling and use solubility models of accessory phases to constrain the P-T conditions of partial melting.

This study focusses on meta-granitoid samples that occur at Trešnjevica geosite in the Papuk UNESCO Global Geopark. The peraluminous foliated orthogneiss shows signs of partial melting such as discordant fine-grained quartz-feldspar veins, thin interstitial quartz films along grain boundaries and cuspate quartz grain boundaries. Metatexite contains foliation-parallel, commonly irregular and coarse-grained leucocratic layers and pockets with subordinate garnet and biotite, which is associated with fibrous-felty muscovite probably pointing to the former presence of sillimanite. Diatexite is leucocratic with an equigranular magmatic texture and primarily consists of felsic minerals with some dispersed biotite.

Zircon textures support igneous crystallization of the protolith while trace elements are characteristic for an S-type granite composition. Zircon extracted from the orthogneiss yields a Cambrian crystallization age of 498.9 ± 6.9 Ma. Conversely, monazite from the orthogneiss and diatexite records only Carboniferous anatexis of the orthogneiss at ca. 350 Ma, while zircon mostly remains unaffected by anatexis.

The results of phase equilibria modelling that account for nearly full zircon preservation (<10% dissolution) and complete monazite dissolution and regrowth indicate P-T conditions of 5-8.5 kbar and 760-800°C. Our results suggest that a low degree of partial melting (<10 vol%) in an orthogneiss with an S-type granite signature may occur without water influx at <800°C. This will preserve protolith ages in zircon but erase them in original monazite. The contrasting behaviour of these accessory chronometers can be used as a tool to bracket the temperature conditions of anatexis.

Applications of electron backscatter diffraction to the study of volcanic rocks and their experimental analogues

Thomas Griffiths[1)], Alessandro Musu[1)], Alessio Pontesili[2)], Stefano Peres[1)], Matteo Masotta[3,4)]

[1)] Department of Lithospheric Research, University of Vienna, Josef-Holaubek-Platz 2, Vienna, Austria

[2)] Instituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata 605, 00143 Roma, Italy

[3)] Dipartimento di Scienze della Terra, University of Pisa, Via Santa Maria 53, 56126 Pisa, Italy

[4)] CISUP, Centro per l'Integrazione della Strumentazione Universita' di Pisa, Lungarno Pacinotti 43, 56125 Pisa, Italy

Correspondence to: th.griffiths@univie.ac.at

Electron Backscatter Diffraction (EBSD) spatially maps crystallographic orientations using the scanning electron microscope and is routinely applied to metamorphic rocks. However, EBSD also offers many advantages for the study of volcanic products and their experimental analogues.

We present EBSD analysis of an experiment on the effect of shear strain rates on crystallisation in a system of trachybasaltic composition (Musu et al. 2026). A trachybasaltic melt in a platinum crucible, kept at atmospheric pressure and controlled temperature (initially 1400°C), was stirred using a central rotating Pt-coated alumina spindle, creating a shear strain rate gradient from the spindle edge (1 s-1) to the crucible rim (~ zero). EBSD scans constrained the area fraction, size, shape and number density of different phases, formed during cooling from superliquidus temperatures to 1130°C under strain and subsequently modified by static cycling between 1130 and 1170°C. Simultaneously the strain rate experienced in different domains was compared by quantifying the strength of crystallographic and shape preferred orientations.

Strain rate shows a strong (but phase-dependent) positive correlation with observed crystal number density (and thus inferred nucleation rate). Further, mineral phase proportions varied in different strain rate domains, interpreted to

arise due to differing nucleation behaviour. These results showcase the unique advantages of EBSD datasets over backscattered electron (BSE) imaging, namely excellent phase discrimination, the possibility to separate touching crystals of the same phase, and the delivery of spatially correlated microstructural and crystallographic orientation information.

To understand the effects of EBSD processing on quantitative microstructural parameters from glass-bearing samples, we also analysed trachybasaltic experimental charges from piston cylinder crystallisation experiments, containing glass and dendritic and/or skeletal clinopyroxene alongside titanomagnetite. Gradients in EBSD indexing quality parameters across glass-crystal boundaries generate a thresholding effect on calculated grain sizes and area proportions, due to the need to define glass pixels using an indexing quality threshold. Thus, careful assessment of thresholding parameters is necessary regardless of whether EBSD or BSE imaging is used for microstructural quantification.

References

Musu et al., 2026. Journal of Petrology 67, egag015. https://doi.org/10.1093/petrology/egag015

Melt inclusions in monazite: How nanogranitoids can provide key insights into understanding crustal melting

David Günzler[1], Dominik Sorger[1], Thomas Müller[2], Matthias Willbold[2], Silvio Ferrero[3]

[1] Department of Earth Sciences, University of Graz, Universitätsplatz 2, 8010 Graz, Austria
[2] Universität Göttingen, Goldschmidtstrasse 1, 37077 Göttingen
[3] Universität Cagliari, Blocco A, Cittadella Universitaria, 09042 Monserrato, Italy

Correspondence to: david.guenzler@uni-graz.at

Key insight into mineralisation processes and petrogenesis in the lithosphere are commonly provided by melt inclusions trapped in minerals. Glassy inclusions formed by igneous processes was the focus of decades of research, helping to characterise a variety of magmatic processes. More recently, inclusions of anatectic melt in high grade metamorphic rocks increasingly gained more interest, providing a direct snapshot of crustal melting processes. In most cases they can be recognised as polyphase crystalline inclusions in metamorphic minerals, consisting of quartz, mica and feldspar polymorphs, consequently referred to as a nanogranitoid. Nanogranitoids must be re-melted to a homogenous glass by recreating their original confinement conditions with subsequent quenching for a complete geochemical analysis.

In this project we analyse nanogranitoid-inclusion (NI) hosted in monazite and garnet from granulite facies gneisses with differing P-T-t paths of the southern Moldanubian Bohemian Massif. Distinct zonation in monazite and garnet were used to reveal their from ca. 370 Ma to 312 Ma lasting complex metamorphic evolution (Sorger et al. 2020). NI within these distinct mineral generations enable us to correlate metamorphic conditions during anatexis. For successful re-homogenisation of NI while ensuring individual host-grain recovery, we apply a modified established experimental routine with a piston cylinder apparatus (Bartoli et al. 2013). Raman, infrared spectroscopy, laser ablation inductively coupled plasma mass spectrometry and electron probe micro analysis are utilized for NI identification, textural and geochemical analysis. Monazite as an important

reservoir for LREE, Th, U and Y, paired with re-homogenised NI provides an ideal toolset for studying partitioning mechanisms under variable conditions in natural systems. Geochemical analysis of the hosted melt inclusions could help us to further enhance our understanding of the dynamics and timing of crustal melting during orogeny, the fluids involved and the conditions of melt-host stability.

References

Bartoli et al. (2013). Geofluids 13 (4), 405-420

Sorger et al. (2020). Gondwana Research 85, S. 124–148

Cryptic and Modal Mantle Metasomatism in Xenoliths from Central/Southern Vietnam and Southern Laos: Evidence for Multi-stage Interaction with Alkali and Carbonatitic Melts

Christoph A. Hauzenberger[1], Jürgen Konzett[2], Hoang Nguyen[3]

[1] Department of Earth Sciences – NAWI Graz Geocenter, University of Graz, Universitätsplatz 2, 8020 Graz, Austria
[2] Institute of Mineralogy and Petrography, University of Innsbruck, Austria
[3] Institute of Geological Sciences, Vietnam Academy of Science & Technology, Vietnam

Correspondence to: christoph.hauzenberger@uni-graz.at

Mantle xenoliths and associated xenocrysts (clinopyroxene, zircon, sapphire, augite, corundum) are widespread in Neogene to Quaternary alkali-basalts of central/southern Vietnam and southern Laos. These xenoliths are mostly spinel-lherzolites and, more rarely, spinel harzburgites, wehrlites and pyroxenites. For this study, samples with sizes ranging from a few cm to tens of cm were collected from Localities in central-to-southern Vietnam and southern Laos (Pleiku, Da Lat, Nui Trai, Xuan Loc, Bolaven Plateau) and from the Ile de Cendres (offshore).

Detailed petrographic and geochemical analysis reveal that the subcontinental lithospheric mantle beneath this region has undergone multiple metasomatic events as evidenced by mineral assemblages, trace element patterns of the mantle phases and textural features. Clinopyroxene commonly occurs in two generations, with texturally primary grains showing depleted mantle signatures and secondary rims characterized by enrichment in light rare earth (LREE) and large ion lithophile elements (LILE), indicative of interaction with carbonatitic and/or alkali-rich silicic melts. Carbonate inclusions in olivine and REE-rich apatite and monazite in wehrlite xenoliths from central Vietnam document nearly simultaneous interaction with immiscible silicate and carbonatite melts at shallow lithospheric depths (~30 km, 700–800°C), resulting in extreme enrichment of P and REE. Combining a U-Pb monazite age of ~2 Ma with host basalt extrusion ages indicates that the monazite-forming metasomatic event must have occurred no more than a few hundred thousand years before transport of the monazite-bearing xenolith to the surface.

In southern Laos, spinel harzburgite xenoliths display evidence for two-stage metasomatism: an initial event involving a P-alkali-rich H_2O-CO_2 fluid, followed by infiltration of a Si-undersaturated alkali basaltic melt, both occurring shortly before xenolith entrainment.

Collectively, these findings highlight cryptic and modal mantle metasomatism beneath Southeast Asia, driven by episodic influxes of volatile-rich, alkali, and carbonatitic melts and fluids, likely linked to regional tectonic processes and subduction-related mantle upwelling.

Geological Evolution of Ophiolite Mélanges in the Albanides: From the Tithonian to Early Cretaceous

Christoph A. Hauzenberger[1], Walter Kurz[1], Kujtim Onuzi[2], Theo Ntaflos[3]

[1] Department of Earth Sciences – NAWI Graz Geocenter, University of Graz, Universitätsplatz 2, 8020 Graz, Austria
[2] Polytechnic University of Tirana, Tirana, Albania
[3] Deptartment of Lithospheric Research, University of Vienna, Austria

Correspondence to: christoph.hauzenberger@uni-graz.at

The Mirdita ophiolite, dating from the Middle Jurassic, forms a prominent northwest–southeast trending belt within the Albanide mountain range. This belt is a remnant of the Tethyan oceanic lithosphere. Notably, segments of these ophiolites exhibit characteristics typical of supra-subduction zone (SSZ) environments, while others display features associated with mid-ocean ridge basalt (MORB) settings. Within this ophiolitic sequence, mélanges of Tithonian to Early Cretaceous age are found in the southeastern Albanides. These mélanges are positioned either transgressively or conformably atop radiolarian cherts of Kimmeridgian-Tithonian age, or over Middle Liassic to Malmian pelagic carbonate sequences along the margins of the ophiolite belt. The mélanges themselves are composed of conglomerates and breccias, containing clasts and blocks ranging from centimeters to meters in size. These include (serpentinized) ultrabasites, gabbros, leucogabbros, troctolites, basalts, marls, sandstones, radiolarites, and limestones, all embedded within a serpentinite matrix. Occasionally, “exotic” components such as amphibolite are present, likely representing the metamorphic sole of the ophiolite. Volcanic rocks sampled from mélange outcrops near Korca include basalt, alkali-basalt, phonolite, and dacite. The basalts exhibit MORB affinities, while the alkali-basalt and phonolite show within-plate characteristics, and the dacite is indicative of an island arc setting. The plutonic suite within the mélange comprises both fine- and coarse-grained gabbros, partially sheared leucogabbro, and troctolite. Some clasts are ultrabasic, representing cumulates and plotting within the peridotite-gabbro field, while others fall within the gabbro field. The few clasts identified as “normal” gabbro (microgabbro, dark medium-grained gabbro) correspond to a mid-ocean

ridge environment. Of the five “exotic” amphibolite samples recovered, four display typical MORB compositions, and one shows alkali-basalt characteristics.

Origin of ekanite-bearing antiskarn from Ampegama, southwestern Highland Complex, Sri Lanka

K. A. Geeth Sameera[1,2,3], Christoph A. Hauzenberger[4], G. W. A. Rohan Fernando[5], Radek Škoda[6], Prasanna L. Dharmapriya[7], Chutimun Chanmuang N.[3], Lutz Nasdala[3]

[1] Geological Survey and Mines Bureau, 569, Epitamulla road, Pitakotte, Sri Lanka
[2] Postgraduate Institute of Science, University of Peradeniya, P. O. Box 25, Peradeniya 20400, Sri Lanka
[3] Institut für Mineralogie und Kristallographie, Universität Wien, Josef- Holaubek- Platz 2, Wien 1090, Austria
[4] Institute of Earth Sciences-NAWI Graz Geocenter, University of Graz, Universitätsplatz 2, Graz 8010, Austria
[5] Department of Physics, Faculty of Natural Sciences, The Open University of Sri Lanka, Nugegoda, Sri Lanka
[6] Department of Geological Sciences, Faculty of Science, Masaryk University, Kotlářská 267/2, Brno 61137, Czech Republic
[7] Department of Geology, Faculty of Science, University of Peradeniya, Peradeniya 20400, Sri Lanka

Correspondence to: sameera.kasthuri.arachchige@univie.ac.at

Ekanite is a rare mineral that was first found in Sri Lankan gem placers; however, its source rock and origin remained unknown until a few years ago. Here we report the primary occurrence of large metamict ekanite in an antiskarn-type mineral assemblage. In general, the term antiskarn describes an uncommon type of metasomatic rock that, due to its formation upon interaction of carbonatitic melt with silicic rock, is composed of unusual mineral assemblages. Antiskarn occurs as dykes up to 2 m wide in a quarry near Ampegama, southwestern Highland Complex, Sri Lanka, where charnockitic gneiss is extracted. The dykes consist of calc-silicate minerals as well as irregularly shaped and variously oriented rock fragments of the charnockitic gneiss. The calc-silicates show gradational boundaries / reaction zones with wall rocks and enclosed fragments. The antiskarn is characterised by three stages of mineral-assemblage formation;

primary assemblage, overprint assemblage and later alterations. Field relations, textural features and variations in mineral chemistry from calc-silicate over contact zone to charnockitic gneiss suggest that wollastonite, scapolite, clinopyroxene, titanite, fluorite and ekanite ($Ca_2Th_{0.9}U_{0.1}Si_8O_{20}$) in primary mineral assemblage are the products of interactions of carbonatitic melt with wall rocks. Other minerals (such as K-feldspar) are assimilation products from wall rocks. Phase equilibria modelling of the charnockitic gneiss implies that peak metamorphism was at ca. 850±50 °C and 6±1 kbar. Field relationships, petrographic observations, and mineral-chemical data indicate that the carbonatitic melt was most likely generated by anatexis of crustal carbonate rocks during regional metamorphism. Carbonatitic melt infiltration is interpreted to have occurred at, or close to, the peak conditions. Primary antiskarn minerals interacted with late-stage CO2- and F-rich fluids forming overprint mineral assemblages. Unaltered ekanite is up to 3 cm size, transparent, bottle-green, and its metamict. Ekanite records at least two stages of alteration; first (Aek-1) through compositionally evolved carbonatitic melts / fluids, second (Aek-2) though later stage, low-temperature hydrothermal interactions. Electron probe microanalyzer chemical dating yielded a Th–U–Pb age of 524.4 ± 6.4 Ma (2σ) for unaltered ekanite, supporting that its primary growth was associated with late-stage regional metamorphism in the Highland Complex.

Paragenetic Evolution and Geochronology of the Samoeng Sn-W deposit, Inthanon Zone, Northern Thailand

Srett Santitharangkun[1], Christoph A. Hauzenberger[1], Etienne Skrzypek[1], Daniela Gallhofer[1]

[1] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Universitätsplatz 2, 8010 Graz, Austria

Correspondence to: srett.santitharangkun@uni-graz.at

The Samoeng Sn-W deposit in Northern Thailand formed via skarn mineralization related to calc-silicate wall rocks and a Late Triassic granite. The varying calcareous lithologies comprise skarn, calc-silicate and marble zone. The primary Sn-W deposit occurs within an intense hydrothermal alteration zone containing cross-cutting clinozoisite-mica veins. The localized precipitation of cassiterite and scheelite within this alteration zone was driven by an influx of external hydrous fluids. This fluid mixing, combined with temperature drop and chemical neutralization, destabilized mobile metal-fluoride complexes, forcing Sn and W to precipitate alongside retrograde clinozoisite, muscovite, and F-rich phlogopite. Besides diopside, amphibole, and grossular, the skarn minerals include humite-group minerals, vesuvianite, phlogopite, muscovite, magnetite, Fe-Ti oxides, spinel, wolframite, scheelite, titanite, rutile, malayaite, allanite, monazite, xenotime, and apatite.

The skarn shows a distinct transition from a high-temperature (~850 °C), shallow, anhydrous prograde skarn to a cooler, fluid-dominated retrograde system. Highly fractionated, F-rich magmatic fluids efficiently mobilized Sn, W, and HFSEs—a process tracked by distinct spatial and temporal variations in titanite compositions. Early proximal fluids precipitated a Sn-rich, F-poor titanite suite characterized by elevated REE concentrations and negative Eu anomalies. As fluids migrated distally and cooled, they shifted into a F-rich, Sn-poor titanite population accompanied by F-rich phlogopite and humite-group minerals in the outer calc-silicate and marble zones.

Zircon dating from the granite yields an age of around 220 Ma. However, in-situ monazite on granitic and skarn samples identified distinct age populations at ~220 Ma and ~75 Ma. This suggests recrystallization and re-precipitation during a Late Cretaceous thermal overprint that partially reset local monazite while preserving the primary Triassic minerals.

Based on these data, we conclude that Sn-W mineralization occurred in the Late Triassic during the emplacement of the granite, which led to skarn formation with contact aureole. This event is related to the Sukhothai-Sibumasu collision during the closure of the Paleo-Tethys. During the Late Cretaceous, a thermal overprint was recorded in monazite from both the granites and the mineralized skarn zone. This overprint is associated with the collision between the Sibumasu and West Burma blocks.

Late Permian diabase dikes from Mt. Papuk (N Croatia): possible evidence for the Neotethys Ocean opening?

Petra Schneider[1)], Daniela Gallhofer[2)], Etienne Skrzypek[2)], Christoph A. Hauzenberger[2)], Dražen Balen[1)]

[1)] Department of Geology, Faculty of Science, University of Zagreb, Horvatovac 102a, 10000 Zagreb, Croatia
[2)] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Universitätsplatz 2, 8010 Graz, Austria

Correspondence to: pschneider@geol.pmf.unizg.hr

Mt. Papuk (Croatia), an inselberg located in the SW part of the Pannonian Basin, is characterised by a complex geological evolution. The core of Mt. Papuk is composed of various pre-Variscan, Variscan and Alpine igneous and metamorphic rocks of the Tisia Mega-Unit. This study investigates the characteristics of mafic rocks that intrude the surrounding country rocks (granitoids, migmatites and gneisses) as dikes within the Šandrovac quarry, NW part of Mt. Papuk.

Medium- to coarse-grained diabase has a homogeneous structure and a porphyritic texture with albite phenocrysts. The microophitic matrix is composed of albite, diopside-augite, chlorite and accessory ilmenite-titanite intergrowths, pyrite and zircon. Additionally, blobs up to 5 mm in diameter, composed of quartz with a chlorite reaction rim, are common. Such quartz blobs in mafic rocks are rare and typically result from magma mingling and assimilation of silica-rich melt.

Preliminary U-Pb age dating of separated zircon grains using LA-ICP-MS reveals a youngest concordant date of 254±3 Ma, a group at 503±4 Ma and an old core of 1930±15 Ma. The youngest date is interpreted as the crystallisation age of the rock, while the older ages are inherited from the surrounding country rocks.

The onset of lithosphere thinning, mantle melting and related magmatism, triggered by extensional and transtensional tectonics associated with the Triassic-Jurassic rifting system, led to the initial fragmentation of the continental lithosphere (De Min et al. 2020). This created pathways for newly formed basic magma to penetrate the continental crust. Such basic magma could have caused

partial melting and assimilation of the surrounding material, as indicated by inherited zircon cores and quartz blobs in the studied diabase. Middle to Late Triassic magmatism related to this event is well documented in the Alpine-Dinaridic-Carpathian realm, including explosive acidic volcanism and pietra verde, followed by diverse mafic to intermediate intrusions (e.g. Strock et al. 2018). The presence of basic effusive rocks intruding the country rocks possibly marks the early stage of Pangea breakup in the studied area, where the zircon age record (~254 Ma) in a diabase from NW part of Mt. Papuk represents the earliest robust age ascribed to Neotethys Ocean opening.

References

De Min et al. (2020): Geol Mag, https://doi.org/10.1017/S0016756820000084

Strock et al. (2018): J Geol Soc London, https://doi.org/10.1144/jgs2018-123

Toward a better understanding of scapolite compositional variability: Implications for scapolite–plagioclase thermometry in HT rocks

Lucas Simian[1], Ralf Schuster[2], Rainer Abart[1]
[1] Vienna, Faculty of Earth Sciences, Geography and Astronomy, Department of Lithospheric Research, Wien, Austria
[2] GeoSphere Austria, Wien, Austria

Correspondence to: lucas.simian@univie.ac.at

Over the last decades, several attempts have been made to develop a reliable scapolite-plagioclase geothermometer. Experimental data indicate that the Na-Ca partitioning between scapolite and plagioclase is temperature dependent, making this exchange a potentially useful geothermometer for high-temperature rocks. However, the complex chemistry and large compositional variability of scapolite complicate the development of robust thermodynamic models. The compositional evolution between the two main scapolite end-members, marialite ($3NaAlSi_3O_8 \cdot NaCl$) and meionite ($3CaAl_2Si_2O_8 \cdot CaCO_3$), is non-linear and requires different coupled substitution mechanisms to reproduce naturally occurring scapolite composition. Currently available thermodynamic mixing models are calibrated for Ca-rich, Cl-free (pure carbonate) scapolite, and therefore neglect potential effects of Cl that may be present even at high calcium content. In addition, the models assume strictly coupled substitutions on the M- (Na-Ca) and T- (Si-Al) sites. These simplifications may lead to inaccurate activity calculations, with implications for thermodynamic calculations. Deviations from the simple substitutional behavior in natural scapolite may reflect partial control by fluid- and bulk-rock chemistry. This project aims to better constrain the influence of fluid- and bulk rock composition on the scapolite compositional variability. The Drosendorf unit in the Moldanubian Zone hosts many calc-silicate rocks, providing an ideal natural laboratory for investigating scapolite chemistry and testing thermodynamic assumptions. Particular attention is given to the occurrence of calcite and plagioclase in equilibrium with scapolite, as well as to the compositions of volatile-bearing phases such as titanite and apatite, to better constrain the fluid evolution in the studied rocks. We compare the results with predictions from Gibbs energy minimization and the subsequent temperature

calculations with existing temperature estimates from the literature. Preliminary results indicate incomplete coupling between the M-site and T-site, with measurable Cl contents showing clear trends, even at high Ca content. Both observations suggest that some assumptions used in existing mixing models oversimplify the compositional behavior of natural scapolite. Eventually, the project may help constrain the effects of bulk-rock and fluid composition on scapolite chemistry and ultimately refine existing thermodynamic mixing models.

The chemical composition of tourmalines from metapelites and metapegmatites as a function of prograde metamorphism

Peter Tropper[1], Vincent Hübner[1]
[1] Institute of Mineralogy and Petrography, University of Innsbruck, Innsbruck, Austria

Correspondence to: peter.tropper@uibk.ac.at

Tourmaline is a chemically complex mineral that sensitively records variations in pressure and temperature conditions during its growth and remains stable over a wide metamorphic range. This study investigates the chemical composition of tourmalines from metapelites andmetapegmatitesof the Matsch Unit (Vinschgau, South Tyrol, Italy) and evaluates compositional changes related to prograde Eoalpine metamorphism. Electron microprobe analyses, including point measurements, line profiles and element mapping, were performed on tourmalines from four samples (AM61, AM81, LM112 and SZ532). Structural formulae were calculated and tourmalines were classified according to the IMA (2011) nomenclature. All investigated tourmalines belong to the alkali group and are classified as dravite or oxy- dravite. The samples show systematic compositional differences between cores and rims. Rim compositions are characterized by higher Ca[X], Al[Y], vacancy[X] contents and higher Mg/Fe^{2+} ratios on the [Y]-position, whereas the cores display higher Na[X] contents. These changes can be linked to exchange reactions with other minerals especially the Na-Ca-exchange with plagioclase and the Mg-Fe-exchange with staurolite and biotite. The trends can also be seen in different tourmalines from the same samples and show a linear correlation with increasing metamorphic grade during prograde metamorphism. This linear correlation was used to empirically calculate the metamorphic conditions using the Ca[X] and Al[Y] contents and the Mg/Fe^{2+} ratio on the [Y]-position using the P-T estimates from previous studies. The correlation between the composition and the temperature and pressure conditions in the metapelites were also compared with correlations from tourmalines from Permian pegmatites from the same area, which show the same correlations for Ca[X] content and the Mg/Fe^{2+} ratio, but differ in the Al[Y] trend with prograde metamorphism. Where in the metapelites the Al[Y] content increases with rising temperature and pressure, it decreases in the pegmatites.

This indicates that correlations between chemical composition of tourmalines and metamorphic conditions is strongly dependent on the host rock composition. The results confirm that tourmaline composition systematically responds to changing metamorphic conditions and can preserve P-T information of metamorphic events.

Carboniferous partial melting of the Variscan High-Grade Metamorphic Complex, Asinara Island (Italy)

Olga Turek[1], Alfredo Idini[1], Leonardo Casini[2], Aratz Beranoaguirre[3], Gabriele Cruciani[1], Dominik Sorger[4], Silvio Ferrero[1]

[1] Department of Chemical and Geological Sciences, University of Cagliari, Cagliari, Italy
[2] Department of Chemical, Physical, Mathematical and Natural Sciences, University of Sassari, Sassari, Italy
[3] Frankfurt Isotope and Element Research Center, Goethe University Frankfurt, Frankfurt, Germany
[4] Petrology and Geochemistry, Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Graz, Austria

Correspondence to: olga.turek@unica.it

Northern Asinara Island belongs to the High-Grade Metamorphic Complex, which is part of the Southern Variscan Chain. This area mainly consists of migmatitic metasediments and orthogneisses. Among them, small bodies of granitoides/diatexites and lenses of partially melted amphibolites crop out. They shared the pressure-temperature (P-T) evolution during the Variscan Orogeny. The peak P-T conditions of metamorphism and partial melting of amphibolites, metapelites and orthogneisses were estimated with phase equilibrium modelling and single-element thermometry. All these rocks display evidence of partial melting at temperatures up to ~750 °C at 0.5 GPa.

To determine the ages of metamorphism, U-Pb geochronology was applied to garnet and apatite from each type of rock cropping out in the area. Garnet from orthogneisses gave an age of ~350 Ma, whereas garnet from granitoides/diatexites and leucosomes produced by partial melting of amphibolites yielded ~300 Ma. The results are, respectively, in agreement with the ages reported before for the Barrovian metamorphism in the Carboniferous and the late Carboniferous-early Permian high-temperature/low-pressure event in northern Sardinia (Carmignani et al., 1994) and in the southern Variscan sector (Martinez-Catalán et al., 2014). Moreover, younger ages of ~280 Ma are recorded in most of the apatite grains in various rock types, and an even younger age of

~260 Ma is recorded in an apatite found in a single fracture of granitoid/diatexite. The older apatite ages may reflect the time when the rock had cooled below the closure temperature of the U-Pb system indicating slow cooling after HT-LP metamorphism. Instead, the younger one has been lately reported in many Variscan rocks as potentially related to hydrothermal mineralisation (Deroin and Bonin, 2003).

References

Carmignani, L. et al. (1994). The hercynian chain in Sardinia (Italy). Geodinamica Acta, 7(1), 31–47. https://doi.org/10.1080/09853111.1994.11105257

Deroin, J. P., and Bonin, B. (2003). Late Variscan tectonomagmatic activity in Western Europe and surround

Martinez-Catalán, J. R., et al. (2014). The late Variscan HT/LP metamorphic event in NW and Central Iberia: relationships to crustal thickening, extension, orocline development and crustal evolution. Geological Society, London, Special Publications, 405, 225–247. https://doi.org/10.1144/SP405.1

Garnet U-Pb ages reset by ultrahigh temperature melt-rock interaction: A case study from the basin and range province

Jesse B. Walters[1], Aratz Beranoaguirre[2,3], Leo J. Millonig[2,3], Andrew Smye[4], Joshua M. Garber[5], Axel Gerdes[2,3], Horst R. Marschall[2,3]

[1] Department of Earth Science, University of Graz
[2] Institute for Geosciences, Goethe University Frankfurt
[3] Frankfurt Isotope and Element Research Center, Goethe University Frankfurt
[4] College of Earth and Mineral Science, the Pennsylvania State University
[5] School of Earth and Environmental Science, University of St. Andrews

Correspondence to: jesse.walters@uni-graz.at

In situ garnet U-Pb geochronology by laser ablation-inductively coupled mass spectrometry (LA-ICPMS) is a powerful tool for rapid and high-spatial resolution dating of metamorphic pressure-temperature–time histories. However, the U and Pb substitute into the structure of common pyralspite garnet and its influence on diffusion and potential age-resetting is poorly constrained. Studies by Mezger et al. (1989), Burton et al. (1995), and Dahl (1997) estimate U-Pb system closure temperatures in garnet of >800 °C. Similarly, Shu et al. (2024) proposed a closure temperature of ≥1100 °C but suggested that recrystallization may have reset some garnet U-Pb ages.

Here we examine the impacts of garnet recrystallization on U-Pb ages by examining ultrahigh-temperature (UHT) crustal xenoliths from the southwestern USA and northern Mexico. These granulites experienced isobaric heating at >900 °C between 36 and 30 Ma and UHT conditions were maintained until eruption at <1 Ma (Droubi et al., 2024; Cipar et al., 2020; 2024). Heating corresponds to the transition between Laramide crustal thickening and basin-and-range extension. Garnet trace element zoning shows a combination of diffusively reset growth zoning overprinted by island-moat structures, which formed via melt-driven loss of REE and HFSE along now-healed fractures (Droubi et al., 2024). Zircon data suggest garnet initially formed at ca. 30 Ma, whereas garnet diffusion modeling indicates that island-moat structures formed <1 Myr before eruption (Droubi et al., 2024). Our in situ split-stream LA-MC-ICPMS U-Pb garnet ages range from 4.6 ± 2.3 Ma to 1.8 ± 0.3 Ma (2s). Trace element data show decreasing U contents with decreasing REE and HFSE, consistent with significant resetting of U contents. In contrast, Pb contents show no trends with REE and HFSE. Combined with ages that overlap with the eruption age of the magmas which entrained the xenoliths, we suggest complete resetting of Pb during melt-garnet interaction. These data show that garnet U-Pb ages are susceptible to (near-)complete resetting via dynamic open-system processes.

References

Burton et al. (1995). Earth Plan. Sci. Lett. 133, 199–211

Cipar et al. (2020). Nat. Geosci. 13(11), 758–763

Cipar et al. (2024). Geochem. Geophys. Geosys. 25(7), e2023GC011177

Dahl (1997). Earth Plan. Sci. Lett. 150, 277–290

Droubi et al. (2024). JGR Soli

Mezger et al. (1989). Contrib. Min. Pet. 101, 136–248.

Shu et al. (2024). Contrib. Min. Pet. 179 (49).

Decoupling of monazite petrochronology from P–T evolution during garnet hydrothermal dissolution–reprecipitation

Di Wang[1,2], Jesse Walters[2], Huixia Ding[1], Matthew Kohn[3]

[1] China University of Geosciences, Beijing, Xueyuan Road 29, 100083 Beijing
[2] University of Graz, Heinrichstraße 26, 8010 Graz
[3] Boise State University, University Drive 1910, ID 83725 Boise

Correspondence to: wd98@foxmail.com

Monazite U–Th–Pb ages are commonly coupled with Y and heavy rare earth element (HREE) contents to link reactions, particularly those involving the formation and breakdown of garnet, with pressure–temperature (P–T) paths to constrain and uncover orogenic processes. This link assumes that changes in garnet abundances are mainly controlled by P–T conditions. Here we show that fluid-driven dissolution-reprecipitation of garnet and monazite can disturb the P–T–time(t) relationship.

We collected metapelitic schists from the Yardoi gneiss dome, southern Tibet, where orthogneiss and metapelites were intruded by Eocene (43–35 Ma) to Miocene (17 Ma) granitoids, providing a critical window investigate fluid–rock interaction in mid-crustal metamorphic rocks. Our data constrain prograde to peak metamorphism from 5.7 kbar and 550 °C to 7.5–8.5 kbar and 650–750 °C, followed by retrograde metamorphism at 5.5–6.5 kbar and 650–700 °C. Low Y+HREE monazite domains dated to 46–41 Ma record growth in the presence of garnet during peak metamorphism, whereas high Y+HREE contents between 23 and 15 Ma indicate garnet breakdown during isothermal decompression. These data indicate 20–30 Myr at 650–700 °C, consistent with near complete resetting of garnet major element zoning.

One sample from the dome core displays atoll garnets along with biotite, muscovite, plagioclase, quartz, and rutile. Monazite from this sample yields ages from 50 to 19 Ma. Y+HREE contents increase between 45 and 38 Ma, and decrease after ~38 Ma, suggesting apparent garnet breakdown followed by (re-

)growth between 45 and 20 Ma. Phase diagram models predict limited variation in garnet modal abundance at >7 kbar and 600–700 °C, and no obvious garnet-consuming phase, such as staurolite, is present. Garnet XGrs maps instead show a pebbly texture, with interconnected low-XGrs moats surrounding high-XGrs islands.

We suggest that garnet recrystallization was driven by the release of magmatic-hydrothermal fluids from nearby 43–35 Ma granite intrusions. Such fluid-assisted recrystallization can generate age-composition trends that mimic monazite zoning patterns of P–T path controlled garnet breakdown or growth. Misinterpretations of such data would propagating significant errors into tectono-metamorphic reconstructions, emphasizing the necessity of microstructurally constrained petrochronology when interpreting monazite U–Th–Pb ages.

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Session 06

Dynamik von Eroberflächen-Prozessen und Quartärgeologie

Earth Surface Dynamics and Quaternary Geology

Conveners:
Franziska Stamm & Dorothee Hippler

NAWI Graz Natural Sciences

TU Graz

UNI GRAZ

Tectonic Unroofing vs. Erosional Denudation: Deconstructing the Exhumation Engine of the Karawanken-Pohorje Region

Forat Albatineh[1)], Jörg Robl[1)], Christoph von Hagke[1)]

[1)] Department of Environment and Biodiversity, Paris Lodron University of Salzburg, Hellbrunnerstraße 34, 5020 Salzburg, Austria

Correspondence to: foratahmadayed.albatineh@plus.ac.at

Disentangling the relative contributions of tectonic unroofing and climate-driven erosional denudation remains a central challenge in understanding mountain belt evolution. While both mechanisms drive the exhumation engine, they generate distinct topographic signatures and characteristic spatial patterns in low temperature cooling ages and catchment-wide erosion rates. The Karawanken-Pohorje region, in the transition from the Eastern Alps to the Southern Alps, provides an excellent setting for investigating the contribution of these two processes to exhumation and landscape evolution. In this region, still-active tectonic structures tectonically detach and shape adjacent mountain massifs that are subject to the same climatic conditions.

To investigate whether these mountain massifs are primarily controlled by tectonic unroofing, erosional denudation, or a combination of both processes, we combine quantitative morphometric analysis with time-temperature history modeling based on (U-Th)/He low-temperature thermochronological data. We describe the temporal evolution of erosion, exhumation, and landscape geometry using a 1D landscape evolution model consisting of two channels and a common drainage divide.

Although all investigated massifs show a significant amount of exhumation, terrain analysis indicates distinctly different states of landscape maturity across adjacent, fault-bounded mountain massifs—with the low-relief, low-channel-steepness surface at the top of the Pohorje Mountains and the overall high channel steepness in the nearby Karawanken Mountains as the most striking features. Within the Karawanken Mountains themselves, a discrete increase in channel steepness across the range-bounding thrust faults is observed, alongside a pronounced asymmetry of the drainage divides featuring contrasting channel steepness on opposing sides.

Although our current dataset is not yet sufficient to fully quantify the relative contributions of tectonic unroofing versus erosional denudation to the exhumation and landscape evolution of these southeastern Alpine massifs, we clearly observe a landscape in transient state. This is underscored by migrating knickpoints within the drainage networks and strong evidence of mobile drainage divides, both indicating active fluvial network reorganization.

River Piracy Events at the Eastern End of the Alps: Evidence from Monazite Fission Tracks in the Mur-Mürz-System

Simon del Negro[1], Martin Masten[1], Etienne Skrzypek[1], Thomas Wagner[1], Kurt Stüwe[1]

[1] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Universitätsplatz 2, 8010 Graz, Austria

Correspondence to: simon.del-negro@uni-graz.at

During the evolution of the Alps, drainage systems changed significantly due to tectonic activity, uplift and ultimately Pleistocene glaciation. The modern drainage systems in the Eastern Alps follow the mean topographic gradient away from the core of the orogen. An exception is the river Mürz in Styria, which flows westward towards the mountain range. Because this region was spared by glacial erosion in the Pleistocene, such morphological features can be used to infer the pre-Pleistocene landscape evolution and uplift history. We present morphological and thermochronological evidence to test an old hypothesis: that the flow direction of the Paleo-Mürz was reversed in the young geological evolution by river piracy events. The morphometric analysis reveals that planation surfaces along the Mürz valley and east of the Semmering pass correlate with the well-known planation surfaces in other parts of the Eastern Alps. Interestingly, the so-called Trahütten level, interpreted to have formed at 3-4 Ma, corresponds to the highest level of Miocene sediment fill in the Mürz valley. The observations suggest that the flow direction of the Mürz river changed in connection with the formation of the Trahütten level (~ 1000 m). To test this interpretation independently, monazite fission track dating (with a closure temperature of 25-45 °C) was performed on samples from topographically low points along the Mürz river. The obtained fission track ages vary around 3.4 Ma in the central Mürz valley and date the cooling of rocks in response to removal of the Miocene sedimentary overburden following river capture by the Mur river. By integrating geomorphological observations with low-temperature thermochronology and stratigraphic records, we reconstruct the evolution of the regional drainage network between 16 and 2 Ma and identify river piracy as a key driver of late Neogene landscape reorganization in the Eastern Alps.

Quarries in 4D - a geoarchaeological remote sensing approach

Erich Draganits[1], Gabrielle Kremer[2], Beatrix Moshammer[3], Andreas Rohatsch[4], Michael Doneus[5]

[1] Institut für Geologie, Universität Wien, Josef-Holaubek-Platz 2/UZA2, 1090 Wien
[2] Österreichisches Archäologisches Institut, Österreichische Akademie der Wissenschaften, Dominikanerbastei 16, 1010 Wien, Austria
[3] Geosphere Austria, Neulinggasse 38, 1030 Wien
[4] Institut für Geotechnik, TU Wien, Karlsplatz 13/220, 1040 Wien
[5] Institut für Urgeschichte und Historische Archäologie, Universität Wien, Franz-Klein-Gasse 1, 1190 Wien

Correspondence to: Erich.Draganits@univie.ac.at

Quarries in Miocene limestones and sandstones in the Vienna Basin (Austria) were documented in high-resolution airborne laser scanning data and orthophotos. Most old quarry areas were quarried also in subsequent periods, commonly destroying virtually all pre-existing traces. Age information has been gained from historical maps, historical photography and paintings and quarry face graffiti. In total, 658 quarries, possible quarries and shallow quarries have been outlined in the detailed digital terrain models, which were compared with 453 quarries indicated in four generations of historical maps between the years 1754 to 1872. The numbers of quarries are generally low in the Walter map (1754-1756), the First Military Survey (1773-1785) and Second Military Survey (1809-1846), but increase dramatically in the maps of the Third Military Survey (1872-1873), probably related to the stone demand of the building programs of the so-called Ringstraßen Periode in Vienna. Documenting the outline of quarries in an GIS environment added important information concerning shape and area compared with only point information. The newly documented quarries substantially increase the number of known quarries and contribute to our understanding of the human impact on the landscape evolution in the Vienna Basin especially during the last 200 years.

References

Draganits, E., Moshammer, B., Kremer, G. & Doneus, M. 2023. Geoarchaeological remote sensing prospection of Miocene limestone stone quarries in the hinterland of Roman Carnuntum and Vindobona (Vienna Basin, Austria). Journal of Austrian Earth Sciences, 116, 39-83. https://doi.org/10.17738/ajes.2023.0003

Dam Good Deposits: Unravelling Secrets of a Dammed Lake in Salzburg's Quaternary Record

Lukas Eder[1], Daniel Le Heron[1]

[1] Department of Geology, University of Vienna, Josef-Holaubek-Platz 2 1090 Vienna

Correspondence to: lukas.eder@univie.ac.at

The Quaternary record of Austria preserves a rich archive of glacial and paraglacial deposits, including thick successions in major trough valleys. At Embach, 60 km southwest of Salzburg in the Salzach Valley, an at least 80 m thick succession of gravels and sands is exposed and capped by a till deposited by the Salzach trunk glacier at the Last Glacial Maximum (LGM). The village of Embach is situated directly above this succession, which forms part of an active mass movement and thus substantial stabilisation efforts were made since the 20th century. Despite this, the origin of the sands and gravels, and the associated landscape evolution have remained poorly constrained. Here, integrated analysis of UAV-based photogrammetry, high-resolution (1 m) laser-scan topography, field profiling and mapping, X-ray diffraction, granulometry and clast fabric demonstrates that the Embach succession records a mixed delta–fluvial system developed in a partly lake-filled Salzach Valley prior to the LGM. Large-scale foreset beds indicate delta deposition, whereas imbricated, channelised and sheet gravels record persistent fluvial activity. Within a sequence-stratigraphic framework, several lake-level rise–fall cycles are recognised, and measured palaeoflow indicators (foresets, imbrications, drumlins) show north- and east-directed flow into the Salzach Valley. The results imply that earlier interpretations of the Vorstoßschotter as purely fluvial deposits require revision. A range of mechanisms is proposed for lake formation and relative lake-level fluctuations, including mass movements and the collapse or reorganisation of lateral moraines and alluvial fans, enabling a detailed palaeoenvironmental reconstruction. These findings extend recent Quaternary sedimentological and geomorphological work in Austrian trough valleys and have direct relevance for hazard assessment in populated areas underlain by Quaternary deposits. For Embach in particular, a robust understanding of sedimentary architecture and Quaternary history is crucial for designing future mitigation measures on the active mass movement.

How Roman aqueduct scale deposits act as environmental archives

Isabel Egartner[1], Sara Raic[1], Franziska Maria Stamm[1], Ronny Boch[1], Martin Dietzel[1], Klaus Grewe[2], Dorothee Hippler[1]

[1] Graz University of Technology, Institute of Applied Geosciences, Rechbauerstraße 12, Graz, 8010, Austria
[2] Tannenstraße 18, 53913 Swisttal-Morenhoven, Germany

Correspondence to: egartner@student.tugraz.at

A special case of freshwater carbonate deposits in man-made settings are calcium carbonate ($CaCO_3$) scale deposits in aqueducts and water conduits of the Roman times. They occur across the ancient expansion of the Roman empire and therefore in different climate zones, from maritime to continental mid-latitude regions. Well comparable to $CaCO_3$ scale deposits in natural environments, such as speleothems or travertines, these mineral deposits can serve as valuable environmental archives, e.g. for the reconstruction of the ambient physico-chemical conditions during their growth, variable paleoclimate, the hydrogeology of the water catchment area and the aquifer. With this in mind, our study integrates archaeological and geoscientific approaches to investigate scale deposits from the major Roman aqueduct known as the 'Eifel-Wasserleitung', which supplied water from the Eifel mountains to the Roman city of Cologne (Germany), using microstructural and geochemical proxies. Therefore, optical microscopy, Raman spectroscopy and LA-ICP-MS analyses have been performed in order to reveal the spatiotemporal relationships between petrography, mineralogy and elemental distribution in the scale deposit. Major and trace elemental data have been evaluated using the software packages GLITTER and moreover the data analysis software ioGasTM.

The polished hand specimen of one carbonate scale deposit (L-W-H size: 12 cm x 6 cm x 8 cm) shows mesofabric characteristics with alternating light and darker layers, ranging from 1 to 5 mm in size, and a massive appearance with no macroscopic porosity. At the microfabric level, the calcite shows different growth types, occurring mainly as microsparite and elongated columnar calcite crystals. Results revealed that the individual laminae are essentially formed by calcite. However, textural differences in CaCO3 nucleation and growth are indicated by distinct crystal shapes and crystal arrangements, e.g. microsparite and columnar

to feather-like sparite. The minor and trace element distribution (e.g. Mg, Sr, Ba, Al, K, Li, Fe, Mn, Ni, Co, Cu, Zn, Pb, Zr, P, U) from the bottom to the top of the hand specimen exhibits well-developed, element-specific (e.g. Al, K and Li contrary to Zn and Zr) patterns as well as subtle cyclic variations (e.g. Sr and Ba) across the vertical axis and thus along time. Careful assessment of the observed patterns indicates variable mineral growth (rate) mechanisms that can be related to changes in water flow and discharge, dilution effects caused by seasonality in the supplied water, provenance and local geology (source rock, ore deposits, detrital and soil-derived components) and potential microorganic influence (e.g. by cyanobacteria; redox-sensitive, Fe-oxidizing bacteria). The high-resolution analyses highlight this archive's promising potential for regional environmental reconstructions.

On the effective coupling of geodynamic and surface evolution models

Menno Fraters[1], Stefan Hergarten[2]

[1] Institut für Erdwissenschaften, Universität Graz, Universitätsplatz 2, 8010 Graz, Austria

[2] Institut für Geo- und Umweltnaturwissenschaften, Universität Freiburg, Albertstr. 23B, 79104 Freiburg, Germany

Correspondence to: menno.fraters@uni-graz.at

The interaction between long-term geodynamics and the surface processes which work on shorter timescales is critical to understanding long-term climate-tectonic feedbacks. The main problems with modeling this interaction are a combination of the complexity of proper coupling and the computational cost due to the very different spatial and timescales on which these models operate.

With the improvement of geodynamic models, allowing for the high resolution 3D investigation of the scales of mantle to lithosphere, the proper integration of surface processes into these models becomes important for the kind of processes that can now be investigated. This is not only for the effect of the geodynamic model on the surface processes, but because the potential influence of surface processes on the evolution of the geodynamic model.

Here we present a numerical workflow to couple the geodynamics model ASPECT (Heister et al., 2017; Kronbichler et al. 2012) with the landscape evolution model OpenLEM (Hergarten, 2020). We use a newly developed approach to couple these of models, which significantly limits numerical diffusion for cases where the surface is moving laterally.

With this coupling, we will be able to better investigate climate tectonic feedback mechanisms and compare the results again observations.

References

Stefan Hergarten. 2020. “Transport-limited fluvial erosion -- simple formulation and efficient numerical treatment” Earth Surface Dynamics 8 (4): 841--854. doi:10.5194/esurf-8-841-2020

Timo Heister, Juliane Dannberg, Rene Gassmöller, and Wolfgang Bangerth. 2017. “High Accuracy Mantle Convection Simulation through Modern Numerical Methods – II: Realistic Models and Problems.” Geophysical Journal International 210 (2) (May 9): 833–851. doi:10.1093/gji/ggx195. h

Martin Kronbichler, Timo Heister, and Wolfgang Bangerth. 2012. “High Accuracy Mantle Convection Simulation through Modern Numerical Methods.” Geophysical Journal International 191 (1) (August 21): 12–29. doi:10.1111/j.1365-246x.2012.05609.x.

Tracing the Anthropogenic Fingerprint: Isotopic and Sedimentological Insights into Vienna';s Floodplain Archives

Diana Hatzenbühler[1,2)], Michael Weißl[3)], Karin Hain[3)], Andreas Lang[4)], Christian Baumgartner[2)], Michael Wagreich[2)]

[1)] GeoSphere Austria, Vienna, Austria
[2)] University of Vienna, Department of Geology, Vienna, Austria
[3)] University of Vienna, Faculty of Physics, Isotope Physics, Vienna, Austria
[4)] Paris Lodron University of Salzburg, Department of the Environment and Biodiversity, Salzburg, Austria

Correspondence to: diana.hatzenbuehler@geosphere.at

Human impact has developed into a major external forcing control on Earth’s environmental and geological processes, yet our understanding of the magnitude of its impact and temporal evolution is still limited. This study investigates the anthropogenic impact of the metropolis Vienna on its peri-urban environment in floodplain archives of the Danube River. By applying sedimentological, geochronological and chemostratigraphic methods, we aim to characterise the interplay between upstream human interventions and local river dynamics, constrain the timing of flood events, and identify and evaluate the geological signal of the Great Acceleration since the 1950s downstream of Vienna.

The study area is located in the National Park Donau-Auen, where minimal direct human intervention allows quantifying the human stratigraphic fingerprint and testing event-based dating using artificial radionuclides in an alluvial setting. Flood deposit ages were successfully determined combining radiogenic nuclide concentrations (137Cs, 239Pu, 240Pu, 237Np, 233U, 236U), field sedimentological methods, and historical records. Preliminary results reveal three distinct sedimentation periods reflecting upstream human interventions. The first phase (1870 – 1954) aligns with extensive river channelization leading to rapid erosion of mid-channel bars and backwater aggradation. The second phase (1954 – 1991) shows laterally extensive and thick, sandy flood deposits from fast and undamped sediment transport through the straightened riverbed during extreme events. The final phase (1991 – 2002) is characterized by thick, silty, and seemingly structureless flood deposits, interpreted as remobilized sediment from barrier lakes since the construction of the nearby hydro-power station Freudenau in 1997.

The role of alkali feldspar exsolution features for ice nucleation in the atmosphere

David Heuser[1)], Michael Hagn[1)], Johanna Seidel[2)], Alexei Kiselev[2)], Elena Petrishcheva[1)], Rainer Abart[1)]

[1)] Department of Lithospheric Research, University of Vienna, Josef-Holaubek-Platz 2, 1090 Vienna, Austria
[2)] Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany

Correspondence to: david.heuser@univie.ac.at

Airborne mineral dust can act as ice-nucleating particles (INPs) and initiate the glaciation of supercooled clouds. This strongly affects cloud properties and thus plays a significant role in the hydrological cycle and Earth';s climate (IPCC, 2021). Among mineral dusts, alkali feldspars have been identified as the most effective INPs (Atkinson et al., 2013; Kumar et al., 2018). However, the relationship between the mineralogical characteristics of alkali feldspars and their ice-nucleating activity (INA) remains poorly understood. Among other factors, Al–Si ordering, perthitic microstructures, and structural similarities between ice and feldspar have been proposed as possible explanations for the high INA of alkali feldspars (e.g., Whale et al., 2017; Kiselev et al., 2017, 2021; Franceschi et al., 2024).

In this study, six natural alkali feldspars were characterized mineralogically and petrographically, and the INA of each sample was investigated using cooling-ramp freezing experiments. In one experimental setup, arrays of 7 nl droplets of ultrapure Milli-Q water were dispensed onto cleaved feldspar (001) and (010) surfaces. In an alternative setup, 7 nl droplets of feldspar suspensions were deposited on Si wafers. The samples were cooled at a rate of 2 K min^{-1}, and droplet freezing was monitored using an infrared camera.

The results indicate a strong relationship between exsolution features and INA. The highest INA was observed for hydrothermally altered perthitic orthoclase and microcline, whereas the lowest INA was found for gem-quality sanidine and orthoclase. Micro- and nano-perthites containing semi-coherent, unaltered film lamellae exhibited lower INA than altered micro-perthites with recrystallized, more irregular exsolution lamellae and micropores along lamellar interfaces. These observations suggest that alteration and exposure of lamellar interfaces enhance ice nucleation. For all samples, (010) cleavage surfaces consistently showed higher INA than (001) cleavage surfaces. In contrast, no correlation between Al–Si ordering and INA was observed.

References

Franceschi et al., 2024: J. Phys Chem Lett, https://doi.org/10.1021/acs.jpclett.3c03235

IPCC 2021: Cambridge University Press, https://doi.org/10.1017/9781009157896

Kiselev et al., 2021: Atmos Chem Phys, https://doi.org/10.5194/acp-21-11801-2021

Whale et al., 2017: Phys Chem Chem Phys , https://doi.org/10.1039/c7cp04898j

ALPHA „Deciphering ALPine HAzard frequencies by amphibious investigation of Holocene lake inventories“

Carolin Kiefer[1], Michael Krautblatter[1], Michael Strasser[2], Jasper Moernaut[2], Leonie Leitgeb[2], Arne Ramisch[2], Laura Schley[2], Christoph Mayr[3], Liliana Gaspar[3]

[1] Chair of Landslide Research, Technical University of Munich, Arcisstraße 21, 80333 München
[2] Department of Geology, University of Innsbruck, Innrain 52f, A-6020 Innsbruck
[3] Institute of Geography, Friedrich–Alexander University Erlangen-Nuremberg, Wetterkreuz 15, 91058 Erlangen

Correspondence to: carolin.kiefer@tum.de

The recent increase of Alpine hazard frequencies and magnitudes documented in studies and predicted in numerical models emphasizes the need for long-term natural hazard records to anticipate their likely non-linear increase in the future. Fluctuations, e.g. in the Holocene Climatic Optimum provide the closest analogy for future scenarios.

ALPHA investigates Alpine sediment cascades from catchments to lake depocentres in four Alpine lakes to distinguish sediment-producing terrestrial hazard processes and derive magnitudes and recurrance rates. We (i) distinguish processes recorded in lake sediment layers and their triggers, (ii) estimate corresponding ranges of terrestrial magnitudes, and (iii) decipher the frequency and magnitude increase in phases with elevated climatic forcing.

The four study sites Plansee, Achensee, Walchensee and Eibsee are located in the Alpine hazard hotspot Bavarian-Tyrolian Landslide Cluster. The project partners TU Munich, FAU Erlangen and UIBK Innsbruck (i) apply a 4D approach on subaquatic sediment transport by repeated geophysical surveys, repeated coring and calibration using sediment traps, (ii) relate erosion, transport and subaquatic deposition in mass and momentum balances, and (iii) link sediment volumes in the lacustrine sink with measured terrestrial mass movement rates.

First results from 54 debris flow fans at Plansee reveal a 9-fold increase in debris flow volumes since 1920 derived from sediment cores. A 36% increase in rainfall days since the 1980s corresponds to a 12% increase in catchment erosion. Comparing photogrammetric reconstruction of onshore debris flow volumes with volumes derived from turbidite deposits in sediment cores shows that results from both methods align: 300*10^3 m^3 of debris flow material have been transported into the lake over the last 7 decades.

ALPHA advances process-understanding of drivers and sediment dynamics under fluctuating environmental controls. Future projections of natural hazards will be based on regional climate models with rainfall intensities evaluating the nonstationary response of Alpine hazard rates to global warming.

This research is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation – Project number 558963977) and the Austrian Science Fund (FWF, grant https://doi.org/10.55776/PIN7180424).

Glacial lineations in the marine environment: a deep time perspective

D.P. Le Heron[1), M.E. Busfield[2), P. Dietrich[3), J.-F. Ghienne[4), P.M. Mejías Osorio[1), S. Schloissnig[1), A.J.B. Smith[5), S. Tofaif[6), R. Wohlschlägl[1)

[1) Department of Geology, Josef-Holaubek-Platz 2, University of Vienna 1090 Vienna, Austria
[2) Department of Geography and Earth Sciences, Aberystwyth University, Penglais, Aberystwyth SY23 3FL, UK
[3) Géosciences Rennes, Université de Rennes, CNRS, UMR 6118, 35000 Rennes, France
[4) Institut Terre et Environnement de Strasbourg, CNRS - Université de Strasbourg, 67000 Strasbourg, France
[5) PPM Research Group and DSTI-NRF CIMERA, Department of Geology, University of Johannesburg, Johannesburg, South Africa
[6) Geological Operations Department, Saudi Aramco, Dhahran, 31311, Saudi Arabia

Correspondence to: daniel.le-heron@univie.ac.at

Understanding the processes at glacier beds is crucial as they regulate ice flow, basal sediment dynamics, and meltwater routing, which collectively control glacier stability and response to climate change. Fields of glacial lineations are a spatially coherent assemblage of elongate subglacial bedforms made of sediment (e.g., soft-sediment striae, flutes, drumlins, megadrumlins, and mega-scale glacial lineations) that share a common flow-parallel orientation and are interpreted to record the geometry and kinematics of past ice flow. These assemblages are widespread in both terrestrial and marine glacial environments. However, in terrestrial environments, these lineation fields degrade rapidly after formation, and the range of structures is much more restricted. In a marine context, they have a protective veneer of glaciomarine muds and exhibit a much greater diversity. By integrating observations from exceptionally preserved Late Ordovician (ca. 445 Ma) and Late Palaeozoic (ca. 300 Ma) examples in Africa and Arabia, we find that a range of scale-independent structures are

characteristic of glaciomarine fields of glacial lineations. A recurrent feature is stacked lobate sediments upon which glacial lineations are superimposed, including kilometre-scale mega-scale glacial lineations, metre-scale flutes, and centimetre-scale soft-sediment striae. These features are referred to as lineated lobes and the largest examples are synonymous with grounding zone wedges, with self-similar examples at the scale of flutes and soft-sediment striae. Outcrop observations show that oversteepened subaqueous flutes collapse laterally, forming fan-shaped deposits, and that lateral margins exhibit scalloped, truncated surfaces that record focused subglacial meltwater discharge.

Tracing the formation of amorphous silica phases during (reverse) silicate weathering – An experimental approach

Rylee Lindner[1], Franziska M. Stamm[1], Martin Dietzel[1]

[1] Institute of Applied Geosciences, NAWI Graz Geocenter, Graz University of Technology, 8010 Graz, Austria

Correspondence to: r.d.lindner@tugraz.at

The formation of amorphous silica phases (ASP) is an important intermediate step for Earth`s surface (reverse) silicate weathering reactions. Various physicochemical parameters such as temperature, pH, solution composition, aqueous speciation, as well as the presence of organic ligands, control ASP formation and are accordingly affecting the global silicon (Si) cycle and stable Si isotope fractionation. Understanding and quantifying the individual effects of these parameters will help bridge existing knowledge gaps: Thus allowing to interpret past elemental and isotopic signals for reconstruction of (paleo) environments and prediction local to global changes of natural systems.

To address these gaps, laboratory experiments are conducted to simulate ASP formation under different physicochemical conditions, thereby elucidating how environmental changes influence mineral precipitation and associated Si isotope fractionation. Experimental results are compared to natural systems where hydrogeochemical shifts are currently observed: e.g. at natural rock glaciers in the Austrian Alp's (lake Ödsee). Experimental vs. natural fluid and solid samples are characterized by various techniques such as ICP-OES, MC-ICP-MS, XRD, Raman and FTIR. Aqueous speciation, in particular Si speciation, is determined by UV/VIS spectrophotometry, which is designed to distinguish polymeric and monomeric silicic acid in aquatic media. Analytical approaches are used to assess silica (de)polymerization and linkage dynamics in both fluid and solid phases throughout (reverse) silicate weathering. The integration of experimental and field-based investigations give insights into global silicate weathering mechanisms to get a better understanding of (i) the evolution of past to modern chemical weathering regimes vs climate change and (ii) the impact of individual physiochemical parameters on driving and sustaining the formation of weathering products.

Challenges and solutions for optical dating of inner-Alpine Pleistocene sediments: integrating quartz OSL and feldspar IRSL

Michael Meyer[1)]

[1)] Institute of Geology, University Innsbruck, Innrain 52, Innsbruck, Austria

Correspondence to: michael.meyer@uibk.ac.at

Optically Stimulated Luminescence (OSL) dating can constrain burial ages for a wide range of sediments over the last ~400 ka, but its application in inner-Alpine settings is hindered by the characteristically dim OSL signal of alpine quartz. Feldspar Infrared Stimulated Luminescence (IRSL) has emerged as a viable alternative, yet is affected by issues such as anomalous fading and incomplete bleaching. We present a unified dating strategy that exploits the complementary strengths of both dosimeters by combining quartz OSL with feldspar IRSL measurements within a single interpretive framework. We apply this approach to three inner-Alpine successions: (i) cave-mouth deposits at Tischofer Cave (Kaiser Valley, Tirol), (ii) glaciolacustrine sediments from the Riss Valley (Karwendel), and (iii) an alluvial-fan to talus-slope succession (Höttinger Brekzie, Inn Valley). The protocol evaluates signal suitability, bleaching behavior, dose recovery, and fading, and integrates age estimates when quality criteria are met. Our results demonstrate that the dual-dosimeter approach can yield coherent and stratigraphically consistent chronologies where quartz alone fails, extending robust optical dating to previously problematic inner-Alpine contexts. This framework offers a practical pathway to constrain depositional ages and refine Pleistocene environmental reconstructions across diverse alpine sedimentary settings.

Intramontane paleoenvironments of the Dinarides Lake System during the Early to Middle Miocene, SE Europe

Mathis Moreau[1], Marlene Loberbauer[1], Gabriela Sanchez Ortiz[2], Oleg Mandic[3], Nevena Andric-Tomasevic[4], Jeremy K. Caves Rugenstein[2], Andre Baldermann[5], Martin Dietzel[5], Davor Pavelic[6], Vedad Demir[7], Bosko Vukovic[8], Gerald Auer[1], Walter Kurz[1], Maud J. M. Meijers[1]

[1] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Graz, Austria
[2] Department of Geosciences, Colorado State University, Fort Collins, United States of America
[3] Geological-Paleontological Department, Natural History Museum Vienna, Vienna, Austria
[4] Institute of Applied Geosciences, Karlsruhe Institute of Technology, Karlsruhe, Germany
[5] Institute of Applied Geosciences, NAWI Graz Geocenter, Graz University of Technology, Graz, Austria
[6] Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Zagreb, Croatia
[7] Federal Institute for Geology Sarajevo, Ilidza, Bosnia and Herzegovina
[8] Rudnik i Termoelektrana Gacko, Elektroprivreda Republike Srpske, Gacko, Bosnia and Herzegovina

Correspondence to: mathis.moreau@uni-graz.at

The Dinarides Lake System is a series of intramontane freshwater lakes that expanded during the Early to Middle Miocene in the Dinaric Alps, a mountain range located in SE Europe. Miocene climate archives have been widely studied and are considered suitable analogues for future climate scenarios. Stable carbon (d13C) and oxygen (d18O) isotope records from marine benthic foraminifera define two global climatic phases during the Early and Middle Miocene: the warm and humid Miocene Climatic Optimum, MCO: ca. 16.9-14.7

Ma, and the Middle Miocene Climatic Transition , MMCT: ca. 14.7-13.8 Ma. The latter is characterized by global cooling and the establishment of permanent Antarctic ice sheets. Here, we reconstruct terrestrial paleoenvironmental and-climate dynamics of the DLS during the MCO-MMCT.

Our new results combine d13C and d18O values from carbonates with new petrological and mineralogical data obtained from thin section analysis, X-ray diffraction and Fourier transform infrared spectroscopy analyses, scanning electron microscope imaging, and energy-dispersive X-ray spectroscopy elemental mapping.

We focus on four lacustrine basins (Pag, Gacko, Bugojno, and Livno-Tomislavgrad), for which existing sedimentological studies and an established geochronological framework are available, including magnetostratigraphy, biostratigraphy, and radiometric ages of ash layers. The deposits reflect a high paleoenvironmental diversity encompassing swamp, marsh, shallow lake, and deltaic environments.

The presence of high-Mg calcite and aragonite in some samples from each section is indicative of the absence of diagenetic alteration. d18O and d13C values for each lake basin are positively correlated, indicative of hydrologically closed lake conditions. At the onset of the MCO, Pag and Livno-Tomislavgrad records display a positive correlation between modern elevation and d18O values, with mean Pag d18O values of -9.1 +- 0.1 permil, n = 89, V-PDB, coastal, and Livno-Tomislavgrad values of -5.0 +- 0.2 permil, n = 22, ca. 50 km inland at ca. 750 m elevation. Contrary to the expected decrease of d18O values with increasing elevation, this suggests a strong effect of evaporation on the chemistry and isotopic composition of the water in the lake basins. Our isotope results therefore reflect local environmental and climatic conditions, driven by lake level variations and environmental changes within the hydrologically closed lake systems during the MCO and MMCT.

Identification of Amorphous Weathering Products Formed in Periglacial Environments and Their Potential as Climate Change Proxies

Karla Resel[1], Christoph Kohler[2,3], Thomas Wagner[2], Rylee Lindner[1], Patrick J. Frings[4], Martin Dietzel[1], Franziska M. Stamm[1]

[1] Institute of Applied Geosciences, NAWI Graz Geocenter, Graz University of Technology, 8010 Graz, Austria
[2] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, 8010 Graz, Austria
[3] 3G ZT GmbH, 8055 Graz, Austria; [4] GFZ Helmholtz Centre for Geosciences, 14473 Potsdam, Germany

Correspondence to: karla.resel@student.tugraz.at

Climate change increasingly affects high-mountain regions, where rising temperatures drive permafrost degradation. Across the Alps, thawing rock glaciers release acidic, heavy-metal-ion-rich water that enhances weathering of primary minerals in sulfide-bearing rocks. When these solutions mix with meteoric-derived water of near-neutral pH, secondary amorphous phases may precipitate. Although these deposits and their isotope signatures are potential indicators of climate-driven environmental changes, their formation as well as elemental and isotopic distribution behavior remain poorly constrained. Herein, we investigate the formation of amorphous weathering products at the periglacial lake Ödsee (Schladminger Tauern, Austria). Water and precipitates were collected, and in-situ parameters (pH, electrical conductivity, dissolved oxygen) were measured. Major ions and trace elements in water samples were analyzed using IC and ICP-OES, while precipitates were dissolved and analyzed for elemental composition by ICP-OES and characterized by XRD and FTIR. Preliminary results indicate that the precipitates are amorphous and mainly contain Al, S, Si and Fe. They are formed by mixing two chemically distinct solutions: one from the rock glacier runoff (pH~4.6; high solute content), and the other from meteoric water (pH~6.5; low solute content). Silicon isotope compositions of the natural waters and precipitates will be measured by MC-ICP-MS to evaluate their potential as environmental proxies and to unravel the

formation mechanisms of these phases. Findings of shifts in alpine water chemistry and amorphous phase formation are discussed as indicative of climate-induced permafrost degradation and potentially providing new geochemical indicators for monitoring environmental change.

Constraining extreme flood events in Corsica with rock surface luminescence dating – feasibility and preliminary results

Sarah Schaffer[1], Stefan Achleitner[2], Peter Tropper[3], Frederic Huneau[4], Emilie Garel[4], Michael Meyer[1]

[1] Institute of Geology, University Innsbruck, Innrain 52, Innsbruck, Austria

[2] Unit of Hydraulic Engineering, University of Innsbruck, Technikerstraße 13, 6020 Innsbruck

[3] Institute of Mineralogy and Petrology, University Innsbruck, Innrain 52, Innsbruck, Austria

[4] Université de Corse Pascal Paoli, Faculté des Sciences et Techniques, Corte, France

Correspondence to: sarah.schaffer@uibk.ac.at

Constraining the timing and magnitude of extreme fluvial discharge events in coarse-grained river systems remains a major challenge in fluvial geomorphology, largely due to the lack of direct dating methods for sediment transport processes. Here, we apply infrared stimulated luminescence (IRSL) rock surface dating (RSD) to fluvial lag deposits in Corsica, France, demonstrating its potential as a novel tool for reconstructing gravel-bed river dynamics.

We sampled cobble- to boulder-sized granite clasts from the Calvi (n = 16) and Solenzara (n = 24) river catchments, located in the northern and southern parts of the island of Corsica, respectively. An IRSL rock-surface exposure and burial dating approach is applied in tandem to samples that exhibit both bleaching and burial signatures. For selected samples, 2D EMCCD imaging complements the conventional 1D drilling-and-slicing preparation, allowing the geometry of the IRSL bleaching front to be investigated in far greater detail than is possible with a 1D approach. By sampling across a spectrum of natural grain sizes, we aim to constrain the recurrence rates of both low- and high-energy discharge events. This study explores the capability of RSD to directly quantify exposure–burial histories at the scale of individual clasts spanning a broad grain-size distribution,

effectively transforming rocks into natural archives of catchment-scale geomorphic processes.

Der quartäre Adler wird flügge!

Mathias Steinbichler[1], Gerit Griesmeier[1], Christoph Kettler[1], Michael Lotter[1], Jürgen M. Reitner[1]

[1] GeoSphere Austria, Neulinggasse 38, 1030 Wien

Correspondence to: mathias.steinbichler@geosphere.at

Wie ist der aktuelle Stand des internen GeoSphere Austria Projekts EAGLe (Erstellung einer Allgemeinen General-Legende für Österreich) für die Fachthemen Quartär und Geomorphologie? Ausgangspunkt für das Projekt EAGLe ist die flächendeckende Verfügbarkeit von geologischen Daten im Maßstab 1:25.000 bis 1:50.000 für ganz Österreich, die mit dem Abschluss des Projektes GeoFAST im Jahr 2024 erreicht wurde. Ziele des Projektes in Bezug auf Quartär und Geomorphologie sind erstens ein Mapping (Übersetzung) aller quartärer und geomorphologischen Legendeneinträge inklusive der gravitativen Massenbewegungen auf den vorhandenen Standard (Steinbichler et al. 2019, Lotter et al. 2021) sowie zweitens die Erstellung eines österreichweiten Datensatzes, der auf das derzeit verwendete geologische Mehr-Schicht-Datenmodell der GeoSphere Austria aufbaut. Anhand von ausgewählten Beispielen und interessanten Statistiken zeigen wir, welche Herausforderungen EAGLe darstellt, welche Möglichkeiten ein österreichweiter, harmonisierter Datensatz mit sich bringt und welche zukünftigen Weiterentwicklungen darauf aufbauen könnten. Ende 2026 wird die erste Version des EAGLe Datensatzes auf https://tethys.at/ zur Verfügung stehen. Bis dahin hat der kleine quartäre Adler noch Zeit, sich hoffentlich gut zu entwickeln!

References

Lotter, M. Steinbichler, M., & Reitner, J. M. (2021): Ergänzung und Erratum zu „Begriffskataloge der Geologischen Landesaufnahme für Quartär und Massenbewegungen in Österreich“ (Steinbichler et al., 2019), Jahrbuch der Geologischen Bundesanstalt, 161, 157–160, Wien

Steinbichler, M., Reitner, J., Lotter, M., & Steinbichler, A. (2019): Begriffskataloge der Geologischen Landesaufnahme für Quartär und Massenbewegungen in Österreich. – Jahrbuch der Geologischen Bundesanstalt, 159, 5–49, Wien

Connecting surface uplift with deep mantle dynamics in the New Zealand using 3D coupled geodynamic and landscape evolution numerical modeling

Simran Suresh[1], Menno Fraters[1]

[1] Department of Earth Sciences, University of Graz, Universitatplatz 2, 8010, Graz, Austria

Correspondence to: simran.suresh@uni-graz.at

Modern New Zealand is undergoing rapid rock uplift of about 7-12mm/yr since 5Ma. This prominent geomorphological change has led to increase in earthquakes, orographic precipitation, erosion and sediment accumulation. Tectonically, New Zealand has two subduction zones: Hikurangi in the Northern island and Puysegur in the Southern island, separated by the Alpine Fault characterized by oblique strike-slip setting. Several smaller faults on the Northern island translate the Hikurangi subduction stress to compression stresses of Pacific-Australian plates before joining the bigger Alpine Fault. Rivers on either side of this fault modify the landscape and record the tectonic history. Therefore, it is essential to have a good understanding of the interaction between deep and surface processes driving these changes.

To achieve this, we are building a 3D geodynamic model with high spatial resolution using constraints from current slab geometry, plate motion and seismic anisotropy measurements using the GWB and ASPECT models (Fraters et al., 2019, Bangerth et al., 2024). We hypothesize that a model run of 10Ma forward in time is sufficient to track the mantle flow beneath, to the granular scale of olivine crystal level and its preferred orientation (CPO). Doing so, the research questions we aim to answer are 1) whether the present-day mantle flow field predicted by the model produce CPO patterns consistent with seismic anisotropy observations?, 2) what are the slab initial geometry, dynamic and rheological constraints that can create the current uplift rates? 3) to that best fit model, what will be the stress field imposed by the subduction forces towards the compressional stress? Currently, we show a initial setting of the region and preliminary model results. To study how recent landscapes have developed given the fluvial and glacial erosion, we plan to couple our 3D geodynamics model in

ASPECT with the surface evolution model OpenLEM (Hergarten, 2020). The fully coupled 3d model will allow us to investigate the dependencies between the tectonic and geomorphic processes in this complex geological setting.

Why the Anthropocene still deserves a formalized chronostratigraphy

Michael Wagreich[1)]

[1)] Department of Geology, University of Vienna, Josef-Holaubek-Platz 2, 1090 Wien

Correspondence to: michael.wagreich@univie.ac.at

The (former) Anthropocene Working Group (anthropocene-working-group.org) investigates, besides interdisciplinary aspects, the potential of the Anthropocene as a chronostratigraphic unit of the Geological Time Scale. The term has evolved into a symbol emblematic of global change, and the current climate, environmental and ecological crises. Besides ample Earth System Science evidence for a fundamental change out of the Holocene system state, the main geological argument for defining an Anthropocene chronostratigraphic unit comes from the stratal record itself. As (traditional) chronostratigraphy is based on rock-time units, the growing stratal archive of the Anthropocene is characterized by new and artificial materials, rocks and prominent stratal units, from massive landfills with all sorts of anthropogenic materials and technofossils, to deep-sea mass flows with marine municipal solid waste, and plastics everywhere down to deep-sea trench deposits. All these strata are not “typical” Holocene anymore and need a chronostratigraphic unit.

There is also controversy about the starting point of a proposed Anthropocene chronostratigraphic unit. Given the requirements by the stratigraphic guidelines for a GSSP, a globally synchronous and widely distributed signal had to be chosen. The most widespread and synchronous signal provides the artificial radionuclide fallout material of the atmospheric nuclear bomb testing of the late 1940s and 1950s to 1963, ending with the first global environmental treaty, the Nuclear Test-Ban Treaty (signed August 5, 1963). These atmospheric nuclear detonations brought globally artificial radionuclides like cesium and plutonium (especially 239+240Pu) into the atmosphere and, consequently, as fallout down to the Earth';s surface. The AWG selected the global 239Pu onset signal during 1952–1953 CE, the “bomb spike”, following the first thermonuclear H-bomb tests, as the primary marker for the Anthropocene proposal, being present across many environments with a half-life of 24,110 years. Secondary markers provide stable isotopes such as δ13C (the Suess effect due to burning of fossil fuels) and SPCs (spheroidal carbonaceous fly ash particles as products of high-temperature combustion of fossil fuels) show also strong upraise during the Great Acceleration.

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Session 07

Angewandte Geowissenschaften und mineralische Rohstoffe

Applied Geosciences and Mineral Raw Materials

Conveners:
Ronny Boch & Florian Steindl

NAWI Graz Natural Sciences

TU Graz

UNI GRAZ

Seismic classes prediction and facies association based on the pre-stack seismic inversion results

Allakhverdi Akhverdievm[1], Mohamed Zaied[1], Adel Mahmoud[1], Tarek Alkhemri[1], Faisal Burghig[1]

[1] Geology and Geophysics, Akakus Oil Operations, El-Tahaddi St off Airport Road, Tripoli, Libya

Correspondence to: a.akhverdiev@gmail.com

The Murzug Basin is a major petroleum province in Libya and originated during the Mesozoic and Cenozoic eras. The Basin is situated in northwestern Africa and originated from successive stages of tectonic uplift and subsequent erosion resulting from orogenesis.

The primary oil-bearing stratum, the Ordovician periglacial sandstone reservoir known as Mamuniyat, was selected for the examination. The seismic data with the most optimal amplitude-frequency characteristics was singled out for the DHI prediction. To perform pre-stack inversion, knowledge of S-wave velocities is required; therefore, S-wave logs were modeled using neural networks in wells where S-wave data did not exist.

As a result of the performed inversion transformations, a number of important parameters were obtained: P-Impedance, S-Impedance, Vp/Vs ratio, LambdaRho, MuRho, Poisson's ratio, Young Modulus, Density, Porosity, etc.

Various attribute combinations were initially tested to select the optimal pair for modeling seismic classes associated with reservoir properties. Ultimately, the Vp/Vs ratio as a function of P-impedance was proposed for 1D modeling. 1D modeling was applied to five wells in the Upper Ordovician formation. The results revealed five distinct classes, which varied in terms of reservoirs characteristics potential.

The resulting 1D class models were applied to construct crossplots based on 3D seismic inverted attributes. It enables us to regroup 5 classes into broader clusters and combine classes referring to their reservoir characteristics significance: Class A, Class B, Class C. Class A shows the highest potential, indicating the most favorable reservoir conditions. Class B exhibits moderate reservoir qualities, whereas C demonstrates the least promising exploration capacity.

To populate defined Classes, maps were generated, and five zones were identified depending on the class distribution. For each zone, facies types were identified according to seismic classifications and correlated with facies interpretations derived from FMI logs. The most promising KFE zone has been associated with deposits of the shoreface-braid-delta front, which, within the Upper Ordovician sequence, comprise Distributary Channels (DC), Sheet Sandstones and Tidalites (ST), and Wave-influenced Sandstones (WS) facies.

The prognosis result enables the determination of subsequent prospects for geological exploration and drilling.

HeavyMin: Scheelite in stream sediments as an indicator for tungsten exploration potential in the Eastern Alps, Austria

Florian Altenberger[1,2], Julia Weilbold[3], Thomas Angerer[3], Joachim Krause[4], Jasper Berndt[5], Annika Geringer[3], Gerald Schuberth[3], Manuel Werdenich[3], Bernhard Neugschwentner[3], Gerhard Feitzinger[2], Johann G. Raith[1]

[1] Chair of Resource Mineralogy, Technical University of Leoben, Peter-Tunner-Straße 5, A-8700 Leoben
[2] ZT-Büro Feitzinger, Salzburger Straße 16, A-5340 St. Gilgen
[3] Competence Unit of Mineral Resources, GeoSphere Austria, Hohe Warte 38, A-1190 Vienna
[4] Helmholtz-Zentrum Dresden-Rossendorf, Institute Freiberg for Resource Technology, Chemnitzer Straße 40, D-09599 Freiberg
[5] University of Münster, Institute for Mineralogy, Corrensstraße 24, D-48149 Münster

Correspondence to: florian.altenberger@unileoben.ac.at

Scheelite ($CaWO_4$) is a very important heavy mineral used in mineral exploration and the principal ore mineral of tungsten in the Eastern Alps. Owing to its high density, resistance to weathering and preservation of chemical signatures during sediment transport, scheelite serves – among other robust indicator minerals – for identifying upstream source areas. Moreover, trace element compositions record physicochemical conditions of ore formation, making detrital scheelite a valuable tool for distinguishing mineralization styles and assessing economic tungsten potential.

In the Eastern Alps, scheelite occurs in a wide range of geological units and mineralization styles, although only a small number of occurrences are associated with economically significant tungsten endowment. Tungsten has been recognized by the European Union as a strategic raw material, reflecting its essential role in key industrial sectors and defense technologies, as well as concerns regarding the resilience of supply chains. Although Austria contributes to European tungsten production through the Felbertal deposit, Europe remains strongly dependent on imported tungsten.

The HeavyMin project combines automated mineralogy and microanalytical methods to characterize and utilize heavy minerals as tools for mineral exploration in the Eastern Alps. For instance, trace element compositions of detrital scheelite grains collected from stream sediments are used to distinguish between different styles of tungsten mineralization and ore-forming environments. These datasets are compared with information from major tungsten deposits worldwide to refine diagnostic signatures of potentially economic tungsten mineralization and place the results within a global exploration framework.

In this study, systematic stream sediment sampling was carried out in the Stubachtal and Felbertal – two valleys in the central Tauern Window – to evaluate the application of detrital scheelite chemistry for tungsten exploration. The Stubachtal dataset is used to assess the overall tungsten prospectivity of a catchment dominated by lithologies of the Habach Group, whereas the Felbertal dataset documents spatial variations in scheelite chemistry within a drainage system hosting a world-class tungsten deposit. These results highlight the value of detrital scheelite as an indicator mineral for both regional-scale exploration assessment and local-scale source tracing.

The Tungsten-Magnesite Connection: A Rare Mineralizing System from the Eastern Alps

Florian Altenberger[1], Johann G. Raith[1]
[1] Chair of Resource Mineralogy, Technical University of Leoben, Peter-Tunner-Strasse 5, A-8700 Leoben

Correspondence to: florian.altenberger@unileoben.ac.at

The Eastern Alps host a rare and unusual association of tungsten mineralization with sparry magnesite, documented at only two localities, Tux-Lanersbach (Tyrol) and Mallnock (Carinthia). At both sites, tungsten-bearing mineralization occurs within Austroalpine Early Paleozoic low-grade metamorphic series and is hosted predominantly by ferroan dolomite and metasomatic magnesite. Petrographic observations, together with trace element data, indicate that tungsten mineralization and magnesite formation are genetically linked through multiple hydrothermal events.

At Tux, tungsten occurs as scheelite within ferroan dolomite and phyllite; direct incorporation into magnesite is rare. The earliest scheelite generation forms disseminated, laminated and porphyroblastic aggregates in dolomitic rocks. Although this mineralization was previously interpreted as syngenetic-syndiagenetic, structural evidence and radiogenic Sr isotope signatures indicate substantial remobilization of tungsten. This remobilization likely occurred during metasomatic magnesite formation and was further modified during greenschist-facies Alpine regional metamorphism.

A similar evolution is observed at Mallnock, where tungsten mineralization consists of both scheelite and wolframite. Early scheelite is hosted by ferroan dolomite, whereas later Fe-rich wolframite (ferberite) formed within Fe-rich magnesite caused by Mg-Fe metasomatism. Wolframite was subsequently replaced partially by a younger scheelite generation. Scheelite U-Pb age dating constrains magnesite formation to between 294±8 Ma and 239±3 Ma.

The consistent spatial and paragenetic association of tungsten minerals with magnesite at both occurrences suggests that magnesite-forming hydrothermal fluids played a key role in mobilizing pre-existing tungsten. Tungsten was likely sourced either from tungsten-enriched country rocks or earlier mineralization and subsequently redistributed during metasomatism. Differences in fluid chemistry

controlled the resulting mineral assemblages: Mg-dominated systems at Tux produced scheelite, whereas Fe-rich hydrothermal conditions at Mallnock favored wolframite formation followed by scheelite replacement. Age data from Mallnock and other magnesite deposits in the Eastern Alps support a Permian-Triassic age for magnesite formation and link both tungsten mineralization and magnesite development to extensional tectonics associated with the breakup of Pangea.

The Tauerngold vein system – structurally controlled fluid flow related to Miocene exhumation tectonics in the eastern Alps

Thomas Angerer[1], Chris McFarlane[2], Phillip Gopon[3], Viktor Bertrandsson Erlandsson[3], Eileen Göbel[3], Konrad Reiter[3], Guillaume Jacques[4], Noreen Vielreicher[5], Christian Auer[1], Annika Geringer[1], Julia Weilbold[1], Rainer Mrazek[6]

[1] Geosphere Austria, Neulinggasse 38, 1030 Wien
[2] University of New Brunswick, 2 Bailey Drive, Fredericton NB, E3B 5A3
[3] Montanuniversität Leoben, Peter Tunner - Straße 5, 8700 Leoben
[4] Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Stilleweg 2, 30655 Hannover
[5] Paris-Lodron Universität Salzburg, Hellbrunner Straße 34/III, 5020 Salzburg
[6] Museum "Erze, Gold und Mineralien", Hüttau 29, 5511 Hüttau

Correspondence to: thomas.angerer@geosphere.at

Austria's well-known gold-producing region, the "Tauerngold" orogenic vein system in the eastern Tauern Window, comprises numerous historic mining districts with extensive abandoned underground workings, including Radhausberg near Bad Gastein, Rauriser Goldberg, Goldzeche, and Rotgülden. Most of these deposits were mined from medieval times into the modern period, with the most recent activities documented in the early 20th century. Renewed interest in generating pre-competitive data on gold ore quality, critical-metal contents, and mineral-system criteria is driven by the need to strengthen European raw-material resilience, particularly with regard to critical and conflict-related commodities. These applied objectives are complemented by the academic relevance of the Tauerngold vein system as a key record of fluid flow during the complex exhumation history of the Eastern Alps.

Within the project Uelg88-ProMet:W-Au, in situ mineral-chemical, isotopic, and geochronological data are being acquired from several gold deposits of the Tauerngold system. The aim is to develop exploration-relevant criteria based on an improved understanding of the regional framework of polyphase mineralisation, including its relative and absolute timing, fluid and metal sources, and structural controls.

Preliminary in situ laser-ablation geochronology of xenotime from an Au–Bi-rich quartz vein in the Goldzeche district, located within the Sonnblick Dome, yields the first direct mineralisation age for the Tauerngold system: 19.77 ± 0.48 Ma. This Miocene age overlaps with the activity of major regional fault systems, such as the Katschberg and Mölltal faults, which accommodated orogen-parallel exhumation in the Tauern Window during the initial phase of Adriatic indentation into the Eastern Alpine orogenic wedge between 23 and 14 Ma (McPhee and Handy, 2024; doi: 10.1029/2024TC008374). These structures may therefore have acted as major conduits for metal-rich, ore-forming fluids.

Ongoing in situ chemical analyses, as well as S and Pb isotope investigations of gold-associated sulfides, will further constrain metal sources and fluid pathways. Integrated with geochronological and structural data, these results will allow a refined interpretation of Tauerngold mineralisation within the tectono-structural framework of Tauern Window exhumation.

Strategies for the evaluation and reduction of mineral precipitates impairing hydrogeothermal energy production

Ronny Boch[1,2], Michael Pettauer[1], Albrecht Leis[3], Martin Dietzel[1], János Szanyi[4]

[1] Graz University of Technology, Institute of Applied Geosciences and NAWI-Graz Geocenter, Rechbauerstraße 12, 8010 Graz, Austria

[2] University of Vienna, Department of Geology, Althanstraße 14, 1090 Vienna, Austria

[3] JR-AquaConSol GmbH, Steyrergasse 21, 8010 Graz, Austria

[4] University of Szeged, Department of Geology, Egyetem Utca 2, 6722 Szeged, Hungary

Correspondence to: ronny.boch@tugraz.at

Hydrogeothermal systems tap into natural thermal waters in deep aquifers. Along the engineered fluid circuit, hydrogeochemical and hydraulic gradients develop that often lead to the formation of undesirable mineral deposits, particle mobilization, and material alteration. Solutions for the often combined processes include site-specific optimization of production conditions, e.g. pressure maintenance, adapted flow geometries and materials, targeted monitoring concepts, and chemical additives (inhibitors).

Regarding the unwanted mineral deposits (scaling) and with a focus on carbonate precipitates, ecologically safe “green inhibitors” are gaining importance in relation to conventional additives (e.g. phosph[on]ates). As part of our current research, 13 different active ingredients/products with sufficient temperature stability were tested. Some green inhibitors are already competitive at low dosages and represent potential alternatives to conventional products. Our methodological approach has also proven valuable: the scaling process is continuously recorded in laboratory-based test series using sensors and control reactors, and is quantified using computer-based numerical modeling. This allows for a process-oriented and comparative evaluation of various active ingredients and dosages. Hydrogeochemical modeling is further helpful for assessing the condition and potential of thermal waters and different working fluids (e.g. CO_2).

The presentation also discusses the data-driven approach of “Scaling Forensics,” in which mineral deposits are systematically analyzed as chemical-sedimentary (environmental) archives. The deposits are interpreted in terms of their mineralogical, chemical, and textural composition (e.g., indicative growth structures). This allows for conclusions regarding (un)favorable production conditions during the test/operational phase of a geothermal installation (gas exchange, deposition rates, effects of interruptions). Key findings stem from our analysis of sample materials and field work in Hungary, Austria and Germany. Our contribution illustrates that sustainable hydrogeothermal utilization requires an early, data-based, and installation/site-specific process understanding. This forms the basis for securing energy yields, reducing operational risks, and operating geothermal plants more efficiently in the long term.

Comparative Analysis of Pore Pressure Prediction Methods Based on Drilling and Logging Data

G.M. Efendiyev[1], O.G. Kirisenko[1], I.A. Piriverdiyev[1], M.B. Asgarov[1]

[1] Oil and Gas Institute Ministry of Science and Education Republic of Azerbaijan, Baku, Azerbaijan; Azerbaijan State Oil and Industry University, Baku, Azerbaijan

Correspondence to: a.akhverdiev@gmail.com

This study explores advanced methods for determining pore pressure using real-time drilling data and acoustic/electrical logging data, highlighting its importance for wellbore stability, safety, and preventing drilling issues like lost circulation and kicks. The research aims to analyze and compare common pore pressure estimation techniques that combine drilling parameters with logging data collected during well construction, specifically evaluating their effectiveness, accuracy, and limitations when dealing with incomplete or uncertain field information in complex geological environments and abnormal pressure zones.

The methodology involved processing and interpreting drilling data alongside acoustic and electrical logging data using specialized software. Established empirical and analytical methods such as Eaton, Zamora, Bowers, and d-exponent techniques were applied, which link drilling performance to formation properties and effective stress. Data preprocessing, anomaly filtering, and trend analysis were conducted to ensure data quality. The study also examined how drilling parameters and rock mechanical properties affect pore pressure estimations.

The study shows that various methods can effectively estimate pore pressure gradients, generally aligning with standard well report values. However, raw field data frequently contains noise and inaccuracies that can impact calculation precision if not addressed. Combining acoustic and electrical logging data improves pore pressure estimation reliability by offering additional information on formation characteristics. The innovation of this research lies in the comparative analysis of multiple prediction methods integrated with acoustic and electrical logging data, enhancing accuracy, particularly with limited or varied input. This approach highlights the benefit of fusing diverse data sources and analytical techniques to minimize uncertainty in pressure prediction.

This work is practically significant for real drilling operations, offering an approach to improve wellbore stability, optimize drilling mud density, and decrease drilling complications. It also establishes a methodological foundation for better decision-making in drilling, especially in complex geological areas with abnormal pressure regimes.

Keywords

pore pressure, d-exponent, Eaton method, Bowers method, acoustic logging, electrical logging, drilling engineering, abnormal pressure.

Decarbonisation of the refractory industry through CCUS technologies

Anna Fehleisen[1)], Christoph Stranzl[1)], Lucija Pustahija[1)], Aram Jamil[1)], Martin Pischler[1)]
[1)] RHI Magnesita GmbH, Leoben, Austria

Correspondence to: ANNA.FEHLEISEN@RHIMAGNESITA.COM

Reducing greenhouse gas emissions from refractory production has become an increasingly critical priority, especially given that refractories are indispensable for high-temperature, energy-intensive industrial processes. Among emerging decarbonisation strategies, Carbon Capture, Utilisation and Storage (CCUS) technologies offer a promising option by enabling the permanent sequestration of CO_2 in thermodynamically stable solid phases. This study proposes a carbon capture and utilisation (CCU) approach based on the use of serpentinite raw materials for CO_2 abatement, with an emphasis on their controlled carbonation into two value added product streams.

A major barrier to the large scale deployment of mineral carbonation lies in the intrinsic variability of natural mineral feedstocks. Serpentinites display pronounced heterogeneity in mineralogical composition, mineral chemistry, and reactivity, which directly affects carbonation kinetics, achievable CO_2 uptake and overall process feasibility. To address this challenge, the present work focuses on the development of an integrated feedstock characterisation framework that forms the basis of a robust quality control concept for industrial implementation. Key parameters evaluated include the distribution of serpentine polymorphs, the presence and abundance of accessory minerals, and the net theoretical CO_2 binding capacity of the material.

By systematically linking feedstock properties to carbonation behaviour, the proposed approach enables improved prediction of process performance and supports the optimisation of carbonation conditions. Over the long term, consistent and structured feedstock profiling is expected to facilitate enhanced process stability, improved material utilisation efficiency, and reliable quality of the resulting carbonated products.

Beyond laboratory scale correlations, this work also highlights the importance of deploying efficient and intelligent characterisation strategies at early stages of the value chain, starting directly at the mine site. Early identification of feedstock

variability enables selective extraction, targeted pre processing, and informed decision making prior to carbonation. By integrating quality control from resource characterisation through to process optimisation, the study outlines a practical and scalable pathway for establishing mineral carbonation as a viable decarbonisation technology within the refractory industry.

Archaeometry and provenance of serpentinite tools in eastern Austria: implications for Neolithic resource management and distribution networks

Michael Gostencnik[1)], Michael Brandl[2)], Christoph A. Hauzenberger[1)]

[1)] Institute of Earth Sciences, University of Graz, Universitätsplatz 2, Graz, Austria; [2)] Austrian Academy of Sciences, Doktor-Ignaz-Seipel-Platz 2, Vienna, Austria

Correspondence to: michael.gostencnik@uni-graz.at

Polished stone tools such as axes and adzes represent significant innovative technologies, which facilitated the spreading of the Neolithic lifeway from Western Asia to central Europe. These tools were essential for establishing sedentary life in villages and agriculture, since they were used for clearing of the land, woodworking, the construction of buildings, and the processing of food, for example butchering. Therefore, such stone artefacts are amongst the most significant implements of Neolithic and Copper Age societies providing deeper insights into resource management strategies, technological developments and choices, and social interactions. Interpretations that consider the full range of these socio-economic processes crucially depend on reconstructing the most fundamental element of resource management. This element can be understood as a dynamic sequence of actions, including the procurement, use, and distribution of raw materials and finished or semi-finished products. Within this sequence, procurement is particularly important, as it requires understanding the provenance of raw materials, whether they come from local or distant geological sources. Only when the origin of the raw materials used for various tasks is known it is possible to draw further conclusions regarding prehistoric socio-economic systems.

The project focuses on determining the provenance of stone axe heads and adzes in the eastern Alpine region, aiming to analyze polished stone tool assemblages from Neolithic and Copper Age sites in present-day eastern Austria (i.e. Lower Austria and Styria). Within these assemblages, particularly

serpentinite has been recognized as a potential indicator of wide-ranging intercultural connections and specialized socio-economic networks. Despite decades of documentation of serpentinite artefacts in an archaeological context, the state of research in eastern and southern Austria remains limited.

To achieve this goal a multi-layer approach will be applied. By combining macroscopic observations, detailed petrography, quantitative mineralogy, vibrational spectroscopy (Raman and FTIR), and geochemical analyses, this multi-layered methodology provides a framework for serpentinite provenance studies. A preliminary dataset of 37 possible resources and 10 artifacts was investigated using optical microscopy, XRD, and XRF analysis. These methods revealed clear differences between serpentinites from the various regions and geological settings.

Quantification of Antigorite in Serpentinites by XRD

Michael Gostencnik[1], Anna Fehleisen[2], Isabella Haas[2], Philip Schantl[2], Christoph A. Hauzenberger[1]

[1] Institute of Earth Sciences, University of Graz, Universitätsplatz 2, Graz, Austria; [2] RHI Magnesita GmbH, Magnesitstraße 2, Leoben, Austria

Correspondence to: michael.gostencnik@uni-graz.at

Serpentinites are metamorphic rocks primarily composed of serpentine minerals, which occur in three polymorphic forms: antigorite, lizardite, and chrysotile. Although these minerals share the same chemical composition, they differ in crystal structure and occupy distinct fields of thermodynamic stability. Antigorite is stable at elevated temperatures and pressures, whereas lizardite and chrysotile typically form under lower-grade metamorphic conditions. Accurate quantification of antigorite is therefore important for geological studies and technical applications where the mineralogical composition of serpentinites influences material properties.

This study investigates the quantification of antigorite in serpentinites using X-ray diffraction (XRD). Measurements were performed with a Rigaku SmartLab SE diffractometer, using CuKα-radiation. Pure antigorite and pure lizardite were prepared and the resulting diffraction patterns were analyzed to identify characteristic reflections suitable for quantitative evaluation. The identification and quantification of serpentine polymorphs present several analytical challenges. In XRD patterns, the main diffraction peaks of antigorite, lizardite, and chrysotile show substantial overlap. Additional interference from olivine and other ultramafic minerals further complicates phase discrimination. Due to the structural complexity of serpentine minerals and the strong peak overlap, conventional Rietveld refinement proved unreliable for quantification.

Detailed examination of the diffraction patterns revealed that the region between 58° and 62° 2θ provides a distinct and reproducible signal that allows differentiation between antigorite and lizardite/chrysotile. To establish a quantitative calibration, artificial mixtures consisting of pure antigorite and pure lizardite were mixed in 10 wt% increments across the entire compositional range.

The calibration measurements demonstrate a systematic relationship between diffraction intensity and antigorite content. The resulting calibration curve exhibits exponential behavior, enabling the quantitative determination of antigorite concentrations in mixed serpentine samples.

Hydrothermal Synthesis of Waterglass from Silica-Rich Waste Materials for Sustainable Alkali-Activated Binders

Anthony Kenny[1], Sara Raic[1], Martin Dietzel[1], Cyrill Vallazza-Grengg[1]
[1] Graz University of Technology, Rechbauerstraße 12, 8010 Graz

DOI: https://doi.org/10.3217/xxx

Correspondence to: anthony.kenny@tugraz.at

Waterglass, typically sodium or potassium silicate solution, is a key component of alkali-activated materials (AAMs), a class of inorganic binders which has gained attention as a low CO2 alternative to conventional construction cement in recent years. Commercial waterglass, however, accounts for as much as 50% of production costs and up to 80% of AAM embodied energy, an impactful metric in its high global warming potential. Consequently, there is a growing need to enhance the sustainability of waterglass production by lowering energy requirements, resource consumption, production costs, and associated CO2 emissions. One promising approach in this context is the development of alternative hydrothermal synthesis routes that employ silica-rich industrial wastes or byproducts as feedstocks, thereby advancing circular economy principles through the valorization of secondary resources.

This study investigates systematically the hydrothermal synthesis of waterglass from two crystalline cristobalite-tridymite silica wastes and an amorphous microsilica reference material by varying synthesis temperature (120 - 180 °C), alkalinity (6.4 - 8.8 M NaOH) at a reaction time of 3 hours. Waterglasses were successfully produced, with total solid contents ranging from 33.5 to 41.3 % wt. and a modulus (molar SiO2:Na2O ratio) from 1.6 to 1.8, with both values similar to a typical commercial waterglass, demonstrating the viability of waste silicas as precursor materials for alkali-activator synthesis.

Raman spectroscopy was used to resolve post-synthesis Qn speciation (Q0 - Q4) which indicate a predominance of Q2 and Q1 silica across all synthesized waterglasses. Preliminary results show no dependence of silica species on

source material or synthesis temperature. However, a decline of peak intensity from the 1040 cm-1 vibration band and a corresponding rise in the 600 cm-1 band with increasing alkalinity, suggest a conversion from Q3 / linear Q2 to cyclic ring Q2 species within our alkalinity range.

This work shows the successful hydrothermal synthesis of waste-source activators under varied material, temperature and alkalinity conditions, with silica dissolution comparable to commercial products, and partial dependence of silica speciation on synthesis conditions. From this we reinforce the viability of alternative, low-energy synthesis routes for activators in circular AAM production.

ExPeg - a ground based exploration tool for pegmatites

Tanja Knoll[1)], Gerald Schuberth[1)], Ralf Schuster[2)], Heinrich Mali[3)], Manuel Werdenich[1)], Julian Gutsch[3)], Jonathan Maranitsch[4)], Max Treitler[3)]

[1)] Department of Mineral Resources and Geoenergy, Geosphere Austria, Neulinggasse 38, 1030 Vienna, Austria
[2)] Division of Geophysical and Applied Geological Services, Geosphere Austria, Neulinggasse 38, 1030 Vienna, Austria
[3)] Department of Applied Geosciences and Geophysics, Montanuniversität Leoben, Peter-Tunnerstraße 5, 8700 Leoben, Austria
[4)] Department of Lithospheric Research, University Vienna, UZA 2, Josef-Holaubek-Platz 2, 1090 Vienna, Austria

Correspondence to: tanja.knoll@geosphere.at

Lithium pegmatites represent critical resources for the energy transition. While airborne geophysical methods are standard for their exploration, their efficacy is often limited by vegetation cover, regulatory hurdles, social friction and high costs. To address these limitations, the ExPEG project aims to develop an alternative ground-based exploration tool centered on the geochemical characterization of magmatic muscovite combined with statistical modeling.

The project proceeds in two stages. Initially, we applied data mining (DM) and machine learning (ML) to an existing database from the Austroalpine Unit Pegmatite Province (AUPP) to understand underlying patterns and develop predictive models. Building on these findings, the approach will be adapted to the pegmatites of the Bohemian Massif (BM), noting their significant variations and diverse genetic origins. This process will enable us to classify genetically related pegmatites into provinces and determine their specific fractionation trends.

Validating DM and ML data science techniques to the AUPP revealed that they are significantly more efficient at identifying spodumene-bearing pegmatites than single elemental concentrations or simple ratios (*e.g.*, K/Rb). Analyses of over 2,600 LA-ICP-MS measurements of magmatic muscovite indicated that Classification and Regression Trees (CART) and the Random Forest ensemble method are more effective. The simplest CART, using two splits (Li ≥ 415 ppm;

Be ≥ 23 ppm), concentrates 56% of all muscovite analyses from spodumene pegmatites into just 3% of the total dataset. With more complex trees, this classification accuracy can be increased to 86% in 1% of cases. This allows for an excellent prediction of whether a muscovite originates from a simple or a spodumene-bearing pegmatite. According to the Random Forest analysis, the elements Li, Ga, Be, Pb, Ge, Zr, Tl, Mn, Cs and Zn - in that order - are most critical for identifying spodumene-bearing pegmatites. Further calculations may provide additional insights, such as heterogeneities of the source rocks.

Since the project';s initiation, pegmatites across the BM are systematically sampled, with excellent support from mineral collectors. Currently, over 250 pegmatites have been sampled and documented regarding their mineralogy and host-rock relationships. LA-ICP-MS analysis of the magmatic muscovite is currently underway.

A comprehensive characterization of Lithium-pegmatite fields in the Austroalpine Unit Pegmatite Province (AUPP)

Tanja Knoll[1], Ralf Schuster[2], Gerald Schuberth[1], Jürgen Konzett[3], Heinrich Mali[4]

[1] Department of Mineral Resources and Geoenergy, Geosphere Austria, Neulinggasse 38, 1030 Vienna, Austria
[2] Division of Geophysical and Applied Geological Services, Geosphere Austria, Neulinggasse 38, 1030 Vienna, Austria
[3] Institute of Mineralogy and Petrology, University of Innsbruck, Innrain 52, 6020 Innsbruck, Austria
[4] Department of Applied Geosciences and Geophysics, Montanuniversität Leoben, Peter-Tunnerstraße 5, 8700 Leoben, Austria

Correspondence to: tanja.knoll@geosphere.at

The Austroalpine Unit hosts Permian lithium-bearing pegmatites, extending over 400 km from west to east. While the concept of the Austroalpine Unit Pegmatite Province (AUPP) was established, a description of its constituent pegmatite fields is pending. This study partly bridges that gap by providing a characterization of the nine main pegmatite fields including spodumene-bearing pegmatites: (1) Wölzer Tauern, (2) Falkenberg, (3) Gleinalm, (4) St. Radegund, (5) Koralpe, (6) Millstätter Seenrücken, (7) Defereggental, (8) Uttenheim, and (9) Martelltal.

According to fieldwork, petrography, and whole-rock/mineral geochemical analysis (EPMA and LA-ICP-MS) and geochronology (*e.g.* Sm-Nd method) the pegmatite fields show regional consistency but with significant local variations.

The individual pegmatite fields typically comprise one up to a dozen of spodumene-bearing pegmatite dikes associated with a larger number of spodumene free dikes. Spodumene-bearing dikes show a length ranging from tens of meters up to more than a kilometer, and a thickness of decimeters to a few meters. Mostly they are concordant with the foliation. Contacts with host lithologies including paragneiss, mica schist, amphibolite or marble are sharp, often featuring narrow reaction zones and boudinage-like structures at marble

contacts. The grade of Alpine deformation and metamorphic overprint of the individual fields is variable. Deformation ranges from weakly deformed to proto-ultramylonitic / proto-ultracataclastic fabrics and the metamorphic overprint is greenschist up to eclogite facies. Notably, none of the fields is associated with large fertile granitic intrusions.

Petrographically, the pegmatites of the AUPP are dominated by K-feldspar, plagioclase, quartz, muscovite, and tourmaline, with spodumene restricted to highly evolved bodies. Garnet appears broadly as an accessory mineral, while minor phases like beryl, apatite, columbite, cassiterite and titanite show local variations. Trace elements in whole rock and magmatic muscovite show identical geochemical evolutionary trends but some regional variations.

While all pegmatite fields of the AUPP formed in Permian time and share a similar anatectic genesis the variations in mineralogy and geochemistry can be explained by heterogenies of the host rocks and geothermal gradient in the source area and slightly differing grades of fractionation. The granular understanding is vital for assessing the economic potential of the AUPP.

Building Vienna's Geothermal Future: From Pilot to Large-Scale Development

Peter Krois[1], Helene Mooslechner[1]
[1] deeep Tiefengeothermie GmbH, Thomas-Klestil-Platz 4, 1030 Wien

Correspondence to: peter.krois@deeep.at

Deep geothermal energy is gaining importance in the energy transition and the growing demand for sustainable heat. As a renewable resource, it offers significant potential to reduce CO_2 emissions and reliance on fossil fuels.

In 2023, OMV and Wien Energie founded the joint venture deeep Tiefengeothermie GmbH to combine expertise in subsurface and energy systems. The goal is to develop deep geothermal resources in the Vienna region to support district heating decarbonization. Wien Energie is responsible for surface installations and network integration, while OMV leads exploration, drilling, and reservoir characterization.

Geological studies and 3D seismic interpretation identified the Badenian Rothneusiedl Formation ("Aderklaa Conglomerate") as a suitable reservoir. This Miocene clastic unit, deposited about 16 Ma ago in a braided river system of the Vienna Basin, shows favorable petrophysical properties such as high porosity and permeability. These enable sufficient transmissivity and storage capacity for viable flow rates, supported by appropriate temperature conditions at depth.

The first phase focuses on a geothermal plant in Aspern (Seestadt) and is based on a hydrothermal doublet system. Production and injection wells were drilled vertically to ~1000 m and then deviated to reach the reservoir. A pilot well with coring and advanced geophysical logging provided high-resolution data on lithology and reservoir properties, forming the basis for modeling.

Production and closed-loop circulation tests assessed flow rates, injectivity, and fluid chemistry, delivering key inputs for surface design.

Plant construction is planned for 2027, with commissioning in late 2028. The plant is designed for ~20 MWth, supplying heat to ~20,000 households. This pilot forms the basis for scaling geothermal energy in Vienna to ~200 MWth and up to 200,000 households by 2040.

Cation exchange capacity- An alternative method to investigate the geological barrier of landfills?

Zora Alice Kumm[1], Susanne Gier[1]

[1] Department of Geology, University of Vienna, Josef Holaubek-Platz 2, 1090 Wien, Austria

Correspondence to: susanne.gier@univie.ac.at

Clays and clay minerals are ideal raw materials for geological barriers and landfill liners because of their low-hydraulic permeabilities, their swelling properties and adsorption capacities. The geological barrier is a supplementary barrier beneath the body of the landfill, intended to protect the environment from uncontrolled leachate from the waste material. An Austrian standard defines the procedure for site exploration and the necessary laboratory tests and parameters for the analysis of the geological barrier. The most important laboratory tests besides grain size analysis are the Atterberg limits and the determination of the clay mineralogy using X-ray diffraction. However, the analysis of the cation exchange capacity (CEC) is not included in the list of laboratory tests. CEC is a numerical value that describes the physical properties of clays, such as the diffusion of charged and uncharged molecules and the cation retention. Hence, the objective of this study is to clarify whether the determination of the CEC using the Cu-trien method represents a possible alternative to currently used laboratory tests.

For this purpose, three samples (loess, sand and clay) from two landfill sites owned by the company Zöchling GmbH as well as six mixtures of these samples were examined for their mineralogical, chemical and geotechnical properties. The samples consist of varying amounts of quartz, feldspar, calcite, dolomite and the clay minerals smectite, illite, kaolinite, vermiculite and chlorite. The results show that the bulk clay mineralogy correlates well with the Atterberg liquid limit (R^2=0.73) and the CEC (R^2=0.88) and furthermore, the results of the two methods – Atterberg liquid limit and CEC- even correlate better (R^2=0.95).

This demonstrates that the CEC is an alternative to the Atterberg liquid limit and/or the mineralogical composition of the material. Advantages of the CEC are rapidness, its good reproducibility and cost-efficiency of the analyses compared to the other two methods. Based on the results of this study, a partial substitution

of the currently used laboratory tests is considered feasible and CEC could at least be used for quick screening.

Der Isotopenatlas österreichischer Rohstoffvorkommen als Informationsebene auf GeoSphere Austrias Applikation IRIS-Online

Piotr Lipiarski[1], Gerd Rantitsch[2], Thomas Angerer[1]

[1] GeoSphere Austria, Neulinggasse 38, 1030 Wien
[2] Montanuniversität, Peter Tunner - Straße 5, 8700 Leoben

Correspondence to: thomas.angerer@geosphere.at

Isotopendaten sind grundlegend für die Interpretation von Gesteinen, Erzen, und Fluiden. In Österreich ist die Bereitstellung solcher Daten für wissenschaftliche und explorative Zwecke ein wesentliches Ziel der Forschungslandschaft und GeoSphere Austria betreut mit dem Interaktiven Rohstoffinformationssystem IRIS© (https://maps.geosphere.at) ein geeignetes System dafür.

Im Zuge des Schwerpunktprogrammes „Isotopenatlas österreichischer Rohstoffvorkommen" der Österreichischen Akademie der Wissenschaften ist im Jahre 2009 eine Isotopen-Datenbasis kompiliert, ausgewertet und visualisiert worden (Rantitsch und Russegger, 2009). Unter Verwendung von Literatur-Datenbanken wurden wissenschaftliche Arbeiten mit Isotopendaten der österreichischen Rohstoffvorkommen weitestgehend erfasst. Die Datenbank umfasst folgende Isotopensysteme: stabile Sauerstoff, Wasserstoff, Schwefel und Kohlenstoff, sowie radiogene Strontium- und Blei-Isotope. Wesentliche Metadaten sind Literaturquelle, analysierte Minerale, Lokalität und geologische Position, sowie metallogenetische Stellung der Mineralisation.

Im Zuge der EU-Vorgaben zur Erforschung der heimischen Rohstoffverfügbarkeit wird die existierende Kompilation nun allgemein und niederschwellig als Isotopen-Zusatzmodul auf IRIS Online verfügbar gemacht. Daten werden nach Kriterien der Geologie und Lagerstättenkunde selektier- und abfragbar erfasst und dargestellt. Als Vorbereitung wurden Isotopendaten mit der IRIS Online Datenbank abgeglichen und mit IRIS-Vorkommen verknüpft. Insgesamt sind fast 5.800 Isotopenwerte bereits in der Datenbank gespeichert. Messergebnisse sind in Form von HTML-Tabellen erstellt und in den Datenbanen der GeoSphere Austria so abgelegt, dass sie online abrufbar sein werden. Messpunkte sind im

ArcGIS File Geodatabase Format (.gdb) gespeichert, mit HTML-Ergebnistabellen verknüpft, und können so mit einer Online Applikation publiziert werden.

Eine Tethys-Publikation (tethys.at) wird als Grundlage für die Freigabe der Daten dienen. Geplant sind eine Neustrukturierung der Datenbank, um andere Isotopen-Typen ablegen zu können und die Befüllung der Datenlücke, die nach dem Jahr 2009 entstanden ist.

References

Rantitsch, G., Russegger, B. (2009): Statistische Auswertung und Visualisierung der Isotopendaten österreichischer Rohstoffvorkommen - Isotopen-Datenbank. Endbericht für das geowissenschaftliche Zentrum der Österreichischen Akademie der Wissenschaften. 17

Transforming dredged sediment from Lake Neusiedl into 3D-printed architectural structures

Britta Nader[1], Vladislav Tadic[1,2], Hana Vašatko[1], Julian Jauk[1], Martin Dietzel[3], Dorothee Hippler[3], Milena Stavric[1]

[1] Graz University of Technology, Institute of Architecture and Media, Kronesgasse 5/III, 8010 Graz, Austria
[2] Institute of Chemistry, Technology and Metallurgy, National Institute of the Republic of Serbia, University of Belgrade, Serbia
[3] Graz University of Technology, Institute of Applied Geosciences, Rechbauerstraße 12, 8010 Graz, Austria

DOI: https://doi.org/10.3217/xxx

Correspondence to: b.nader@tugraz.at

The construction industry is under growing pressure to adopt sustainable practices and materials to reduce its environmental impact. To address these issues, we explore an innovative approach for transforming dredged sediment from Lake Neusiedl in Austria, an abundant and largely untapped resource, into a 3D-printable material for building applications. Due to its heterogeneous mineralogical composition and high organic content, dredged lake sediments present unique challenges for additive manufacturing. In addition, we combine the dredged sediment with reed fibers from Phragmites australis, to investigate whether and how fiber reinforcement enhances consolidation and the material's properties. This study therefore investigates the material processing requirements, printability and performance characteristics of this material for additive manufacturing applications.

The project employs an integrated research approach, including detailed material characterization, optimization of material preparation and printing parameters, and mechanical testing of the printed objects. Hence, we apply analytical techniques, such as X-ray diffraction and fluorescence, scanning electron microscopy and grain size analysis, firstly to determine the dredged sediment's mineralogical and geochemical composition and secondly to decipher the potential phase transformation processes during consolidation and optional firing. A custom-built paste-based extrusion 3D printer (nozzle diameters 5–50 mm) is

used for extruding the dredged sediment in various geometries, such as brick-sized elements (20 x 20 x 7 cm). The reed fibers were added to the viscous sediment as one-cm-sized chopped pieces or as fine-ground reed fiber flour with an apparently controlled moisture release and thus improved consolidation behavior. Most tested geometries remained dimensionally stable during drying and exhibited only predictable failure mechanisms, similar to what we typically observe in our experience with pure clay used for 3D printing. This provides a useful reference context for interpreting the material behavior.

This research suggests a repurposing of dredged sediment as a viable, sustainable material for 3D printing in construction. By combining it with natural reed fibers to improve its consolidation behavior, the project offers a new perspective on the development of site-specific building materials. The creation of a specialized 3D printer for on-site use further highlights its potential to advance sustainable building practices.

Towards Austria's First High-Temperature ATES: Geological and System-Level Insights from Fürstenfeld

Nikolaus Petschacher[1], Marcellus Schreilechner[3], Arthur Borzi[6], Gerald Zotter[5], Heinz Binder[3], Christiana Neuhold[3], Maha Nasri[3], Michael Brunneder[4], Moritz Reiser[4], Jakob Huetter[5], David Muhr[1], Vilmos Vasvári[1,2]

[1] Hydro GmbH, Graz, Austria
[2] Ingenieurbüro für Kulturtechnik und Wasserwirtschaft Dipl.-Ing. Dr. techn. Vilmos Vasvári, Graz, Austria
[3] Geo5 GmbH, Leoben, Austria
[4] RED Drilling and Services GmbH, Gampern, Austria
[5] AEE INTEC, Gleisdorf, Austria
[6] University of Graz, Graz, Austria

Correspondence to: petschacher@hydro-gmbh.at

Aquifer Thermal Energy Storage (ATES) is a key technology for balancing seasonal heat supply and demand and supporting the decarbonisation of district heating systems. While ATES is widely applied in several European countries, no large-scale operational ATES system currently exists in Austria. The ATESref project investigates the feasibility of implementing a high-temperature ATES (HT-ATES) system in the Styrian Basin near Fürstenfeld, aiming to establish Austria's first high temperature aquifer thermal energy storage.

The project integrates geological characterisation, sequence-stratigraphic interpretation, energy system analysis and numerical modelling. Reprocessed seismic data and borehole information were used to identify suitable storage horizons. The Sarmatian Carinthian Gravel formation, located at depths of approximately 560–650 m, was identified as the primary target aquifer. This unit shows substantial thickness, high permeability and effective confinement by clay-rich layers, making it suitable for high-temperature heat storage. Hydraulic properties derived from pumping tests were incorporated into coupled 3D flow and heat-transport simulations.

Modelling results indicate that cyclic injection and extraction of water at temperatures of up to approximately 100 °C can be sustained over multi-decadal operation, with limited thermal losses and only minor thermal plume migration despite regional groundwater flow. System integration studies show that ATES can be coupled effectively to the Fürstenfeld district heating network using surplus summer heat from biomass plants, power-to-heat systems, industrial waste heat and an existing deep geothermal installation. In winter, the stored heat can substantially reduce fossil fuel demand and increase the share of renewable heat in the local energy system.

Unidirectional Aquifer Thermal Energy Storage for Urban Heating and Cooling in High-Flow Aquifers: A Case Study from State Hospital Graz South, Austria

Nikolaus Petschacher[1], Vilmos Vasvári[1,2]

[1] Hydro GmbH, Gleisdorf, Austria

[2] Ingenieurbüro für Kulturtechnik und Wasserwirtschaft Dipl.-Ing. Dr. techn. Vilmos Vasvári, Graz, Austria

Correspondence to: petschacher@hydro-gmbh.at

Large-scale thermal use of shallow groundwater in urban areas is often constrained by extensive thermal plumes and the risk of impacting third-party groundwater rights. Unidirectional Aquifer Thermal Energy Storage (UD-ATES) offers a promising alternative to conventional open-loop systems by aligning injection and abstraction wells with the natural groundwater flow, enabling partial seasonal recovery of injected thermal energy while limiting off-site impacts.

This study evaluates the feasibility and performance of a UD-ATES system designed to supply heating and cooling to State Hospital Graz South, Austria. Detailed hydrogeological investigations, pumping tests and groundwater monitoring were used to develop a conceptual model of a shallow, highly permeable gravel aquifer characterized by strong natural groundwater flow. Based on these data, analytical pre-design calculations and a coupled groundwater-flow and heat-transport model were applied to optimize well placement and operational parameters.

Model results show that an optimized spacing of approximately 463 m between reinjection and extraction wells aligns thermal plume travel time with the seasonal load cycle. Despite an imbalance between heating and cooling demand, the system achieves a thermal recovery efficiency of about 38%, significantly outperforming conventional pump-and-dump schemes, which provide no seasonal energy reuse. Simulated temperature anomalies remain largely confined to the hospital property, with groundwater temperature changes falling below 1 K within a few hundred metres downstream, thereby complying with regulatory requirements.

The results demonstrate that UD-ATES can substantially reduce the thermal footprint of groundwater-based heating and cooling systems in high-flow aquifers. The approach represents a viable pathway for decarbonizing large, space-constrained energy consumers in urban environments and provides a transferable design framework for similar hydrogeological settings.

Acetic and citric acid control on MgO–CaO hydration – Implications for binder and refractory materials

Michael Pettauer[1], Andre Baldermann[1], Sabrina Steindl[1], Stefan Eder[2], Martin Dietzel[1]

[1] Institute of Applied Geosciences, Graz University of Technology & NAWI Graz Geocenter, Rechbauerstraße 12, 8010 Graz, Austria

[2] RHI-AG, Magnesitstraße 2, 8700 Leoben, Austria

Correspondence to: michael.pettauer@tugraz.at

Understanding the hydration behavior and formation pathways of MgO- and CaO-based phases in aqueous systems is essential for the design of advanced binders, cementitious materials, refractories, and energy storage products. Hydration of Mg- and Ca-oxides is accompanied by heat generation and volume expansion, processes that can be beneficial by enhancing energy release and strength development, but may also induce cracking in hardened materials due to high crystallization pressures. Carboxylic acids such as acetic and citric acid are increasingly used to regulate the hydration of MgO and CaO. However, the mechanisms governing their influence remain incompletely understood. To address this knowledge gap, we combined thermodynamic modelling of potential MgO/CaO hydration pathways with targeted validation experiments. The resulting reactions were characterized through solution chemistry analyses and solid-phase investigations, including X-ray diffraction, infrared spectroscopy, and scanning electron microscopy. The developed thermodynamic models successfully reproduce the observed evolution of solution chemistry and provide robust predictions of Mg/Ca-organic phase formation. Distinct pH stability fields for the organic phases, brucite, and portlandite were identified. Acetate strongly influences the crystal morphology of brucite and portlandite, while citrate suppresses their formation through effective Mg/Ca complexation in solution. This integrated modelling and experimental approach improves the understanding of crystallization pathways in the MgO-CaO-H_2O-organic system and provides a thermodynamic framework for defining system boundaries relevant to the development of binder, refractory, and energy storage materials.

Charakterisierung ausgewählter Tonrohstoffe Österreichs

Julia Rabeder[1], Nikola Braunsteiner[2], Alina Mayer[2], Bernhard Neugschwentner[1], Doris Rupprecht[1], Ingrid Schattauer[3], Arnulf Schiller[3]

[1] Department Rohstoffgeologie und Geoenergie, GeoSphere Austria, Neulinggasse 38, 1030 Wien

[2] Institut für Geologie, Universität Wien, Josef Holaubek-Platz 2, 1090 Wien

[3] Department Oberflächennahe Geophysik, GeoSphere Austria, Neulinggasse 38, 1030 Wien

Correspondence to: julia.rabeder@geosphere.at

Tonrohstoffe gehören zu den ersten von Menschen genutzten mineralischen Rohstoffen überhaupt und behaupten sich seit Jahrtausenden als Baurohstoff sowie als Grundmaterial für keramische Erzeugnisse. Darüber hinaus stehen sie für eine Vielzahl von modernen Spezialanwendungen im Einsatz. Die Anforderungen an den Rohstoff variieren je nach Verwendungszweck, umso wichtiger ist die genaue Kenntnis der spezifischen Eigenschaften unterschiedlicher Tonrohstoffe. Das Projekt MRI_SpekDroTon, ein Kooperationsprojekt von GeoSphere Austria, Universität Wien und Wienerberger Österreich AG im Rahmen der Forschungspartnerschaften Mineralrohstoffe, widmet sich der Detailcharakterisierung ausgewählter Tonvorkommen. Spezielles Augenmerk gilt dabei der Erfassung von Schwankungsbreiten der Rohstoffqualität, insbesondere hinsichtlich der Einflüsse von Sedimentationsraum, Bildungsmilieu, tektonischen Gegebenheiten und Verwitterungsphänomenen. Dazu kommen neben gut etablierten Aufnahmetechniken und Analysemethoden auch an der GeoSphere Austria noch nicht bzw. erst wenig etablierte Methoden wie Punktspektroskopie und drohnengestützte geophysikalische Messmethoden zum Einsatz, deren Anwendbarkeit für spezielle, Tonrohstoffe betreffende Fragestellungen, getestet wird. Die Implementierung dieser neuen Untersuchungsverfahren erfordert Grundlagenarbeit. Zur besseren Abschätzung der Nachweisbarkeit einzelner Phasen in Tonmineralgemischen mittels Punktspektrometer wurden Mischreihen aus jeweils zwei Mineralphasen in definierten Abstufungen hergestellt und analysiert. Dabei zeigt sich, dass bestimmte Tonminerale dominante Spektren aufweisen, die den Nachweis anderer Minerale deutlich erschweren. Die im

Rahmen des Projektes bearbeiteten Tonvorkommen repräsentieren unterschiedliche Bildungsmilieus, die von pelagisch über flachmarin, brackisch, limnisch-lakustrin, fluviatil bis hin zu terrestrisch-kontinental und äolisch reichen und jeweils charakteristische Korngrößenverteilungen, sowie gesamt- und tonmineralogische Zusammensetzungen aufweisen. Variationen und spezifische Besonderheiten zeigen sich aber auch innerhalb der einzelnen Tonvorkommen. Diese Unterschiede spiegeln sich zumindest zum Teil auch in den Spektraldaten wider und können zur Gliederung der Vorkommen herangezogen werden. Erste Auswertungen der drohnengestützten Radiometriemessungen deuten darauf hin, dass diese Methodik dazu beitragen könnte, karbonatarme von karbonatreichen Bereichen zu unterscheiden.

Mineralogical and geochemical characterization of serpentinites in the Speik Complex (Austroalpine Unit, Eastern Alps)

Gerald Schuberth[1], Manuel Werdenich[1], Ralf Schuster[2], Andreas Ahl[3]

[1] Department Mineral Resources and Geoenergy, GeoSphere Austria, Neulinggasse 38, 1030 Wien

[2] Division Geophysical and Applied Geological Services, GeoSphere Austria, Neulinggasse 38, 1030 Wien

[3] Department Near Surface Geophysics, GeoSphere Austria, Neulinggasse 38, 1030 Wien

Correspondence to: gerald.schuberth@geosphere.at

This study presents a systematic material characterization of the serpentinites within the so-called Speik Complex of the Austroalpine Unit. Beyond geological relevance, this geomaterial has gained significant interest in recent years as raw material industries face decarbonization challenges. For certain sectors — such as cement production and magnesite processing — CO2 emissions are intrinsic to the production process. Ultramafic rocks like serpentinites are recognized as suitable materials for CO2 sequestration (in- and ex-situ), where knowledge of specific serpentine phases is crucial.

From a field geological perspective, serpentinites occur in two main areas from north to south: (1) the Hochgrößen–Lärchkogel–Kraubath–Traföß zone, where serpentinites form large bodies associated with (ultra)mafic rocks such as harzburgite, dunite and amphibolite; and (2) the southern side of the Gleinalpe, where serpentinites occur as lenticular bodies within a ca. 40 km SW-NE striking garnet-amphibolite unit. Serpentinites of the first zone contain a large amount of primary minerals and show little deformation while those of the latter zone lack primary minerals but partly show a high degree of deformation.

Material characterization methods include detailed geological mapping, whole-rock geochemical analyses, LECO (C/S) analyses, thin-section petrographies, XRPD measurements, density determinations, and SEM analyses of opaque phases. Additionally, drone-based magnetic measurements and 3D-modelling were conducted in the central Gleinalpe area.

Preliminary results identify antigorite as the dominant serpentine phase, with lizardite also present in the Kraubath area. Two distinct compositional regions emerge: one depleted with higher chromium content, and another geochemically richer with lower chromium. The degree of serpentinization varies from partially hydrated ultramafic rocks to fully serpentinized rocks. Not all units mapped as serpentinites meet strict mineralogical definitions. Protoliths are inferred to be peridotites, mainly harzburgite and dunite, likely refertilized.

The prominent magnetite content enables geophysical detection and 3D-modelling of these rock bodies. The surface part of this model has been validated by fieldwork and confirmed accurate.

These findings provide essential baseline data for evaluating the Speik Complex serpentinites potential in carbon capture and storage applications while advancing regional geologic understanding.

Ultramafic rocks in the Raabs and Gföhl Unit (Austrian Bohemian Massif): characterization, mineralogy and degree of serpentinization

Gerald Schuberth[1), Manuel Werdenich[1), Ralf Schuster[2), Tanja Knoll[1), Julia Weilbold[1)

[1) Department Mineral Resources and Geoenergy, GeoSphere Austria, Neulinggasse 38, 1030 Wien

[2) Division Geophysical and Applied Geological Services, GeoSphere Austria, Neulinggasse 38, 1030 Wien

Correspondence to: gerald.schuberth@geosphere.at

The Austrian part of the Bohemian Massif hosts ultramafic rocks that have received little systematic attention until now. This study presents a investigation of ultramafic rocks in this region, combining petrography, geochemical and mineralogical analyses. Beyond their geological significance, these serpentinites represent a potential raw material for carbon capture and utilization by mineralization storage (CCUM), increasingly relevant for industrial decarbonization efforts in sectors such as cement production and magnesite processing where CO_2 emissions are intrinsic to manufacturing.

The analytical dataset includes thin-section examinations, whole-rock geochemical analyses, LECO C/S determinations, XRPD, SEM investigations and density measurements. The data delineate two populations of ultramafic rocks with contrasting origins. Group I comprises generally garnet-free ultramafic rocks associated with amphibolite interpreted as relics of an oceanic mantle sequence (Raabs unit). In contrast, Group II contains generally garnet partly or fully replaced by symplectites. These ultramafic rocks are interlayered with or overlain by felsic orthogneisses (Gföhl orthogneiss, granulite) and are interpreted as subcontinental mantle (Gföhl unit).

The dominant serpentine phase identified is lizardite. Carbonate veins are present in few outcrops and often a thin opal/chalcedony crust can be observed. This mineralogical assemblage suggests serpentinization in uppermost crustal level during late stages of exhumation. The degree of serpentinization varies widely, from partly hydrated ultramafic rocks to serpentinites. Protolith

reconstruction indicates these bodies originated as refertilized peridotites with harzburgitic to lherzolitic compositions. Structurally, the distribution reveals a mosaic of numerous small bodies interspersed with fewer, larger exposures.

This characterization establishes a baseline for understanding the serpentinites of the Raabs and Gföhl unit. The identification of lizardite as the dominant serpentine phase is crucial for assessing CO_2 sequestration potential, as reaction kinetics and technical realizations are heavily dependent on the specific serpentine polymorph. Furthermore, the occurrence of oceanic and subcontinental ultramafics in various units, along with their mineralogy, will influence insights into the geodynamic evolution of the region and the architecture of the deep crust of the southeastern Bohemian Massif.

Integrated 3D Static Modeling and Rock Typing of the Hawaz Formation, H-NC186, Murzuq Basin, South West Libya

Mohamed Shagoush[1], Emadeddin Elsaleni[1], Mostafa Rashrash[1]

[1] Akakus Oil Operations company, El Tahaddi St (OffAirport Rd), P.O.Box: 91987, Tripoli – Libya

Correspondence to: mshaghoush@akakusoil.com

Understanding the spatial distribution and elastic properties of clastic reservoirs remain challenging due to their heterogeneous mineralogical composition. The Hawaz Formation represents one of the most prospective reservoir intervals in the Murzuq Basin, southwestern Libya, characterized by relatively high reservoir quality, with porosity ranging from 11 to 14 percent and permeability between 680 and 1700 mD. Hawaz is subdivided into upper, middle, and lower units based on reservoir quality, with the Middle Unit, deposited in fluvial to tidal channel and shoreface environments, exhibiting the most favorable petrophysical properties.

This study presents the development of a robust three-dimensional static reservoir model for the H NC186 Field, integrating seismic interpretation, data from 53 wells, and approximately 815 ft of core. A structural framework was constructed using a fault grid derived from interpreted seismic horizons. Facies modeling was performed using stochastic methods, including Sequential Gaussian Simulation and object-based modeling, followed by upscaling into petrophysical facies. Porosity distribution was modeled using well log–derived data, facies-controlled statistical analysis, vertical trend modeling, and a co-kriging approach. Permeability was populated through harmonic upscaling combined with Gaussian random function simulation, using porosity as a secondary variable.

Rock typing was established through the integration of RCAL and SCAL measurements using hydraulic flow unit method, resulting in the identification of five reservoir rock types and the construction of a representative porosity–permeability transform. Net-to-gross was derived from reservoir property cutoffs, while water saturation was modeled using a calibrated Saturation Height

Function. Volumetric calculation was estimated using updated petrophysical parameters, including oil–water contact, oil saturation, net pay, net-to-gross, and pore volume.

The novelty of this work lies in the integrated multi-scale stochastic modeling workflow and the combined application of hydraulic flow units and saturation height functions to reduce uncertainty in volumetric estimation. Uncertainty and sensitivity analyses conducted across multiple realizations identified net pay and saturation parameters as the primary drivers of volumetric variability. The resulting static model provides improved reservoir understanding and forms a reliable foundation for dynamic simulation

Seal integrity for Carbon Capture and Storage: Improved simulation workflows

Lukas Skerbisch[1), David Misch[1), Thomas Hantschel[2)

[1) Technical University Leoben, Peter Tunner Straße 5, 8700 Leoben, Austria; [2) Terranta GmbH, Rathausstraße 37a, 52072 Aachen, Germany

Correspondence to: Lukas.skerbisch@unileoben.ac.at

Carbon Capture and Storage (CCS) is an important technology to achieve global decarbonisation goals. While this fact is acknowledged by most energy agencies and carbon management strategies are established all over the European Union, the CCS approach is still controversially discussed and public acceptance remains low.

Despite the proven technical feasibility of high TRL CCS technologies such as sequestration in depleted fields or saline aquifers, studies on long-term (post-operational) safety of CO_2 storage are relatively scarce and information is mostly based on natural analogues. Long term integrity studies must be tailored to the geological setting of the respective storage prospects and will be a key factor in increasing public acceptance.

While caprock integrity was a less important factor in the development of hydrocarbon fields, it is a major factor in any subsurface storage operation. Considering the foreseeable data limitations and challenging accessibility of direct proof of storage integrity, e.g. via long-term experiments, improved numerical modelling solutions will be required to gain an understanding of CO_2 mobility in the storage complex.

Reactive transport modelling with complex rock-fluid interaction is currently not implemented in standard reservoir simulators but is needed to obtain information about hydrochemical and resulting mineralogy and porosity changes in the different elements of the storage complex. Furthermore, the long observation time spans needed to make a clear statement on CCS safety are beyond (i.e. 100s to 10,000s of years) what is usually simulated in conventional resource production and storage cases, therefore posing an additional challenge to the modelling software.

This work addresses these knowledge gaps by building on the existing reactive transport simulator TerrantaFlow and corresponding 1D models and optimizing it for CO_2 reactive transport modelling over long timespans in intermediate to low permeability environments. The anticipated outcomes are exemplary 2D and 3D models of a multi-reservoir and multi-barrier system, proving the capability of TerrantaFlow to deliver quantitative information on CO_2-induced changes in the storage complex post-operation as well as geochemical models of the CO_2-related fluid-rock interactions in low-permeable barrier rocks.

Integrated Multi-Vendor Seismic Interpretation for Uncertainty Reduction: A Case Study from Murzuq Basin

Ahmed Smida[1)], Mohamed Zaied[1)], Mohamed Alfassi[1)], Walid Abusaq[1)], Tarek Elosta[1)]

[1)] Geology and Geophysics, Akakus Oil Operations, El-Tahaddi St off Airport Road, Tripoli, Libya

Correspondence to: a.akhverdiev@gmail.com

The studied field in eastern Murzuq Basin, Libya, is a complex hydrocarbon area. It has a four-way dip closure measuring about 12 km by 2 km. Hydrocarbon production mainly comes from the Hawaz and Mamuniyat sandstone reservoirs, with the oil-water contact in the Hawaz Formation at -2692 ft TVDSS.

Seismic interpretation is still uncertain despite having good well control. Four 3D seismic datasets collected from 2003 to 2011 complicate identifying the most reliable volume and creating a unified structural framework due to different parameters and workflows.

An integrated, in-house technical reassessment was done due to delays in external studies from budget issues. It included seismic volumes, well logs, vertical seismic profiles (VSPs), and historical reports to evaluate dataset discrepancies and their impact on future well placement.

A standardized workflow was used to interpret seismic cubes, including identifying processing issues and calibrating with well data from five VSP datasets. Key stratigraphic horizons: Top Demabeb, Top BDSI, Top and Base Tanezzuft reservoir, Top H7, and the Achebyat Formation were interpreted consistently across all datasets, generating 24 time-structure maps for comparative analysis. Results showed consistent structural trends in simpler areas, while variations were noted in regions affected by sand dunes.

The analysis performed that static correction errors associated with complex near-surface conditions - particularly dune-related velocity variations - are the dominant source of seismic mis-ties and time shifts. In contrast, differences in seismic resolution between datasets were found to have a secondary effect.

To address these challenges, the study proposes a zonation approach whereby the field is divided into four interpretational domains, each associated with the seismic cube providing the most reliable imaging in that area. This strategy enables more accurate structural mapping and reduces uncertainty in future drilling campaigns.

This study emphasizes the critical importance of robust static correction methodologies and consistent seismic processing standards in desert environments. Furthermore, they demonstrate the value of integrating multi-vendor seismic datasets within a unified interpretation framework. The adopted workflow provides a practical approach to mitigating uncertainty, improving subsurface understanding, and optimizing field development strategies in studied and analogous fields within the Murzuq Basin.

Mineralogical and geochemical assessment of innovative primary and secondary raw materials: Unlocking their potential for sustainable mineral binders and industrial synergies

Florian Roman Steindl[1,2)], Cyrill Vallazza-Grengg[1)], Isabel Galan[2)], Florian Mittermayr[3)], Sara Raič[1)], Ognjen Rudić[1,2)], Sarah Steiner[2)], Joachim Juhart[2)], Martin Dietzel[1)]

[1)] Institute of Applied Geosciences, member of the NAWI Graz Geocenter, Graz University of Technology, Rechbauerstraße 12, 8010 Graz, Austria

[2)] Institute of Technology and Testing of Building Materials, Graz University of Technology, Inffeldgasse 24, 8010 Graz, Austria

[3)] Working Group for Material Technology, Institute for Construction and Material Sciences, University of Innsbruck, Technikerstraße 13, 6020 Innsbruck, Austria

Correspondence to: florian.steindl@tugraz.at

Decarbonization and material shortages in the construction industry and adjacent sectors drive the shift towards circularity of mineral resources. This study explores the mineralogical and geochemical potential of a range of newly identified primary as well as waste and secondary raw materials (WSRMs) for usage as innovative binder components.

A key focus lies on the mineralogical and geochemical characterization of a range of materials, including calcined clays, iron carbonates, metallurgical slags, construction and demolition wastes, incineration ashes, and spent refractories. Geochemical parameters such as their crystalline and amorphous phase composition and oxide ratios (e.g. CaO, SiO_2, Al_2O_3) determine phase reactivity and, in turn, the material's suitability for hydraulic, pozzolanic, or alkaline activation pathways. Advanced analytical techniques, such as reactivity assessments coupled with in-depth phase and reaction kinetics characterization, further refine the selection of materials for targeted applications, balancing mechanical performance with long-term stability, chemical resistance, and environmental impact. For instance, calcined clays exhibit enhanced pozzolanic reactivity after thermal treatment, while iron carbonates like siderite demonstrate unique “ferrolanic” reactions, improving durability and reducing calcium leaching in cementitious systems. Similarly, thermochemically processed slags and ashes achieve high hydraulic reactivity through controlled vitrification, enabling their use in both Portland cement blends and alkali-activated materials (AAMs).

Beyond binders, the upcycling of WSRMs can offer cross-sectoral benefits. Notably, Thermochemical treatment enables the recovery of critical elements like phosphorus, supporting circular economy goals. The integration of WSRM into binders not only reduces CO_2 emissions and landfill volumes but also can enhance material properties, such as chemical resistance or refractory qualities. These properties can be further improved by tailored processing to optimize reactivity while mitigating environmental risks (e.g., leaching of heavy metals).

This contribution underscores the pivotal role of applied mineralogy in surveying new primary building materials and unlocking the circular economy potential of WSRMs, paving the way for next-generation, low-carbon binders that align with global sustainability goals while fostering synergies across industrial sectors.

Frequency-Domain Detection of Controlled-Source Sparker Pulses with Low Signal-to-Noise Ratio Using Seismic Arrays

Bernd Trabi[1)], Andrew Greenwood[1)], Florian Bleibinhaus[1)]

[1)] Lehrstuhl für Angewandte Geophysik, Montanuniversität Leoben, Peter-Tunner-Straße 25, 8700 Leoben

Correspondence to: bernd.trabi@unileoben.ac.at

We present a field experiment conducted on a drill site near Megolo (Val d'Ossola, Italy) to investigate the detectability of weak seismic signals generated by subsurface processes in the shallow crust, such as fluid migration. Upward-migrating fluids (e.g., natural hydrogen) can generate seismic signals if their flow pathways interact with heterogeneous geological structures or encounter resistance. Such signals are typically weak but stationary. A controlled borehole sparker source provides a suitable analogue for testing this detection problem, as it allows the generation of repeatable impulsive signals. The sparker source was deployed in a pre-existing borehole down to a depth of approximately 300 m. The signals were recorded at the surface using a pre-installed 3C MEMS sensor array, consisting of two receiver lines, one aligned along the bedrock and the other oriented perpendicular to it across a sedimentary wedge. The test site is located in a geologically complex environment characterized by strong anthropogenic and environmental noise. For signal detection, we apply a frequency-domain array method originally developed for small-magnitude earthquakes and later adapted for microseismic events, both of which are often difficult to identify in the time domain. The method exploits the coherence of seismic energy across multiple sensors in the frequency domain, while incoherent noise is suppressed through statistical averaging. Signals that remain obscured in individual traces can be enhanced. Additionally, we investigate the potential of the array layout for subsequent source localization and evaluate the detectability of impulsive drilling-related events (e.g., core barrel drops) in available seismic-while-drilling data, as these events may serve as seismic sources for monitoring applications.

Minerals in extremely high-T environments: the occurrence of armalcolite in fulgurites and pseudofulgurites

Peter Tropper[1], Salome Lanz[1], Monika Rabanser[1]

[1] Institute of Mineralogy and Petrography, University of Innsbruck, Innsbruck, Austria

Correspondence to: peter.tropper@uibk.ac.at

Armalcolite, a titanium-rich oxide mineral, named after the astronauts Armstrong, Aldrin and Collins, with the general formula (Fe^{2+}, Mg)Ti_2O_5, was first identified in lunar basalts returned by the Apollo 11 mission and has since been recognized as a rare phase in terrestrial ultramafic and mafic igneous rocks. Its stability is constrained to high-temperature and very low oxygen fugacity conditions. Terrestrial occurrences of armalcolite are typically limited to rapidly quenched basaltic lavas, kimberlitic melts, and differentiated alkaline complexes, where it crystallizes as an early magmatic phase. The mineral also forms from ilmenite and rutile during high-grade metamorphism. Here we describe this mineral from extremely high-T (T between 2000°C and >10000°C) rocks such as fulgurites (lightning-strike rocks) as well as pseudofulgurites (rocks that formed during a ground fault of a high-voltage power cable). In the course of this work petrological investigations were carried out using polarization microscopy, scanning electron microscopy (SEM) and electron probe microanalysis (EPMA). Textures were investigated using BSE images from the EPMA and SEM. An attempt was made to constrain (most likely lower) formation temperature limits using diagnostic high-temperature mineral assemblages. The fulgurite sample comes from the collection of the Tiroler Landesmuseen and was collected in the Lybian desert. The matrix of the tube-shaped rod consists of silicate glass with relicts of quartz, rutile, zircon and ilmenite. The newly formed minerals are armalcolite from the breakdown of rutile or ilmenite and baddeleyite from the breakdown of zircon. Tiny Fe-metal spheres also occur in former gas bubbles and pure SiO_2 glass also occurs. Former biotites and muscovites are completely replaced by spinel, mullite and corundum. The pseudofulgurite from Vitis in Lower Austria is defined by a glassy matrix, which contains both Fe-P spheres and mineral fragments. During the ultra-high temperature event the following phases formed: hercynite

($FeAl_2O_4$), fayalite (Fe_2SiO_4), mullite ($Al_6Si_2O_{13}$) armalcolite (Fe^{2+}, Mg)Ti_2O_5 and baddeleyite (ZrO_2). Again, armalcolite replaces rutile along the rims. Finally, the occurrence of rare armalcolite provides key insights into the redox state and crystallization sequences of planetary magmatic and metamorphic systems, and its presence is considered a petrogenetic indicator of very high-temperature, low-fO_2 environments.

Mapping of Middle Miocene fluvial deposits at the southern margin of the Vienna Basin: Implications for the quality and distribution of hydrothermal reservoirs

Johannes Weitz[1), Alexander Pengg[1), David Misch[1), Wolfgang Siedl[1), Gregor Götzl[2)

[1) Montanuniversität Leoben, Peter-Tunner-Straße 5, 8700 Leoben;

[2) EVN Wärme GmbH, Untere Bachgasse 6, 2340 Mödling

Correspondence to: johannes.weitz@unileoben.ac.at

Heat production from hydrothermal reservoirs is an established and sustainable technology but makes up only a small fraction of Austria's energy mix currently, emphasizing an exploration gap. A major challenge is the limited knowledge of suitable reservoirs outside hydrocarbon provinces. New seismic surveys are currently in planning and need to be linked to existing data and regional geological models to speed up project development.

The Vienna Basin has a long history in hydrocarbon exploration. Furthermore, conglomerates of the Middle Miocene (Lower Badenian) Rothneusiedl Formation likely hold a huge hydrothermal potential. While first projects were successfully launched in the central basin (e.g., Hydros Seestadt), future hydrothermal utilization in its southern part relies on the acquisition of new subsurface data, complemented by extensive surface mapping to improve regional geological concepts and the understanding of distribution and quality of target reservoirs in the basin fill and the directly underlying basement. This contribution presents the preliminary results of a mapping study targeting conglomerates and karstified Mesozoic basement carbonates in the southern Vienna Basin with a special focus on its southwestern margin and the Leithagebirge. The study is based on (i) outcrop observations, (ii) component analysis, and (iii) thin section analysis and aims at reconstructing changes in deposition environment and sediment provenance.

In total 67 outcrops were studied. First results indicate that the conglomerates occur in fan-shaped deposits on the SW and in channel systems on the SE

margin (Leithagebirge). The distribution of components as well as the compositional and textural maturity of the conglomerates vary significantly. The conglomerates on the SW margin exhibit a gradual shift from predominantly siliciclastic components (wackes and sandstones) at the base to predominantly carbonate components at the top. The ongoing mapping will facilitate a comprehensive understanding of the depositional setting and compositional evolution of basal conglomerate reservoirs in the southern Vienna Basin, as well as further hydrothermal potential related to the directly underlying basement units (e.g., karstified and/or fractured zones). Future investigations will help to clarify the age of the conglomerates, their provenance controlled by the basin evolution, and the timing of secondary processes controlling reservoir quality (e.g., karstification).

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Session 08

Wasser als Ressource und Risiko: Geowissenschaftliche, geotechnische und praxisorientierte Perspektiven

Water as a resource and a risk: Geoscientific, geotechnical, and practical perspectives

Conveners:
Christine Stumpp, Steffen Birk & Gerfried Winkler

Ermittlung der Grundwasserneubildung mittels Zeitreihenmodellierung von Grundwasserständen

Steffen Birk[1)]

[1)] Institut für Erdwissenschaften, NAWI Graz Geozentrum, Universität Graz

Correspondence to: steffen.birk@uni-graz.at

Viele wasserwirtschaftliche Fragestellungen, etwa im Zusammenhang mit den Auswirkungen des Klimawandels und der nachhaltigen Nutzung von Grundwasserressourcen, erfordern die Kenntnis der Grundwasserneubildung aus dem Niederschlag. Eine unmittelbare Messung der Grundwasserneubildung ist praktisch jedoch kaum möglich. Daher verwendet man in der hydrogeologischen Forschung und Praxis verschiedene Verfahren, bei denen die Neubildung indirekt aus anderen Beobachtungen ermittelt wird. Beispielsweise können Schwankungen von Grundwasserständen zur Abschätzung verwendet werden, sofern diese durch die Neubildung aus dem Niederschlag verursacht sind. Diese Voraussetzung führt allerdings zu Limitierungen und Unsicherheiten. Zudem können nur Neubildungsraten aus vergangenen Zeiträumen ermittelt werden, für die Grundwasserstandmessungen vorliegen. Alternativ kann aus meteorologischen Messungen die Versickerung unterhalb der Wurzelzone mittels Bodenwasserbilanzmodellen abgeschätzt werden. Damit ist es auch möglich, Neubildungsraten für künftige Bedingungen abzuschätzen, beispielsweise auf Grundlage von Klimaprojektionen. Die Versickerung aus der Wurzelzone ist allerdings nicht immer zwangsläufig mit der Neubildung an der Grundwasseroberfläche gleichzusetzen. Außerdem bestehen oftmals Unsicherheiten in Bezug auf die für die Modellierung erforderlichen bodenhydrologischen Kennwerte.

Dieser Beitrag diskutiert anhand von Beispielen, wie die beiden oben genannten Ansätze mittels Zeitreihenmodellierung kombiniert werden können. Dabei wird die aus meteorologischen Eingangsgrößen, wie Niederschlag und Temperatur, ermittelte Neubildung zur Simulation von Grundwasserstandschwankungen verwendet. Durch Kalibrierung des Modells an gemessene Grundwasserstände, werden die erforderlichen Kennwerte sowohl der Wurzelzone als auch des

Aquifers abgeschätzt. Das kalibrierte Modell ermöglicht dann auch Prognosen künftiger Änderungen der Grundwasserneubildung. Mögliche andere Beeinflussungen der Grundwasserstände, beispielsweise durch Oberflächengewässer oder Wasserentnahmen, stellen auch hier eine erhebliche Herausforderung dar, können aber grundsätzlich in der Modellierung berücksichtigt werden.

Neuerkenntnisse zur Geologie und Hydrogeologie der Mühlauer Quelle (Innsbruck): Mittelpleistozäne Sedimente im Liegenden der Höttinger Breccie als Schlüssel für das hydrogeologische Modellverständnis

Manuel Egger[1,2], Katharina Wex[1], Gerhard Poscher[1], Rainer Brandner[3]

[1] geo.zt gmbh-poscher beratende geologen, Saline 17, 6060 Hall in Tirol
[2] Dibit Messtechnik GmbH, Framsweg 16, 6020 Innsbruck
[3] Institut für Geologie, Universität Innsbruck, Innrain 52f, 6020 Innsbruck

Correspondence to: manuel.egger@geo-zt.at

Die Trinkwasseranlage „Mühlauer Quelle“ an der Innsbrucker Nordkette ist mit einer jahreszeitlichen Schüttung von rund 600 l/s bis zu 1500 l/s die zentrale Trinkwasserressource der Stadt Innsbruck. Die bestehende Versorgungsanlage aus den 1950er-Jahren, fasst am südlichen Abhang der Nordkette mit zwei kürzeren sowie einen längeren Quellstollen untertägige Bergwässer. Betreiber der Anlage sind die Innsbrucker Kommunalbetriebe AG.

Um die Versorgungssicherheit bei steigendem Trinkwasserbedarf langfristig zu sichern und trübungsanfällige Stollenabschnitte zu umgehen, wurde zwischen 2021 und 2024 ein umfangreiches Bauprojekt zur Errichtung eines Umgehungs- und eines neuen Quellstollens umgesetzt.

Die baubegleitende geologische Dokumentation wurde durch interdisziplinäre wissenschaftliche Untersuchungsmethoden ergänzt. Mittels Isotopenhydrologie, Mineralogie, Palynologie und Altersdatierungen konnten bedeutende neue Erkenntnisse gewonnen und das bisherige geologische Modell überarbeitet werden. Das zentrale Ergebnis ist die Neuentdeckung der sogenannten

„Mühlauer-Einheit“ bei der es sich um mittelpleistozäne, dicht gelagerte Abfolgen aus diamiktischen bis feinlaminierten, glaziolakustrinen Sedimenten handelt.

Diese bislang unbekannte, im Zuge der Vortriebe weiträumig durchörterte Abfolge quartärer Ablagerungen fungiert als effizienter hydraulischer Stauer und ist ursächlich für die Position der ergiebigen Quellaustritte an dieser Stelle der Nordkette.

Hydrogeologisch zeichnet sich das System durch stabile Verhältnisse aus. Die im neuen Quellstollen und durch bis zu 310 m tiefe Bohrungen erschroteten Wässer zeigen ausgeglichene δ18O-Werte, Wassertemperaturen von rund 4,0 °C, elektrische Leitfähigkeiten von 185-200 µS/cm sowie eine hohe Korrelation mit den Bestandsquellen. Die mittels Tritiummethode ermittelten mittleren Verweilzeiten von etwa 10-15 Jahre zeigen ähnliche Werte zu den Bestandsquellen und bestätigen ein robustes Wasservorkommen.

Mit der erfolgreichen Erschrotung von zusätzlich 350 l/s hochwertigem Bergwasser seit 12/2024 wurde ein maßgebliches Projektziel erreicht.

Die Ergebnisse zeigen, dass die Kombination aus strukturgeologischen Faktoren der Nördlichen Kalkalpen und den Eigenschaften der Mühlauer-Einheit ein hocheffizientes natürliches Reservoir schaffen. Diese Neuerkenntnisse sind nicht nur für das lokale hydrogeologische und geologische Modell von Bedeutung, sondern liefern auch Erkenntnisse für vergleichbare Karst-Kluft-Aquifere im alpinen Raum.

(Neue) Alter von Tiefengrundwässern im Steirischen Becken

Marlies Gold[1], Stefan Moser[2], Albrecht Leis[3], Christian Kriegl[1], Antonia Maier[1]

[1] Aquifer GmbH, Lessingstraße 30, 8010 Graz
[2] Amt der Steiermärkischen Landesregierung Abteilung 14 - Wasserwirtschaft, Ressourcen und Nachhaltigkeit, Wartingergasse 43, 8010 Graz
[3] JR-AquaConSol, Steyrergasse 21, 8010 Graz

Correspondence to: marlies.gold@aquifer.at

Die drei Tiefengrundwasserkörper in der Ost- bzw. Weststeiermark stellen sowohl in Dürreperioden als auch in Katastrophenfällen, etwa bei Verunreinigungen des oberflächennahen Grundwassers, eine strategische Trinkwasserreserve dar. In Hinblick auf eine fundierte hydrogeologische Interpretation der räumlichen Fließsysteme und die Abgrenzung unterschiedlicher Grundwasserstockwerke ist neben den kontinuierlichen Druckspiegelmessungen des Hydrographischen Dienstes der Steiermark in aktuell ca. 40 Tiefengrundwassermessstellen auch die Bestimmung des Alters und damit der Verweilzeiten der Tiefengrundwässer von Bedeutung.

Im Zeitraum 2021 - 2025 wurden an den 40 Messstellen Wasserproben entnommen und hinsichtlich des Alters analysiert. Ziel der Untersuchungen war die Bestimmung der mittleren Verweilzeiten sowie die klimatisch-hydrogeologische Einordnung der Wässer. Die Abschätzung des Wasseralters erfolgte mittels kombinierter hydrochemischer und isotopenhydrologischer Analysen von Tritium, $\delta^{2}H$, $\delta^{18}O$, ^{14}C-DIC, $\delta^{13}C$-DIC und den Hauptinhaltsstoffen des Wassers.

Die ^{14}C-Modellalter der beprobten Tiefengrundwässer variieren deutlich und reichen von etwa 1.700 Jahren bis über 40.000 Jahre. Der Großteil der Proben zeigt Modellalter zwischen 6.000 und 20.000 Jahren und ist damit dem Holozän bis Spätglazial zuzuordnen. Besonders alte, fossile Wässer mit ^{14}C-Gehalten unter 5 pMC stammen aus dem Spätpleistozän und sind während des Hochglazial infiltriert. Die Gegenüberstellung von Deuteriumgehalt und ^{14}C-Modellalter zeigt eine enge Kopplung zwischen Isotopenzusammensetzung und

Alter, wobei sich die neuen Daten in den Trend früherer Untersuchungen einordnen und die klimatisch bedingte Staffelung der Tiefengrundwässer von holozänen bis hochglazialen Bildungsphasen bestätigen.

Im Zuge der Untersuchungen konnten zudem deutliche regionale Trends festgestellt werden. Die Altersdifferenzierung zeigt insbesondere im Grundwasserkörper „Steirisches und Pannonisches Becken“ tendenziell jüngere Wässer in größerer Nähe zu den Neubildungsbereichen. Holozäne Wasseralter treten hier vor allem am nordwestlichen Beckenrand sowie an der Südgrenze des Grundwasserkörpers auf.

Die hydrochemischen und isotopenhydrologischen Untersuchungen verbessern das Verständnis der drei Tiefengrundwasserkörper und bilden damit eine wesentliche Grundlage für künftige Bewirtschaftungsstrategien.

Climate Change Impacts on Alpine Springs in Austria: Shifts in Discharge Seasonality and Water Availability

Martin Masten[1], Magdalena Seelig[1], Simon Seelig[1], Matevž Vremec[1,2], Thomas Wagner[1], Maria Obwegs[1,3], Matthias Hausleber[1], Jutta Eybl[4], Gerfried Winkler[1]

[1] Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Heinrichstrasse 26, 8010 Graz, Austria
[2] Department of AI and Digital Technologies, Alma Mater Europaea University, Slovenska ulica 17, 2000 Maribor, Slovenia
[3] now at Geo Group Austria ZT GmbH, Reininghausstraße 13a, 8020 Graz, Austria
[4] Federal Ministry of Agriculture and Forestry, Climate and Environmental Protection, Regions and Water Management, Marxergasse 2, 1030 Vienna, Austria

Correspondence to: martin.masten@uni-graz.at

Spring water is a vital resource in Austria, covering approximately half of the drinking-water demand and serving as the sole source in some regions. Climate change is rapidly altering hydrological conditions, particularly in the Alpine region. Understanding future changes in spring discharge dynamics is therefore essential for sustainable water resources management. This study investigates climate change impacts on 70 alpine springs across the Austrian Alps covering diverse climatological and hydrogeological settings. For each spring, several potential catchments are delineated, and a rainfall–runoff model including a snow module determines the most plausible catchment. Subsequently, the model is driven by climate input data from three Representative Concentration Pathway scenarios (RCP 2.6, 4.5, and 8.5) and 40 model realizations to assess impacts until 2100. Comparing three periods (historical reference 1980–2009, near future 2030–2059, and far future 2070–2099) enables a systematic assessment of temporal changes and climate impacts on alpine spring catchments. Analyses are conducted for individual springs and hydrologically classified groups with specific discharge characteristics. Results show decreasing spring discharge in western Austria across all emission scenarios and time periods relative to the reference period. Under higher-emission scenarios (RCP 4.5, 8.5), decreasing trends also emerge in southern Austria. Annual discharge changes of the spring groups remain within the single-digit percentage range, but their direction and temporal evolution differ. The snow-dominated and recession-dominated groups show higher sensitivity to emission scenarios, while the fast-responding group maintains positive annual discharge changes under all scenarios. For fast-responding and snow-dominated springs, seasonal discharge shifts are observed, with a strong spring time increase for the latter group and significant summer and autumn decreases for both. Importantly, low flows shift from late winter and early spring toward summer and autumn across all analyzed groups, with increasing intensity under higher-emission scenarios. These findings provide a strategic reference for sustainable water management in Austria, highlighting potential trends while acknowledging scenario-based uncertainties.

New Insights into the Distribution and Structure of the Carinthian Gravel Formation in the Fürstenfeld Basin Based on Seismic and Well Data

Christina Neuhold[1,3], Maha Hasni[1], Heinz Binder[1], Marcellus Schreilechner[1], Arthur Borzi[4], Nikolaus Petschacher[2], David Muhr[2], Vilmos Vasvári2,[5], David Misch[3]

[1] Geo5 GmbH, Leoben, Austria
[2] Hydro GmbH, Graz, Austria
[3] Technical University of Leoben, Leoben, Austria
[4] University of Graz, Graz, Austria
[5] Ingenieurbüro für Kulturtechnik und Wasserwirtschaft Dipl.-Ing. Dr. techn. Vilmos Vasvári, Graz, Austria

Correspondence to: christina.neuhold@geo-5.at

The Carinthian Gravel Formation of the Fürstenfeld Basin represents a potential reservoir horizon for Aquifer Thermal Energy Storage (ATES) applications in the Eastern Styrian Basin. A new analysis of seismic reflection data and additional reprocessed seismic data, combined with geological information from boreholes, has enabled the distribution and structure of the Carinthian Gravel Formation to be remapped. Geological and geophysical borehole measurements were correlated with available core information from several boreholes, thereby informing the discussion of the sedimentary composition and stratigraphy of the Carinthian Gravel Formation.

Located at depths of approximately 560–650 m, the Sarmatian Carinthian Gravel Formation is overlain by sandy deposits of the Gleisdorf Formation and forms the primary target horizon of this study. The Carinthian Gravel is characterized by considerable thickness, high permeability and effective confinement by clay-rich strata below and sandy deposits above. Particular attention was given to the relationship between the Carinthian Gravel and the overlying sandy deposits, including their stratigraphic relationship and possible role as additional reservoir units.

The results contribute to the geological characterization of potential ATES reservoirs and provide new insights into the Middle Miocene evolution of the Fürstenfeld Basin.

Junges Wasser in Österreichs Quellen: Einfluss von Untergrundeigenschaften und Abflussdynamik

Simon Seelig[1), Felix Thalheim[2), Magdalena Seelig[1), Paul Töchterle[2), Matevž Vremec[1,3), Martin Masten[1), Heike Brielmann[4), Jutta Eybl[5), Gerfried Winkler[1)

[1) Institut für Erdwissenschaften, NAWI Graz Geocenter, Universität Graz, Heinrichstraße 26, AT-8010 Graz
[2) Energieagentur Tirol GmbH, Bürgerstraße 1–3, AT-6020 Innsbruck
[3) Alma Mater Europaea University, Solvenz 17, SI-2000 Maribor
[4) Team Grundwasser, Umweltbundesamt GmbH, Spittelauer Lände 5, AT-1090 Wien
[5) Bundesministerium für Land- und Forstwirtschaft, Klima- und Umweltschutz, Regionen und Wasser-wirtschaft, Marxergasse 2, AT-1030 Wien

Correspondence to: simon.seelig@uni-graz.at

Die Verweilzeit des Wassers im Untergrund stellt – als Spiegel der Grundwasserdynamik – eine zentrale hydrogeologische Kenngröße dar. Sie bestimmt die maßgebliche Zeitskala hydrogeochemischer Prozesse und beeinflusst damit Stoffkreisläufe sowie ökologische Regenerationsmechanismen. Während die Bestimmung der mittleren Verweilzeit häufig mit erheblichen Unsicherheiten verbunden ist, bietet der Anteil jungen Wassers am Quellabfluss eine robuste Alternative zur Charakterisierung von Strömungs- und Speicherprozessen. In der vorliegenden Studie wurde dieser Anteil erstmals systematisch für 496 Quellen untersucht und in Bezug auf unterschiedliche Aquifertypen ausgewertet. Die Datengrundlage umfasst Messreihen aus dem Zeitraum 1972–2025 und deckt ein breites Spektrum geologischer, klimatischer und topographischer Rahmenbedingungen in ganz Österreich ab. Der mittlere Anteil jungen Wassers aller Quellen beträgt 6 %. Karstquellen weisen mit bis zu 53 % die höchsten Werte auf, allerdings bei großer Variabilität. Schuttquellen zeigen mittlere Anteile, während Kluft- und

Porengrundwasserleiter durch geringe Anteile jungen Wassers und eine vergleichsweise geringe Streuung gekennzeichnet sind. Darüber hinaus verändert sich der Anteil jungen Wassers in Abhängigkeit von den Abflussverhältnissen und nimmt tendenziell mit steigender Quellschüttung zu. Dabei reagieren Karstquellen am deutlichsten auf steigende Abflussmengen, was auf eine temporäre Verschiebung der Beiträge schneller und langsamer Fließwege hindeutet. Kluftquellen zeigen dagegen die geringste Reaktion und damit eine stabile Schüttungsdynamik. Im Vergleich zu 565 untersuchten Flüssen sind die Anteile jungen Wassers in Quellen signifikant geringer, da die Transport- und Speicherprozesse im Untergrund vergleichsweise träge sind. Diese Ergebnisse liefern Einblicke in die Dynamik unterschiedlicher Grundwassersysteme und schaffen eine wichtige Planungsgrundlage für die Bewirtschaftung von Wasserressourcen sowie die Bewertung von Schadstoffrisiken.

Die Großquellen Tirols: Landesweite Erhebung und Datenintegration zur hydrogeologischen Bewertung strategischer Wasserressourcen

Felix Thalheim[1], Paul Töchterle[1], Sandra Petersmann[1], Stephanie Benischke[1]
[1] Energieagentur Tirol, Bürgerstraße 1-3, 6020 Innsbruck

Correspondence to: stephanie.benischke@energieagentur.tirol

Tirols Trink- und Nutzwasserbedarf wird zu rund 90 Prozent aus Quellwässern gedeckt. Großquellen (Q_{min} > 20 l/s) sind daher von zentraler strategischer Bedeutung. Vor dem Hintergrund fehlender harmonisierter Datengrundlagen, veränderter Nutzungsbedingungen und möglicher Klimawandelfolgen wurde von 2019 bis 2026 eine Neubewertung der Tiroler Großquellen durchgeführt.

Ziel des Projekts war die Identifikation, hydrogeologische, hydrochemische und isotopengeochemische Charakterisierung sowie einheitliche wasserwirtschaftliche Bewertung der Großquellen. Dafür wurden behördliche, hydrographische und wasserqualitätsbezogene Datensätze sowie Unterlagen von Gemeinden, Wasserversorgern, Planungsbüros und historische Daten gesammelt, digitalisiert und harmonisiert. Ergänzend umfassten die Arbeiten Geländebegehungen, Vor-Ort-Messungen sowie hydrochemische, isotopengeochemische und bakteriologische Untersuchungen zur Bestimmung von Wasserqualität und Herkunft der Wässer, zur Abschätzung mittlerer Einzugsgebietshöhen und Verweilzeiten sowie zur Auswertung statistischer Langzeittrends von Schüttung, Wassertemperatur und Mineralisierungsgrad.

Insgesamt wurden 92 Großquellen identifiziert. Ihre räumliche Verteilung wird wesentlich durch die regionale Geologie bestimmt, die Mehrheit ist an Karbonatgesteine der Nördlichen Kalkalpen und des Brennermesozoikums gebunden. Die theoretische aggregierte Minimalschüttung beträgt rund 222 Mio. m³/a. Das nutz- und erschließbare Potenzial wurde mit etwa 101 Mio. m³/a abgeschätzt und liegt bilanziell über dem Tiroler Trinkwasserbedarf von 70,2 Mio. m³/a. Die Isotopendaten ergeben im Durchschnitt mittlere Einzugsgebietshöhen von rund 1.500 m ü. A., im Mittel etwa um den Faktor 1,5 über den jeweiligen Austrittshöhen. Die Einzugsgebietsgrößen variieren zwischen 1 und über 30 km²,

Schutz- oder Schongebiete sind häufig nicht ausgewiesen. Erste Trendanalysen zeigen steigende Wassertemperaturen von etwa 0,02 °C/a. Ein eindeutiger Klimaeffekt auf die Schüttungsmengen ist bislang nicht flächendeckend nachweisbar. Klimawandelbedingte Veränderungen der Schneedeckendynamik sowie des Speicher- und Abflussverhaltens sind jedoch künftig zu erwarten.

Die landesweite Erhebung und Integration hydrogeologischer Informationen vertieft das Verständnis von Grundwasserneubildung, Speicherverhalten und Resilienz von Großquellen und schafft damit eine belastbare Grundlage für wasserwirtschaftliche Entscheidungen auf lokaler bis regionaler Ebene.

Towards preventive groundwater management: network assessment, time-series modelling and anomaly detection in two cross-border pilot aquifers

Matevž Vremec[1], Edith Grießer[2], Aljaž Vogrinčič[2], Stefan Moser[3], Aleš Erker[4], Matej Levstek[4], Goran Anders[4], Saša Fluher[5], Tina Tement[5], Tadej Žurman[5], Steffen Birk[2]

[1] Department of Artificial Intelligence and Digital Technologies, Alma Mater Europaea University, Maribor, Slovenia
[2] Department of Earth Sciences, University of Graz, Graz, Austria
[3] Department 14 – Water Management, Resources and Sustainability, Water Management Planning Unit, Government of Styria, Graz, Austria
[4] Mariborski vodovod d.o.o., Maribor, Slovenia
[5] National-level Institute for Sustainable Environmental Solutions, Maribor, Slovenia

Correspondence to: matevz.vremec@uni-graz.at

Climate change, longer and more severe droughts, more intense rainfall events and increasing water demands are putting pressure on groundwater resources in the forealpine Drava and Mura basins, including areas that have long been considered relatively stable. Although groundwater monitoring data are widely collected on both sides of the Slovenian–Austrian border, they are not yet fully used for operational decision-making. The GW-CARE project (Interreg VI-A SI-AT, 2026–2028) addresses this gap by developing a Python-based approach for more preventive groundwater management in cooperation with water utilities and regional authorities. The approach combines time-series modelling with Pastas and machine learning models to analyse long groundwater-level records, describe well responses to precipitation, recharge conditions and abstraction, support the assessment of the monitoring network, and develop operational groundwater-level forecasting. Model residuals and irregular time-series

behaviour will be used for anomaly detection to identify possible measurement problems, system failures or changes in well condition, which will then be compared with field observations and technical documentation. The modelling workflow will be complemented by interactive Jupyter-based modules for groundwater flow, climate-impact assessment, and managed aquifer recharge scenarios, allowing drought, altered recharge and abstraction strategies to be explored before field application. The approach will be tested at two contrasting pilot sites: the Vrbanski plato wellfield near Maribor, which supplies about two thirds of the city's drinking water and includes active managed aquifer recharge from the River Drava, where forecasting will support the evaluation of recharge and abstraction strategies; and a Styrian monitoring network of roughly 180 observation wells, where anomaly detection will be linked to field inspection and network maintenance. Together, these pilots provide a basis for testing whether one open workflow can support groundwater management across different aquifer settings, monitoring histories and national contexts.

This work is part of the GW-CARE project, co-financed by the European Union through the European Regional Development Fund under the Interreg Slovenia–Austria Programme 2021–2027.

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Session 09

Hydrogeochemie und Wasserqualität:
Natürliche Prozesse, anthropogene Einflüsse und praxisorientierte Lösungen

Hydrogeochemistry and water quality:
Natural processes, anthropogenic influences, and practical solutions

Conveners:
Christine Stumpp, Steffen Birk & Gerfried Winkler

NAWI Graz Natural Sciences

TU Graz

UNI GRAZ

NAWI Graz
Natural Sciences

TU Graz

UNI GRAZ

Environmental change and Alpine hydrochemistry - initial findings from a 30-year trend analysis of springs in Austria

Sylke Hilberg[1)]

[1)] Department Environment and Biodiversity, University of Salzburg, Hellbrunner Str. 34, 5020 Salzburg

Correspondence to: sylke.hilberg@plus.ac.at

The Alpine region has undergone significant changes in recent decades. Higher temperatures and altered precipitation patterns are changing the catchment areas of springs and, consequently, the dynamics of groundwater recharge in various ways. In addition to changes in flow dynamics, atmospheric composition and processes in the unsaturated zone affect the hydrochemical composition of the recharged water, which in turn can influence water-rock interactions. The presented study examines whether significant trends in hydrochemistry have emerged over the past 30 years, and if so, whether they can be attributed to regional conditions, hydrogeology, discharge dynamics, temperatures, or other factors that have changed in recent decades.

Data on the hydrochemistry of 19 selected springs in the Austrian Alps over the past 30 years were collected from the “H2O Fachdatenbank”, (a freely accessible database provided by the Austrian Federal Environment Agency) and subjected to statistical analysis. Based on the identified trends, a principal component analysis was performed to divide the springs into four clusters. The study revealed an increase in total mineralization and karst parameters, as well as a decrease in the concentrations of SO_4, NO_3 and trace metals. These hydrochemical changes appear to be only indirectly related to climate change parameters, instead being influenced by changes in atmospheric composition. This assumption is supported by the clusters being distributed regionally rather than according to hydrogeological characteristics, as was initially expected.

Mixing and age of deep thermal groundwater revealed by 81Kr, 18O and 87Sr-isotopes in the Austrian Alpine Foreland Basin

Martin Kralik[1)], Michael Heidinger[2)]
[1)] Department of Environmental Geosciences, University of Vienna, Josef-Holaubek-Platz 2, A-1090 Vienna
[2)] Hydroisotop Ltd., Woelkestr. 9, D-85301 Schweitenkirchen, Germany

Correspondence to: martin.kralik@univie.ac.at

The Austrian Alpine Foreland Basin (AAFB) is home to a large population and an important industrial location. The subsurface of the AAFB has been intensively used for decades for drinking, energy (hydrocarbons and geothermal energy) and balneology purposes. To accommodate these diverse interests and to secure a sustainable usage of the resources, the understanding of the basin history, the hydrostratigraphic ages and their interactions are crucial.

Major ion chemistry, $\delta^{2}H$, $\delta^{18}O$, and $^{87}Sr/^{86}Sr$ ratios suggest the Malmian thermal waters to be a mixture between meteoric Na-HCO_3 waters with $\delta^{18}O$ values <-11.5‰ and NaCl-brines ($\delta^{18}O$-values >-4.5‰), with a small fraction of young CaMg-HCO_3 waters.

^{81}Kr investigations on ten deep groundwater samples (including 1 from Germany) from different hydrostratigraphic units of the AAFB imply a differentiated picture of the groundwater residence times. Exceptionally high ^{81}Kr-model-ages of deep Malmian thermal groundwater samples (around 500,000 years) would suggest extremely low velocities (incl. the cross-formation flow) which contradict the existing hydrogeological model concepts of a dynamic thermal water flow in the Malmian reservoir. Samples from younger strata (Oligocene) exhibit the youngest ^{81}Kr- model-ages (< 25,000-240,000 years; Heidinger et al., 2019; Groß et al., 2022).

The discrepancy between the derived ^{81}Kr-model-ages of the deep Malmian thermal groundwaters is difficult to reconcile with the most recent numeric thermal-water model based on a recharge area “Tertiäres Hügelland” (SE of Regensburg) only 100 km northwest of the main users (Expertengruppe, 2024).

Possible explanations include diffusion processes in contact areas between the aquifers with the aquicludes or mixing with ^{81}Kr-free Cenozoic formation waters and the presence of hydrocarbons within the aquifer that could influence the ^{81}Kr-model-ages.

The very old age of the dominating thermal Na-HCO_3-water component is supported by $^{3}He/^{4}He$-ratios and ^{4}He-contents saturated with a purely crustal helium-ratio and content. The exchange of the Malmian thermal water with its aquifers during this pathway is shown by radiogenic $^{87}Sr/^{86}Sr$ ratios (0.7098-0.7108) and elevated F, Li and Rb concentrations.

References

Groß, D., Götzl, G., Kriegl, C., Heidinger, M., Kralik, M., Sachsenhofer, R.F., Goldbrunner, J., Hartl, I., Pytlak, L., Gusterhuber, J., Fölserl, V. and Irrgeher, J. (2022): Research Project

Atmospheric imprinting and coinciding metamorphic drivers of stable water isotope evolution in Alpine seasonal snow

Jasper Lammers[1,2], Martin Masten[1], Thomas Wagner[1], Simon Seelig[1], Wolfgang Schöner[2], Gerfried Winker[1]

[1] Department of Earth Sciences, University of Graz, Heinrichstraße 26, Graz

[2] Department of Geography and Regional Science, University of Graz, Heinrichstraße 36, Graz

Correspondence to: jasper.lammers@uni-graz.at

Seasonal Alpine snowpacks are critical freshwater reservoirs, regulating river discharge, groundwater recharge, and downstream water supply. Stable water isotopes ($\delta^{18}O$, $\delta^{2}H$) and deuterium excess (dxs) trace hydrometeorological processes and snowpack dynamics, yet the atmospheric controls establishing meteoric isotopic signals and the processes altering them after deposition remain poorly constrained in Alpine field settings.

Weekly high-resolution isotope profiles were sampled from three snowpacks in an Austrian Alps cirque at 1500, 1600 and 1700 m a.s.l. Atmospheric conditions at the field site and moisture origin were characterised using HYSPLIT and ERA5. Individual snow layers were tracked using Dynamic Time Warping, and multi-linear regression identified drivers of temporal isotopic change.

Established $\delta^{18}O$ and $\delta^{2}H$ correlate strongly with cloud temperature and cloud top pressure, reflecting Rayleigh fractionation during condensation. Deuterium excess correlates with relative humidity at the moisture source, consistent with the Craig-Gordon framework — confirming its non-local origin.

The vertical isotopic gradient is the strongest predictor of temporal isotopic change, consistent with diffusive homogenisation between adjacent layers. The temperature gradient significantly co-drives $\Delta\delta^{18}O$ and Δdxs, whilst its effect on $\Delta\delta^{2}H$ remains insignificant. The temperature gradient induces preferential $\delta^{18}O$

displacement towards colder layers rather than the classically assumed δ^2H — contrary to conventional non-equilibrium fractionation expectations.

Diffusive homogenisation and temperature gradient heterogenisation coincide during the snow season. Constraining the depth at which isotopic records transition from active modification to preservation has direct implications for the interpretation of cryoclimatological archives.

Indikatoren zur Identifikation von Denitrifikation im Grundwasser

Ralph Benko[1)], Rainer Siedler[1,2)], Clemens Karwautz[2)], Christian Griebler[2)], Grit Rasch[2)], Christine Stumpp[1)]

[1)]: Institut für Bodenphysik und landeskulturelle Wasserwirtschaft, Universität für Bodenkultur Wien, Muthgasse 18, 1190 Wien

[2)]: Department für Funktionelle und Evolutionäre Ökologie, Universität Wien, Djerassiplatz 1 (UBB), 3rd floor, 1030 Wien

Correspondence to: ralph.benco@boku.ac.at

Grundwasser ist eine der wichtigsten Trink- und Nutzwasserressourcen, doch häufig von Nitrateinträgen in seiner Qualität gefährdet. Im Grundwasser wird Nitrat umgewandelt, wobei die Denitrifikation räumlich und zeitlich variiert. Bisher fehlen aber einfache, robuste und aussagekräftige Methoden, um diese Dynamik zu erfassen und Denitrifikation besser nachzuweisen. Ziel dieser Studie ist es, mit einem integrierten geochemischen, isotopenhydrologischen und molekularbiologischen Ansatz die zeitliche und räumliche Dynamik des reaktiven Transports sowie die Herkunft von Nitrat in Grundwasserkörpern zu erfassen.

Als Untersuchungsgebiet wurde der Donauschotter-Aquifer in und um Wien gewählt. An zehn ausgewählten Brunnen in urbanen, landwirtschaftlichen und Naturschutzgebieten wurden monatliche Proben erhoben und auf folgende Parameter analysiert: Isotope (δ^2H-H_2O, $\delta^{18}O$-H_2O & $\delta^{15}N$-NO_3^-, $\delta^{18}O$-NO_3^-), Kationen und Anionen, gelöste Gase und mikrobiologische und molekularbiologische Daten (ATP-Gehalt, TCC, DOM, 16s-Sequenzierung).

Vorläufige Ergebnisse einer mehrmonatigen Grundwasser Beprobung zeigen, dass die Nitratkonzentrationen in den Herbst-/Wintermonaten weitgehend konstant sind, jedoch eine ausgeprägte räumliche Spannweite von <1 bis >350 mg/L aufweisen. An Standorten mit gelöstem Sauerstoff <1 mg/L und einem Oxidations-Reduktions-Potenzial (ORP) <220 mV beobachteten wir erhöhte $\delta^{15}N$-NO_3^- – Werte und eher geringere Nitratkonzentrationen (<12 mg/l), sodass hier Düngemittel und Abwasser die hauptsächlichen Nitratquellen sind und Denitrifikation stattfindet. An Standorten mit erhöhten Konzentrationen (>78 mg/l) stammt das Nitrat entweder aus Mineraldünger oder aus organischem

Bodenstickstoff; an diesen Standorten ist das ORP >180 mV. Die Erkenntnisse basieren bislang auf vier Probenahmen und werden im Rahmen einer laufenden Jahreskampagne validiert. Durch die Kopplung mit molekularbiologischen Daten erwarten wir eine belastbare Trennung von Quellen und Prozessen sowie Einblicke in die mikrobiellen Mechanismen des Nitratumsatzes und beteiligten Organismen.

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Session 10

Ingenieurgeologie und Naturgefahren

Engineering Geology and Natural Hazards

Conveners:
Markus Kasper, Klaus Voit, Gert Furtmüller
& Christian Zangerl

NAWI Graz Natural Sciences

TU Graz

UNI GRAZ

Engineering geological characterisation of a rock slope affected by permafrost thawing and glacier retreat (Schaufelspitze, Tyrol)

Caroline Beindl[1], Hannah Andlinger[2], Christine Fey[2], Christian Zangerl[2]

[1] Department of Geology, University of Vienna, Josef-Holaubek-Platz 2, 1090 Vienna

[2] Institute of Applied Geology, Department of Landscape, Water and Infrastructure, BOKU University, Peter-Jordan-Straße 82, 1190 Vienna

Correspondence to: caroline.johanna.beindl@univie.ac.at

This study represents the analysis of the geological structure of the Schaufelspitze (3332 m a.s.l.) located in the high alpine, periglacial environment of the central Stubai Alps (Tyrol, Austria). The rocks composing the Schaufelspitze are part of the Ötztal-Stubai Crystalline Complex and mainly comprise gneiss, mica schist and amphibolite. By integrating structural and engineering geology the structural control on slope instability hazards is investigated, trying to understand and mitigate the risk to surrounding infrastructure.

Firstly, a detailed field survey is conducted in order to generate a detailed geological map of the study area. Thin sections of the rock samples are analyzed petrographically under the microscope to classify the different lithologies. XRD is used to further analyze mineralogical compositions. Moreover, characteristical parameters of brittle discontinuities controlling the rock mass are collected and classified to identify its structural inventory. Additionally, ductile deformations are recorded to reveal the deformation history of the rock mass and assess their control on the potential failure mechanisms.

Secondly, past, recent and ongoing landslides are mapped to investigate the activity and frequency of failure mechanisms in the rock mass. Apart from structural controls, the ongoing decrease of permafrost and glacier retreat are driving forces for instability within the study site.

Finally, the software ShapeMetriX is used to obtain discontinuity data from non-accessible parts of the study site. By combining the collected field and software data to produce geological cross sections of the area, a geological model is generated.

Preliminary results reveal multiple joint and fault sets with a dominant steeply dipping N-S striking joint set in combination with relatively uniform N dipping foliation and mostly N-S striking faults. Intense folding, refolding and shear zones indicate ductile deformation. The favorable structural conditions for instability seem to be produced dominantly by the brittle and secondarily by the ductile deformation component. Therefore, rock fall, toppling and rock sliding can be identified as the most commonly occurring failure mechanisms.

Ingenieurgeologische Analyse und Sanierung der Felsgleitung an der B33 bei Aggsbach/ Wachau

Martin Müllegger[1], Jonas Weil[2], Dinis Joao[1], Bernd Rösler[1], Fabian Auer[1]

[1] iC consulenten ZT GesmbH, Zollhausweg 1, 5101 Bergheim
[2] iC consulenten ZT GesmbH, Schönbrunner Straße 297, 1120 Wien

Correspondence to: m.muellegger@ic-group.org

Am 3. Juni 2024 ereignete sich an der B33 bei Aggsbach-Dorf in der Wachau eine Felsgleitung mit einem Volumen von rund 3.600 m³ bei dem die B33 komplett und der Radweg teilweise verschüttet wurde. Es wurden keine Personen verletzt und ein größeres Unglück konnte verhindert werden. Nach einer ersten Absicherung der Abbruchkante wurden geologische und geotechnische Untersuchungen und eine detaillierte ingenieurgeologische Kartierung durchgeführt: Mithilfe von ALS (airborne laser scans) und photogrammetrischen Drohnenbefliegungen wurden Trennflächen vermessen, im Gelände mit Farbspray markiert und in einem 3-D-Modell lagerichtig verortet. Die kartierten Flächen wurden im Modell extrapoliert, verschnitten, und im Gelände felsmechanisch untersucht. Der Zustand der Felswand unmittelbar vor dem Sturzereignis, bzw. im Moment des Versagens konnte so rückgerechnet werden, was Rückschlüsse auf die Ursachen der Felsgleitung zuließ. Ursache für das Ereignis war der geometrisch ungünstige Verschnitt mehrerer offener Großtrennflächen im Gföhler Gneis mit hoher Ausbisslänge in Kombination mit dem steilen Hang. Der Gföhler Gneis ist feinkörnig und sehr hart, aber auch aufgrund der nahe gelegenen “Diendorfer Störung” tektonisch stark zerlegt und tiefgründig verwittert. Die für das Ereignis maßgeblichen Trennflächenorientierungen bilden exakt die tektonischen Spannungsverhältnisse im Bereich der Diendorfer Störung ab. Ein erhöhter Wasserdruck in den offenen Klüften nach Starkregen Ende Mai 2024 hat schlussendlich als Auslöser für das Abgleiten des keilförmigen Felskörpers fungiert. Die Kenntnis über Ursachen und Auslöser der Felsgleitung erlaubte die genaue Beurteilung der Standsicherheit der verbliebenen Felswand und bildete die Grundlage für die Planung adäquater Sicherungs- und Schutzmaßnahmen: Labile Lockermaterialmassen die im oberen Hangbereich in Form einer extrem labilen Blockhalde liegen geblieben waren, wurden mit einem Schreitbagger

abgeräumt, ein großer Einzelblock in der Halde kontrolliert abgesprengt und die verbliebenen Felskeile mittels vorgespannter Anker dauerhaft gesichert. Im unteren Teil des Hangs wurden Steinschlagschutzzäune errichtet. Die Sanierung der Gefahrenstelle war kompliziert, gefährlich und aufwändig, Arbeitssicherheit hatte höchste Priorität. Nach einer mehrmonatigen Sperre konnte die Straße im Frühjahr 2025 wieder für den Verkehr frei gegeben werden.

Struktur und Dynamik tiefgründiger gravitativer Hangdeformationen bei Partschins, Südtirol

Matthias Steinkasserer[1], Hannah Pomella[1], Martin Rutzinger[1], Daniel Costantini[2], Ulrich Burger[3], Volkmar Mair[4]

[1] Universität Innsbruck, Innrain 52, 6020 Innsbruck
[2] Amt für Geologie und Baustoffprüfung, Eggentaler Straße 48, 39053 Kardaun (IT)
[3] BBT SE, Amraser Straße, 8, 6020 Innsbruck
[4] Amt für Geologie und Baustoffprüfung, Eggentaler Straße 48, 39053 Kardaun (IT)

Correspondence to: matthias.steinkasserer@student.uibk.ac.at

Deep-Seated Gravitational Slope Deformations (DSGSDs) pose a persistent hazard to settlements and infrastructure in the Alps because they deform large slope sectors and may generate secondary processes such as rockfalls and landslides. A DSGSD on the south-facing slope above Partschins (South Tyrol, Italy) has long been recognised but had not previously been investigated systematically. This study presents its first multi-method characterisation based on geomorphological and structural geological field mapping, hydrological observations, and DInSAR analysis using Sentinel-1A data from 2018 to 2023.

The active slope deformation covers approximately 3 km², has a longitudinal extent of 2.6 km, and comprises an estimated volume of 0.9 km³. Its morphology is characterised by double ridges, tension cracks, uphill-facing scarps, and pronounced slope steps. A typical toe bulge is absent, presumably due to continuous fluvial erosion along the Töllgraben. The movement is interpreted as combined translational and rotational sliding along polygonal failure zones controlled by the local discontinuity network, locally superimposed by toppling, flow, and fall processes. Based on morphological and structural evidence, the slope was subdivided into six blocks moving predominantly towards the SE to SSE.

The deformation kinematics are primarily controlled by the tectonic inheritance of the Texel Unit, while glacial overprinting and post-glacial unloading are considered key factors in the development of slope instability. DInSAR results

show spatially variable displacement rates of up to 25 mm/year, confirming very slow but ongoing deformation. Comparison with the neighbouring DSGSD of Algund highlights the importance of local structural and fluvial controls. The results provide a basis for targeted subsurface investigations, long-term monitoring, and future hazard assessment.

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Session 11

Quantifizierung geologischer Informationen für die Ingenieurpraxis

Quantifying geological information for engineering practice

Conveners:
Helmut Wannenmacher & Paul Unterlaß

NAWI Graz Natural Sciences

TU Graz UNI GRAZ

Geomechanische Charakterisierung von Störungszonen im Tunnelbau

Manuel Entfellner[1], Robert Holzer[2]
[1] Implenia Österreich GmbH, Innsbrucker Bundesstraße 67, 5020 Salzburg
[2] Geoconsult Wien ZT GmbH, Hütteldorferstraße 85, 1150 Wien

Correspondence to: manuel.entfellner@implenia.com

Die Trasse des Semmering-Basistunnels durchörtert eine Vielzahl geologisch-geotechnischer Störungszonen, deren ausgeprägte Heterogenität eine Charakterisierung erheblich erschwert. Die im Zuge der Erkundungsphase abgeteuften vertikalen Bohrungen ermöglichten lediglich eine grobe Erfassung und Quantifizierung dieser Strukturen. Während des Tunnelvortriebs war daher der Einsatz der Beobachtungsmethode zwingend erforderlich. Die täglichen geologischen Aufnahmen der Ortsbrust wurden systematisch in geomechanische Parameter überführt, um eine belastbare Kurzzeitprognose der anstehenden Gebirgsverhältnisse zu ermöglichen und den Vortrieb und Ausbau bestmöglich zu optimieren.

Die komplexe interne Struktur der Störungszonen führte zu grundlegenden Fragestellungen: Welche Kennwerte definieren eine Störungszone? Wie können diese Kennwerte zuverlässig ermittelt werden? Die Gewinnung ungestörter Proben mittels Kernbohrungen erwies sich als besonders problematisch, da stark zerrüttete Bereiche kaum intakt beprobt werden können. Ergänzend wurden daher alternative Bohrmethoden sowie geophysikalische Verfahren eingesetzt, um interne Homogenbereiche zu identifizieren und die geomechanische Charakterisierung zu verfeinern.

Nach der geologischen Charakterisierung müssen die erhobenen Kennwerte in bautechnisch relevante Parameter überführt werden. Die Festlegung der Gebirgskennwerte stellt dabei einen kritischen Schritt dar, da selbst geringe Variationen erhebliche Auswirkungen auf die Bemessung des Tunnelausbaus haben.

Ein zentrales Element des Beitrags ist die enge interdisziplinäre Zusammenarbeit zwischen Geotechnik und Ingenieurgeologie. Die gemeinsame Analyse, Interpretation und Überführung der Daten durch einen Geotechniker und einen Ingenieurgeologen ermöglichte eine konsistente Bewertung der Störungszonen und eine robuste Ableitung der bautechnischen Maßnahmen. Der Vortrag wird daher bewusst gemeinsam gehalten, um die Bedeutung dieses integrativen Ansatzes zu unterstreichen und anhand ausgewählter Fallbeispiele aus dem Semmering-Basistunnel zu demonstrieren.

Gesteins- und Gebirgseigenschaften von Phylliten und Glimmerschiefern – Quantifizierung im Spannungsfeld von Normen, Regelwerken und Erfahrungspraxis

Maria Honisch[1], Gerhard Poscher[2]

[1] Universität Innsbruck, Institut für Infrastruktur, Technikerstraße 13, A-6020 Innsbruck

[2] ZT-Büro für Geologie, Neunergasse 2, A-6403 Flaurling

Correspondence to: gerhard.poscher@geo-zt.at

In den letzten Jahrzehnten wurde ein auf wissenschaftlichen Grundlagen fußendes Regelwerk zur Quantifizierung der physikalischen Gesteinseigenschaften anisotroper Gesteine erarbeitet, das national und international in der Planung und Bauausführung Anwendung findet. Die Kalkulation von Vortriebs- und Bohrleistungen, von Verschleiß und Sprengstoffverbrauch setzt auf diesen Grundlagen auf, wobei dafür auch quantitative Angaben zu den grundlegenden geologischen Parametern und Gebirgseigenschaften wie beispielsweise zum Schieferungs- und Trennflächenabstand erforderlich sind.

Diesbezüglich bietet das Normen- und Regelwerk als auch die Fachliteratur sowie die Projektierungspraxis ein Spektrum an Begriffen und Definitionen von der „integralen Trennfläche“ über die „mechanisch wirksame Schieferungsfläche“ bis hin zur „effektiven Trennfläche“, was unterschiedliche fachliche Auffassungen begünstigt.

Die grundlegende Problematik, das Trennflächengefüge und die Trennflächeneigenschaften für eine Gebirgsart insitu zu erfassen, stellt sich bei Phylliten und Glimmerschiefern in besonderer Weise dar, da die Frage, ob und in welchem Maße die Schieferung eine Trennfläche darstellt von zentraler Bedeutung ist.

Für die Prognose ist zu berücksichtigen, dass selbst direkte Aufschlüsse je nach Bohrverfahren und Bohrtechnik eine Überprägung des Gebirges bedingen und auch natürliche Aufschlüsse kein „unverritztes Gebirge“ darstellen. Die

Dokumentation und Quantifizierung des Trennflächengefüges und der Trennflächeneigenschaften unter Berücksichtigung der Schieferung für die Ermittlung der Gebirgsarten erfordert daher ein differenziertes Herangehen. Hinzuweisen ist, dass zudem zahlreiche Indexwerte zur Felsklassifikation im Tunnelbau unmittelbar auf den Trennflächenparametern aufsetzen.

Im Zuge der baugeologischen Dokumentation bei Tunnelvortrieben oder an Böschungen und Einschnitten wird ein bautechnisch überprägtes Gebirge dokumentiert. Dabei liegt die Herausforderung in der Differenzierung von primär vorhandenen (insitu) Trennflächen und von Schieferungsflächen, die im Zuge der Gebirgslösung als Trennflächen aktiviert wurden. Die Problematik besteht dabei im Soll-Ist-Vergleich der Gebirgsarten zwischen Prognose und Bauausführung, soferne Trennflächen- und Schieferungsparameter als Schlüssel- bzw. Identifikationsparameter festgelegt wurden.

Einmeldeportal Geodaten – Geodata Registration Portal for Reporting Geological and Geophysical Exploration and Data Collection Work in Accordance with the GeoSphere Austria Act

Gerlinde Posch-Trözmüller[1)], Eva-Maria Ranftl[1)], Thomas Fuhrmann[1)], Robert Supper[1)], Martin Schiegl[1)]

[1)] GeoSphere Austria, Division of Geophysics and Applied Geological Services Neulinggasse 38, 1030 Wien

Correspondence to: gerlinde.posch-troezmueller@geosphere.at

The GeoSphere Austria Act (GSAG) has been in force since January 1, 2023. Since then, GeoSphere Austria, as the responsible federal agency, must be notified of the execution of exploration and data collection work throughout Austria (§11 GSAG). For this purpose, the Geodata Registration Portal was designed, which can be accessed via the GeoSphere Austria website and became operational in 2025. Link: https://www.geosphere.at/de/daten/datenzentrum/einmeldeportal-geodaten

The rationale for legally enshrining the reporting requirement lies in the central importance of high-quality geoscientific information and knowledge about the subsurface, which enables more precise planning in applied fields. Examples from neighbouring countries, particularly Bavaria, served as models for the geodata registration portal.

The notification obligation for exploration and data collection work applies not only to drilling and large-scale excavations, but also to geophysical measurements and the establishment of monitoring stations and networks for natural hazard observation. Geological drilling and excavation work must be reported at least 14 days in advance if drilling depths exceed 50 meters or excavation depths exceed 25 meters. In all other cases, a notification period of three days in advance is required.

Upon receipt of a notification, it will be reviewed by GeoSphere staff, who may then request further technical or assessment data. Technical data (information obtained during investigations, such as geological borehole profiles) submitted to GeoSphere Austria will be made publicly available on the GeoSphere Austria website in compliance with legal and agreed-upon confidentiality periods and without identifying individuals.

The geodata registration portal was set up using ESRI';s ArcGIS Survey123 software. At this moment an initial version with a deliberately simple and user-friendly input interface is online. Submitted information is transferred to a metadata management database located on an in-house database server.

Currently, work is underway on a data management system that will enable the automated import of data in various common data formats, as well as simplified management of metadata, subject-specific and evaluation data, research materials (e.g., photos), and legal agreements. Furthermore, this software will allow subject-specific data to be made available to different user groups in various categories, depending on legal requirements.

Quantifying Geological Information from TBM Operational Data Using Machine Learning-Based Anomaly Detection

Paul Unterlaß[1)], Mario Wölflingseder[1)], Thomas Marcher[1)]

[1)]Institute of Rock Mechanics and Tunnelling, Graz University of Technology, Rechbauerstraße 12 8010 Graz

Correspondence to: unterlass@tugraz.at

The increasing availability of high-resolution Tunnel Boring Machine (TBM) operational data offers new opportunities to transform excavation process information into engineering-relevant geological knowledge. Continuous monitoring of machine parameters provides indirect observations of ground behaviour, enabling the identification of geological anomalies that may affect excavation performance and project risk. This study presents a framework for quantifying geological information from TBM operational data through data-driven anomaly detection.

Four anomaly detection approaches were evaluated on hard rock TBM datasets from two underground infrastructure projects: Vector Auto Regression (VAR), K-MEANS clustering, Isolation Forest, and Variational Autoencoders (VAEs). The methods were applied to multivariate time-series data comprising excavation parameters such as thrust force, cutterhead torque, penetration rate, and derived performance indicators. Detected anomalies were compared against mapped fault zones and geological classifications to assess their capability to identify engineering-geologically relevant ground conditions.

The results demonstrate that machine learning approaches outperform conventional statistical forecasting methods in recognizing deviations associated with changing rock mass conditions. Isolation Forest and VAE models achieved the highest detection performance, with area-under-curve (AUC) values reaching 0.99. In particular, the VAE approach effectively captured complex non-linear relationships within the operational data and successfully identified collective anomalies related to faulted and disturbed ground. A data-driven thresholding

strategy based on skewness-adjusted reconstruction error distributions enabled robust application across different projects without extensive manual calibration.

To address the common challenge of data confidentiality in underground construction, synthetic TBM datasets were additionally employed for model pre-training. The results indicate that VAEs trained on synthetic data retain strong anomaly detection capabilities when transferred to real projects, enabling deployment from the onset of excavation before sufficient site-specific data become available.

The presented framework demonstrates how large TBM operational datasets can be translated into quantitative geological information for engineering practice.

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Session 12

Modellbasierte Ingenieurgeologie und Georisiken

Model-Based Engineering Geology and Geohazards

Conveners:
Franz Tschuchnigg & Barbara Schneider-Muntau

NAWI Graz Natural Sciences

TU Graz

UNI GRAZ

Segmentierung des Steinschlagrisikos für lineare Infrastrukturen auf Basis von Daten aus verschiedenen Quellen und GIS-gestützter Verarbeitung.

Edith Grießer[1], Qian Liu[1]
[1] TU Graz, Rechbauerstraße 12, 8010 Graz

Correspondence to: edith.griesser@student.tugraz.at

Steinschlaganalysen im Kontext ingenieursgeologischer Untersuchungen erfordern, zusätzlich zu einer klassischen, rein geomorphologischen Betrachtung eine detaillierte Analyse der potenziellen Auswirkungen auf bestehende Infrastruktur. Im Fall linienförmiger Infrastrukturelemente, etwa einer Straße, variiert die Exposition gegenüber der Gefahrenquelle entlang ihres Verlaufs, weshalb Bereiche mit erhöhter Ereignisfrequenz nicht zwingend eine erhöhte Gefahr für Verkehrsteilnehmer*innen darstellen. Um knappe finanzielle Mittel zielgerichtet für die Errichtung von wirksamen Schutzmaßnahmen einsetzen zu können, ist eine detaillierte Untersuchung besonders steinschlaggefährdeter Bereiche unter Berücksichtigung aller relevanten Parameter notwendig.

Auf internationaler Ebene wird zur Eingrenzung besonders steinschlaggefährdeter Straßenabschnitte häufig eine getrennte Betrachtung der Eintrittswahrscheinlichkeit von Steinschlagereignissen (Gefährdung) und der Wahrscheinlichkeit, dass ein gelöster Block die Straße beziehungsweise Verkehrsteilnehmer*innen erreicht (Konsequenzen) herangezogen. Aus der Kombination dieser Parameter kann die Gefährdung einzelner Straßenabschnitte abgeleitet werden. Derartige Analysen über mehrere Kilometer lange alpine Straßenabschnitte stellen eine große Herausforderung dar.

Hier wird ein System zur Bewertung der Gefährdung von Gebirgsstraßen durch Steinschlag vorgestellt. Durch die Bearbeitung öffentlich zugänglicher Fernerkundungsdaten, insbesondere digitaler Gelände- und Oberflächenmodelle sowie Orthofotos mehrerer Befliegungsperioden, werden Schlüsselparameter analysiert. So wird eine effiziente Bewertung auch über längere Straßenabschnitte möglich.

Angewendet wurde die Methode auf einen etwa 10 Kilometer langen Abschnitt der obersteirischen B146 Gesäuse Bundesstraße. Zunächst wurde das Untersuchungsgebiet anhand historischer, geologischer und morphologischer Daten sowie der Exposition der Straße in drei unterschiedliche Gefahrenbereiche gegliedert. Schlüsselparameter in Bezug auf Steinschlaggefährdung und Konsequenzen werden schließlich anhand von Fernerkundungsdaten sowie einer vorausgehenden Geländeuntersuchung bewertet. Parameter, die nicht oder unzureichend aus der digitalen Datenanalyse hervorgehen (etwa Verwitterungsgrad und Gebirgsfestigkeit) werden im Gelände erhoben. Die vorgestellte Methodik ermöglicht die Identifikation besonders gefährlicher Straßenabschnitte.

„New Horizons in Geosciences and Geotechnics“

Session 15

Lehrer:innenseminar „Geology4School“

Conveners:
Bernhard Hubmann, Kurt Krenn & Pamina Loretto

NAWI Graz
Natural Sciences

Naturgefahren verstehen: Hangrutschungen in der Steiermark als Brücke zwischen Forschung, Lehre und Schule

Christian Bauer[1)]

[1)] **Institut für Geographie und Raumforschung**

Correspondence to: christian.bauer@uni-graz.at

Hangrutschungen zählen zu den folgenreichsten Naturgefahren der Steiermark. Besonders im Dauersiedlungsraum des Steirischen Beckens treffen gefährdete Hangbereiche unmittelbar auf Siedlungs- und Infrastrukturflächen. Jüngste Schadensereignisse verdeutlichen diese Verwundbarkeit und unterstreichen die gesellschaftliche Relevanz einer vertieften Auseinandersetzung mit dem Thema.

Die geologische Grunddisposition in der Steiermark ist aufgrund stark variierender geotechnischer Eigenschaften räumlich heterogen. Obwohl Rutschungen in allen geologischen Großeinheiten auftreten, konzentrieren sie sich vor allem auf neogene Sedimente des Steirischen Beckens sowie auf niedrigmetamorphe, tonreiche Gesteine und deren Verwitterungsprodukte. Im Kontext des Klimawandels ist von einer zunehmenden Bedeutung von Hangrutschungen auszugehen. Intensivere Starkregenereignisse könnten Frequenz und Magnitude von Massenbewegungen erhöhen. Belastbare statistische Nachweise stehen noch aus, doch erste Beobachtungen und Modellierungen weisen auf diesen Zusammenhang deutlich hin.

Aktuelle Forschungsarbeiten betrachten Hangrutschungen verstärkt als Naturgefahr und gehen über statische Gefahrenzonenpläne hinaus: Moderne Ansätze integrieren dynamische Einflussfaktoren, insbesondere Niederschlagsereignisse, in probabilistische und prozessbasierte Naturgefahrenmodelle. Diese Entwicklungen bilden den wissenschaftlichen Rahmen, in dem regionale Studien und Bildungsansätze verortet werden. In der universitären Lehre wird das Thema forschungsgeleitet vermittelt: Geländeübungen, GIS-basierte Fallstudien und projektorientierte Formate ermöglichen Studierenden, wissenschaftliche Methoden mit realen Problemstellungen zu verknüpfen.

Der Beitrag zeigt, wie sich Hangrutschungen als Systemphänomen auch im Bildungsprozess aufbereiten lassen. Über Bezüge zu Naturgefahren, Klimawandel und Raumplanung können geologische und geomorphologische Konzepte lebensweltlich vermittelt werden. Vorgestellt werden aktuelle Entwicklungen der Naturgefahrenforschung und deren mögliche Einbindung in den Bildungsprozess: Kartenanalysen, regionale Fallstudien aus der Raumplanung und vereinfachte Modellansätze sowie deren Potenzial für einen praxisorientierten Unterricht. Ziel ist es, Brücken zwischen Forschung, universitärer Lehre und schulischer Praxis zu schlagen.

Vom Ton zum Scherben – Geogene Rohstoffe mit pädagogischem Potenzial im schulischen Kontext

Gernot Eder-Hoffmann[1)]
[1)] Universität Graz, Heinrichstraße 26, 8010 Graz

Correspondence to: g.eder.graz@gmail.com

Im schulischen Kontext ermöglicht keramisches Arbeiten vielfältige Potenziale für erlebnisorientiertes Lernen, fächerübergreifende Lernerfahrungen und bleibende Erinnerungen. Dabei geht es um nichts Geringeres als etwas Besonderes zu schaffen und etwas auf dem Weg dorthin zu erleben. Fragen zu stellen, Pläne zu schmieden, auszuprobieren, womöglich zu scheitern, zu adjustieren und erneut zu probieren. Zu forschen! Und zwar gemeinsam, in einem Projekt, das Schüler*innen und Lehrpersonen möglicherweise noch lange in guter Erinnerung bleibt.

Die Vorgaben sind denkbar einfach: Ausgangspunkt ist die Gewinnung der Rohstoffe in der unmittelbaren Natur der eigenen Umgebung, womit nahezu automatisch ein tieferes Bewusstsein für die Herkunft alltäglicher Rohstoffe aufkommt. Dem folgt die Aufbereitung der heimgebrachten Materialien durch diverse Reinigungsprozesse um daraus einen formbaren Werkstoff zu gewinnen, der sich schlussendlich künstlerisch gestalten und brennen lässt.

Im Zuge einer Masterarbeit wurde im vergangenen Jahr keramisches Arbeiten im schulischen Kontext mit Schülerinnen und Schülern einer Mittelschule in der Oststeiermark von der Rohstoffgewinnung im Nahbereich der Schule bis hin zur Herstellung von Gefäßen im Werkunterricht durchgeführt. Die manuellen Arbeiten wurden dabei integrativ durch begleitende Informationen (grundlegende chemische und geologische Kenntnisse, Einblicke in kulturhistorische Themen und lokale Geschichte sowie ökologische Zusammenhänge) ergänzt.

Das neue Lehramtscurriculum für Biologie und Umweltbildung und die Erdwissenschaften. Die Grazer Perspektive

Bernhard Hubmann[1], Kurt Krenn[1], Pamina Loretto[2]

[1] Institut für Erdwissenschaften, NAWI Graz Geozentrum, Universität Graz, Heinrichstrasse 26, 8010 Graz
[2] BG/BRG/BORG Graz-Liebenau, Kadettengasse 19, 8041 Graz

Correspondence to: bernhard.hubmann@uni-graz.at

Im Zeitfenster vom 2. März - 13. Mai 2026 konnte man sich für die neuen Lehramtsstudien Sekundarstufe Allgemeinbildung an der Grazer Universität anmelden, ein Nebentermin war Anfang Juli 2026. Anzumerken ist, dass zur Überprüfung der studien- und berufsbezogenen Eignung die Studienwerber:innen ein Aufnahme- und Eignungsfeststellungsverfahren bis zum 24. August 2026 durchlaufen mussten. In diesem Kontext bemerkenswert spät, angekündigt für den 29. Juni 2026 – „vorbehaltlich Genehmigung durch die entsprechenden Gremien der Bildungseinrichtungen – wurde eine zweistündige Online-Information zur Vorstellung der neuen Curricula für Lehramt Sek AB avisiert.

Erstinskribierende hatten also drei Monate vor Beginn ihres Studiums nur basale Kenntnis vom „Lehramt neu“: ab dem 1.10.2026 wird das Bachelorstudium einheitlich 6 Semester (180 ECTS) dauern, dem ein 4-semestriges Masterstudium (120 ECTS) folgt. Die Gesamtdauer des neuen Studiums sinkt somit gegenüber dem vorherigen auf 5 Jahre (300 ECTS).

Im Vergleich zum vorangegangenen Curriculum ist der neue Bachelorgang um 60 EC-Punkte weniger ausgestattet. Diese Tatsache macht nicht nur den Weg ins Klassenzimmer um ein ganzes Jahr schneller, wie das Bundesministerium für Bildung festhält, sondern hat auch eine entsprechend geringere fachliche Ausbildungsbreite zur Folge. Zudem erhält der Bachelor, mit dem man bereits unterrichten darf, zusätzlich höhere Praxisanteile und die Schwerpunkte Inklusion and Deutsch als Zweitsprache (DaZ) in allen Fächern.

Nach EC-Punkten ist der Master, der innerhalb von fünf Jahren nach dem Bachelorabschluss absolviert werden muss um in ein unbefristetes Dienstverhältnis eintreten zu können, gleichgeblieben. Inhaltlich mussten aber die fehlenden Fachstunden durch die Kürzung des Bachelors – zumindest teilweise – im Master aufgefangen werden.

Für das Lehramtsstudium des Schulfachs Biologie und Umweltbildung in Graz bedeutet dies, dass die Erdwissenschaften zukünftig nur mit je einer einzigen Lehrveranstaltung im Bachelor und im Master vertreten sein werden. Im Bachelor können die bislang von Studierenden sehr positiv evaluierten Geländelehrveranstaltungen nicht mehr abgehalten werden.

Konkret: Im „Bachelor neu“ wird es eine Lehrveranstaltung (LV) mit 2,5 Wochenstunden (WSt) zu 4 ECTS (statt im „Bachelor alt“ vier LVs zu 5 Wst mit 5 ECTS) und im „Master neu“ eine LV mit 2 Wst zu 3 ECTS (statt „Master alt“ 2,5 LVs mit 2,5 Wst zu 3 ECTS) geben.

GEOsumm - Summende Gesteine der Steiermark

Thomas Kabas[1]
[1] BORG Dreierschützengasse

Correspondence to: t.kabas@borg-graz.at

Im Rahmen des Lehrplans (u.a. in „Biologie und Umweltbildung“ sowie „Geographie und wirtschaftliche Bildung“) setzen sich Jugendliche zwar auch mit erdwissenschaftlichen Fragestellungen auseinander, jedoch fällt den Schüler:innen die Anknüpfung an ihre Lebenswelt zunehmend schwerer, insbesondere im städtischen Umfeld. Gesteine als Zeugen der Vergangenheit wahrzunehmen und unterschiedliche Eigenschaften zwischen verschiedenen Gesteinsformationen auszumachen, erscheint vielen jungen Menschen als etwas sehr Abstraktes. Um dem entgegenzuwirken, entstand die Idee einer praxisorientierten Verknüpfung von ökologischen und geologischen Inhalten. Die Schüler:innen einer 5. Klasse (NAWI-Zweig) zeigten sich dem theoretischen Vorhaben mit Praxiseinheiten sehr offen gegenüber. In einem nächsten Schritt wurde das Umfeld des im vorangehenden Schuljahr angelegten Schulgartens als Umsetzungsort festgelegt. In der Konzeptentwicklung bündelten sich schließlich anfängliche Gedanken hin zur Installation von Insektenhotels, welche zudem geologische Informationen transportieren. Gemäß der grundsätzlichen Idee, dient die Basis als ein Insektenhotel. Im Wesentlichen handelt es sich dabei um einen Turm aus handelsüblichen Thermoziegeln, die teilweise seitlich angebohrt oder mit verschiedenen Materialen aufgefüllt werden. Eine wasserdichte Betonplatte, von den Schüler:innen in „Kunst und Gestaltung“ selbst gegossen, bildet den Abschluss, worauf dann ein größerer Gesteinsbrocken fixiert wird. Das Gestein stellt dabei ein typisches Beispiel aus der Steiermark dar und soll in weiterer Folge auch mit einem Namensschild (z.B. inkl. Fundort und Datum) versehen werden. Für jene drei Exemplare, welche während des Schuljahres 2025/2026 errichtet wurden, umfasst die geologische Auswahl folgende Gesteine: (1) Ein Schöcklkalk aus dem Grazer Bergland (St. Radegund) dient als ein Beispiel für ein Gestein aus dem Paläozoikum, (2) ein Sandstein aus dem weststeirischen Raum (Kainach) steht stellvertretend für Gesteine aus dem Mesozoikum und (3) ein Vulkanit aus der Südoststeiermark (Feldbach) für das Känozoikum. Von gemeinsamen Recherchetätigkeiten im Regelunterricht, bis hin zu den praktischen Einheiten im Laborunterricht, wurden Themen rund um den Gesteinskreislauf, der Bodenbeschaffenheit und -bildung aufgegriffen. Der

unmittelbare physische Kontakt sowie die Verbindung mit Geländeausgängen, unterstützte die Schüler:innen dabei einen Zugang zu den vielfältigen Themengebieten der Erdwissenschaften zu erhalten.

Schritt für Schritt durch die Erdgeschichte - Ein geologischer Treppenspaziergang im Akademischen Gymnasium Graz

Georg Knittelfelder[1)]
[1)] Akademisches Gymnasium Graz, Bürgergasse 15, 8010 Graz

Correspondence to: georg.knittelfelder@akademisches-graz.at

Im Rahmen eines schulischen Vermittlungsprojekts wurde das Stiegenhaus im Akademischen Gymnasium Graz in einen begehbaren Zeitstrahl der Erdgeschichte umgestaltet. Die Treppenstufen repräsentieren dabei Zeitsprünge und ermöglichen einen räumlich erfahrbaren Weg von der Entstehung der Erde bis zur Gegenwart. Beginnend im Erdgeschoß vor rund 4,6 Milliarden Jahren führt der Aufstieg über drei Stockwerke durch die wichtigsten geologischen, biologischen und klimatischen Ereignisse der Erdgeschichte. Fossilien, Gesteinsproben, Grafiken und didaktische Informationen begleiten den „musealen Treppenspaziergang“ und veranschaulichen die unterschiedlichen Erdzeitalter. Das Projekt verbindet geowissenschaftliche Inhalte mit einem innovativen Vermittlungskonzept und macht die Dimension geologischer Zeit für Schülerinnen und Schüler unmittelbar erfahrbar. Es zeigt, wie Räume innerhalb des Schulgebäudes als besondere Lernorte genutzt werden können, um Interesse an den Geowissenschaften zu fördern.

Erdwissenschaften in der Wissenschaftskommunikation am NHM Wien

Agnes Mair[1], Monika Müller[1], Alice Thinschmidt[1], Babette Hengst[1], Marianne Sophie Hollinetz[1]

[1] Naturhistorisches Museum Wien, Burgring 7, 1010 Wien, Österreich

Correspondence to: Monika.Mueller@NHM.AT

Warum ändert sich das Klima auf der Erde? Wann ist das Leben auf unserem Planeten entstanden? Woher kommen die Rohstoffe in unseren Smartphones?

Als Bundesmuseum mit Bildungsauftrag bietet das Naturhistorische Museum Wien ein vielfältiges Vermittlungsprogramm für Schulklassen zu erdwissenschaftlich relevanten Themen. An Alter und Vorkenntnisse angepasste Formate wie Führungen durch die Schausammlung des Museums und umfangreichere Aktionsführungen finden sich unter den Angeboten.

Weiters gibt es die Möglichkeit geowissenschaftliche Themen in halbtägigen Workshops vertiefend zu bearbeiten. Workshops setzen sich aus einer Führung in die Schausammlung in Kombination mit praktischen Modulen zusammen, in denen die Schüler*innen angeleitet sowie auch selbstständig in Kleingruppen arbeiten.

Wir werden diese Angebote kurz präsentieren und vom NHM Wien ausgearbeitete Materialien zum Thema „Klimawandel und Energiewende" vorstellen. Die Materialien werden einerseits im NHM Wien bei Schulprogrammen verwendet, können aber auch unabhängig davon im Unterricht eingesetzt werden. Das aus vielen modular einsetzbaren Elementen bestehende Unterrichtstool ist auf der Website des Museums downloadbar. Es ermöglicht Schüler*innen, Schritt für Schritt verschiedene klimabestimmende Faktoren in ein großes Erdpuzzle einzufügen und dabei Prozesse zu erkennen. Wie der Mensch diese Prozesse beeinflusst, kann über den Einbau zusätzlicher Elemente, wie z.B. Straßen, Gebäude, Konsumgüter, … sichtbar gemacht werden.

Die einladenden, kindgerechten Materialien ermöglichen den Schüler*innen ein tieferes Verständnis des natürlichen Klimasystems, bieten Einblick in den menschlichen Einfluss auf unser Klima und fördern das selbstständige Erarbeiten von Strategien, die auf einen nachhaltigeren Lebensstil abzielen.

An der Schnittstelle zwischen aktueller Wissenschaft und moderner Wissenschaftsvermittlung bieten sich die angebotenen Programme als fachvertiefende Ergänzung, aber auch Einstieg oder Nachbesprechung erdwissenschaftlicher Inhalte für unterschiedliche Altersgruppen an.

Geologie in unserer Zeit: Forschung und Lehre am Schnittpunkt von Rohstoffen und Gesellschaft

Frank Melcher[1)]
[1)] Montanuniversität Leoben

Correspondence to: frank.melcher@unileoben.ac.at

Die Geologie hat sich in den vergangenen Jahrzehnten von einer vorwiegend naturwissenschaftlichen Disziplin zu einem zentralen Bindeglied zwischen Umwelt, Wirtschaft, Politik und Gesellschaft entwickelt. Angesichts der Herausforderungen des Klimawandels, der Energiewende und einer nachhaltigen Rohstoffversorgung kommt geowissenschaftlicher Forschung und Lehre eine besondere Bedeutung zu. Ein wesentlicher Treiber dieser Entwicklung ist der europäische Green Deal. Das Ziel, Europa bis 2050 klimaneutral zu machen, erfordert einen tiefgreifenden Umbau von Energieversorgung, Mobilität und Industrie. Für die „grünen" Technologien werden große Mengen sogenannter kritischer Rohstoffe benötigt. Dazu zählen unter anderem Lithium, Seltene Erden, Kobalt und Graphit. Die Nachfrage nach diesen Rohstoffen steigt weltweit stark an. Geologische Forschung spielt daher eine entscheidende Rolle bei der Erkundung neuer Lagerstätten, der Bewertung von Ressourcen sowie der Entwicklung nachhaltiger Methoden für Abbau und Recycling.

Ein weiteres Beispiel für die gesellschaftliche Relevanz der Geologie ist die Suche nach geeigneten Endlagern für radioaktive Abfälle. Auch in Österreich müssen radioaktive Stoffe über Zeiträume von mehreren hundert Jahren sicher von Mensch und Umwelt isoliert werden. Die wissenschaftliche Bewertung von möglichen Standorten ist jedoch nur ein Teil der Herausforderung. Erfahrungen aus verschiedenen Ländern zeigen, dass Transparenz, Bürgerbeteiligung und nachvollziehbare Entscheidungsprozesse entscheidend sind, um Vertrauen in die Sicherheit von Endlagerprojekten zu schaffen.

Im Burgenland beschäftigt seit Monaten das Vorkommen von gesundheitsschädlichem Asbest in der Umwelt die Öffentlichkeit. Geologische Untersuchungen helfen dabei, Risiken zu bewerten und geeignete Maßnahmen zum Schutz der Bevölkerung zu entwickeln. Das Beispiel zeigt, wie wichtig eine verständliche Kommunikation wissenschaftlicher Erkenntnisse ist, um Unsicherheiten und Ängste in der Bevölkerung zu reduzieren.

Geologie trägt dazu bei, Lösungen für die Herausforderungen der Gegenwart zu entwickeln. Ob bei der Umsetzung des Green Deal, der Sicherung kritischer Rohstoffe, der Endlagerung radioaktiver Abfälle oder dem Umgang mit natürlichen Gefahrenstoffen– geowissenschaftliche Expertise ist unverzichtbar. Die Zukunft der Geologie liegt daher nicht nur im Verständnis der Erde, sondern auch in der aktiven Gestaltung einer nachhaltigen und gesellschaftlich akzeptierten Entwicklung.

Gedankensplitter zu erdwissenschaftlichen Synergien im Bio- und Geo-Unterricht

Florian Mühlbacher[1)]
[1)] BG/BRG/MG Dreihackengasse

Correspondence to: 90280592@bildung.gv.at

Obwohl Biologie und Geographie sowohl an Schulen als auch an Universitäten als strikt getrennte Disziplinen vermittelt werden, bestehen zahlreiche fachliche Überschneidungen. Als AHS-Lehrer mit dieser Fächerkombination beschäftige ich mich insbesondere mit den Synergien im Bereich der Erdwissenschaften.

Der Beitrag beleuchtet ausgewählte Themenfelder an der Schnittstelle beider Fächer und diskutiert deren Potenzial für den Unterricht. Durch die Verknüpfung biologischer und geographischer Perspektiven können Zusammenhänge besser verständlich gemacht, interdisziplinäres Denken gefördert und die isolierte Vermittlung von Faktenwissen reduziert werden.

Anhand ausgewählter Beispiele werden fachliche Berührungspunkte sowie mögliche Unterrichtssettings vorgestellt.

Geothermie: Unerschöpfliche Energie aus der Tiefe

Marcellus Schreilechner[1,2)]
[1)] Geo5 GmbH, Leoben
[2)] Technische Universität Graz, Graz

Correspondence to: marcellus.schreilechner@geo-5.at

Geothermie wird angesichts der Wärmewende und des verstärkten Fokus auf nachhaltige Energiequellen zunehmend wichtiger. Als erneuerbare Energiequelle kann sie einen bedeutsamen Beitrag zur CO_2-Reduktion leisten und die Abhängigkeit von fossilen Brennstoffen verringern. Doch was genau ist Geothermie?

Geothermie, oder Erdwärme, bezeichnet die Wärmeenergie, die unterhalb der Erdoberfläche gespeichert ist. Je tiefer man in die Erde eindringt, desto wärmer wird es. In Mitteleuropa steigt die Temperatur etwa um 3 °C pro 100 Meter Tiefe. Man schätzt, dass die Temperaturen im Erdkern bei etwa 5.000 bis 7.000 °C liegen. Diese in der Erde gespeicherte Wärme gilt als unerschöpflich.

Der Endenergieverbrauch für Wärme und Kälte macht rund die Hälfte des gesamten Endenergieverbrauchs aus und kann durch Geothermie teilweise substituiert werden. Die Geothermie ist damit ein wesentlicher Bestandteil der Energie- und Wärmewende. Sie schont die Landschaft, ist klimafreundlich und gilt nach menschlichem Ermessen als unerschöpflich. Zudem sorgt sie für eine zuverlässige, stabile und sichere Energieversorgung. Geothermie ist immer verfügbar, unabhängig vom Wetter. Mit den bereits bestehenden Technologien kann das Potenzial der Erdwärme fast überall genutzt werden. Durch ihre vielen Anwendungsmöglichkeiten wird die Abhängigkeit von fossilen Energieträgern weiter reduziert und eine hohe Versorgungssicherheit gewährleistet.

Wie steht es um das Interesse von Schülern*innen der Sekundarstufe an Geowissenschaften? Analysen und Herausforderungen, um naturwissenschaftliche Begeisterung zu fördern

Nadine Schriebl[1)]

[1)] Universität Graz, Heinrichstraße 26, 8010 Graz

Correspondence to: nadine.schriebl@hotmail.de

Interesse und Motivation für Geowissenschaften im schulischen Kontext – Ergebnisse einer Schüler*innen-Befragung der Sekundarstufe 1 und 2 im Raum Kärnten und der Steiermark

Die Förderung von Motivation und Interesse gilt als zentrale Voraussetzung für erfolgreiches Lernen. Besonders die Geowissenschaften besitzen aufgrund ihrer gesellschaftlichen Relevanz, wie etwa im Zusammenhang mit Klimawandel, Ressourcenmanagement oder Naturgefahren, ein hohes Bildungspotenzial, sind jedoch im österreichischen Bildungssystem nur eingeschränkt sichtbar. Im Zuge einer laufenden Masterarbeit wird untersucht, welche Faktoren das Interesse von Schüler*innen an geowissenschaftlichen Themen beeinflussen und welche Maßnahmen aus Sicht der Lernenden zur Förderung von Motivation beitragen können.

Die empirische Untersuchung basiert auf einer quantitativen Online-Befragung von Schüler*innen der Sekundarstufe I (n = 1949) und Sekundarstufe II (n = 1686) aus der Steiermark und Kärnten. In der Steiermark und in Kärnten konnten alle Bezirke mit der Befragung abgedeckt werden, sowohl in der Sekundarstufe I als auch (wenn ein Standwort vorhanden ist) in der Sekundarstufe II. Der Fokus lag vor allen auf Allgemeinbildende höhere Schulen, da ein nachfolgendes Studium im Bereich der Geowissenschaften wahrscheinlicher erscheint. Die Online-Umfrage war zwischen dem 22. Mai 2025 und dem 15. Jänner 2026 aktiv. Im Juli, Oktober und Dezember 2025 wurde jeweils ein Zwischenstand erhoben und danach wurden laufend neue und bereits in die Umfrage aufgenommene

Schulen kontaktiert, um möglichst breitflächig in der Steiermark und Kärnten Umfragedaten erheben zu können, die wissenschaftliche Relevanz zeigen.

Bisherige Ergebnisse zeigen, dass praxisnahe und handlungsorientierte Lernformen als besonders motivierend wahrgenommen werden. Vor allem mehr Experimente im Unterricht, Exkursionen sowie anschauliche Vermittlungsformen werden von den Befragten als wichtige Maßnahmen zur Förderung des Interesses an Geowissenschaften genannt. Ebenso wird der Wunsch nach mehr Informationen zu Berufsfeldern und Zukunftsaussichten im geowissenschaftlichen Bereich deutlich. Die Daten weisen darauf hin, dass lebensweltbezogene Zugänge und aktivierende Unterrichtsmethoden eine zentrale Rolle für die Interessensentwicklung spielen.

Erdwissenschaften im naturwissenschaftlichen Unterricht an der HAK und HAS

Clara-Louisa Unger[1)]

[1)] Bundeshandelsakademie und Bundeshandelsschule Weiz, Dr.-Karl-Widdmann-Straße 40, 8160 Weiz, Österreich

Correspondence to: unger@hakweiz.at

An berufsbildenden höheren Schulen wie der HAK werden Chemie, Physik und Biologie nicht als getrennte Fächer, sondern in einem gemeinsamen Fach „Naturwissenschaften" unterrichtet. Gerade in diesem Fach bietet sich der Einbezug der Erdwissenschaften besonders an, da sie verschiedene naturwissenschaftliche Perspektiven miteinander verbinden und aktuelle gesellschaftliche sowie wirtschaftliche Fragestellungen verständlich machen können.

Durch die Einführung neuer Lehrpläne in den Oberstufen stellt sich die Frage, inwiefern erdwissenschaftliche Themen darin verankert sind und wie sie im Unterricht aufgegriffen werden können. Erdwissenschaftliche Grundlagen sind nicht nur für das Verständnis natürlicher Prozesse wie Klimawandel, Stoffkreisläufe oder Ressourcenbildung relevant, sondern auch für zahlreiche Wirtschaftsbereiche. Besonders an Handelsakademien und Handelsschulen können Themen wie Kreislaufwirtschaft, Rohstoffnutzung, Nachhaltigkeit oder Umweltveränderungen eine Brücke zwischen naturwissenschaftlichem Grundwissen und wirtschaftlicher Bildung schlagen.

Im Rahmen des Lehrer:innenworkshops soll dargestellt und diskutiert werden, inwiefern Erdwissenschaften in den neuen Lehrplänen der berufsbildenden höheren Schulen und in den nach diesen Lehrplänen überarbeiteten Schulbüchern vorkommen. Vertiefend werden dabei die HAK und die HAS betrachtet. Es wird analysiert, wie erdwissenschaftliche Inhalte sowohl im Fach „Naturwissenschaften" als auch in wirtschaftlichen Unterrichtsgegenständen eingebunden sind und wie diese Themen fachlich und didaktisch in Schulbüchern aufbereitet werden. Dabei soll erörtert werden, welche Möglichkeiten bestehen, erdwissenschaftliche Zusammenhänge noch stärker in den naturwissenschaftlichen und wirtschaftlichen Unterricht und die Schulbücher zu integrieren und dadurch ein besseres Verständnis aktueller ökologischer, gesellschaftlicher und ökonomischer Herausforderungen zu fördern.

Inhaltliche Änderungen in Schulbüchern umzusetzen, ist ein komplexer Prozess. Von der Hand der Schulbuchautor:innen bis zur Verwendung im Unterricht durchläuft ein Schulbuch mehrere Verfahren, darunter ein Approbationsverfahren des Bundesministeriums für Bildung, bei dem die Schulbücher meist mehrmals nach Gutachten überarbeitet werden müssen. Ein Teil des Vortrags widmet sich daher der Frage, welche realistischen Möglichkeiten bestehen, erdwissenschaftlichen Inhalten künftig in den Lehrplänen (und somit auch in den Schulbüchern) einen höheren Stellenwert einzuräumen.

Grundwasser, eine unserer grundlegendsten Ressourcen

Thomas Wagner[1)]

[1)] Institut für Erdwissenschaften, NAWI Graz Geozentrum, Universität Graz, Heinrichstrasse 26, 8010 Graz

Correspondence to: thomas.wagner@uni-graz.at

Das unsichtbar im Untergrund gespeicherte Grundwasser spielt eine zentrale Rolle für die Wasserversorgung in Österreich. Etwa 55 % des benötigten Trinkwassers stammen aus Brunnen, die restlichen 45 % werden aus natürlichen Quellen gewonnen.

Grundwasser als natürliche unterirdische Speicher reagiert langsamer auf Trockenperioden als Oberflächengewässer und selbst wenn unsere Bäche ausgetrocknet sind, haben wir meist genug Grundwasser zur Verfügung. Dieses kann aber durch Übernutzung und Verschmutzung gefährdet werden und in einzelnen Jahren stärker eingeschränkt sein. Die Grundwasserneubildung aus infiltrierendem Regen und der Schnee- und Eisschmelze erfahrt einen Wandel durch die sich ändernden klimatischen Rahmenbedingungen. Besonders die sich ändernde Schneedeckendynamik bewirkt eine erkennbare Veränderung der Saisonalität des Wasserdargebots. In Zukunft wird sich die Grundwasserneubildung durch Schnee vor allem auf höhere Lagen beschränken. Ob dies insgesamt positive oder negative Auswirkungen hat, sollte jeweils regional untersucht und sachlich beurteilt werden.

Es soll anhand von einzelnen Beispielen in verschiedensten hydrogeologischen Rahmenbedingungen in unterschiedlichsten Regionen von Österreich versucht werden, ein sachliches Bild der Ressource Grundwasser zu vermitteln.

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Field Trip 1

Geologische Entwicklung der Seckauer Tauern / Geological Evolution of the Seckauer Tauern

Organizers:
Kevin Karner-Rühl & Walter Kurz

NAWI Graz Natural Sciences

TU Graz

UNI GRAZ

Geological Evolution of the Seckau Tauern (Eastern Alps)

Walter Kurz[1)], **Kevin Karner-Rühl** [1)], **Magdalena Mandl** [1)]

[1)]**Institut für Erdwissenschaften, Universität Graz, Heinrichstraße 26, A-8010 Graz**

DOI: https://doi.org/10.3217/xxx

Preface

This field guides provides an overview of the pre-Alpine evolution of Austroalpine basement units exposed in the Seckau Tauern. These units are generally summarized and described as Seckau Complex. An overview of the geological units, also including a summary of geochronological data, is provided in Figures 1 to 3. For details regarding the geochronological and geochemical data, also discussed during the field trip, we refer to the publications by Pfingstl et al. (2015) (https://doi.org/10.17738/ajes.2015.0011), Mandl et al. (2018) (https://doi.org/10.1016/j.lithos.2017.11.022) and Mandl et al. (2022) (https://doi.org/10.1007/s00710-022-00781-3). The original data and also related figures, that are/were shown during the field trip, are available there.

1 Introduction

The Alps incorporate various crustal fragments that derived from the earlier Variscan orogen, and even pre-Variscan elements are part of the pre-Alpine basement within the Alpine orogenic edifice (e.g., see the reviews by Neubauer et al., 2022; Kurz et al., 2024, and references therein). The Austroalpine unit, for instance, comprises distinct Variscan intrusives as well as fragments that derived from the Ceneric orogen (e.g., Zurbriggen, 2017; Burda et al., 2021; Finger and Riegler, 2023), and Late Cambrian and Early Ordovician crustal fragments that are attributed to the closure of the proto-Rheic-Quaidam ocean (e.g., von Raumer et al., 2002; von Raumer et al., 2003; Stampfli et al., 2002). Several microcontinents/terranes, which rifted off along distinct sectors of the northern Gondwana margin, were later incorporated and reworked by subsequent orogenic events, in particular during the Variscan and Alpine orogenies (Neubauer et al., 2022; Finger and Riegler, 2023, 2025). Hence, their evolution, formation ages and deformation history are important for the paleogeographic and tectonic reconstruction of Variscan and Alpine tectonics.

The understanding of the tectono-metamorphic evolution of the Austroalpine Unit has made significant progress in the last few years (Schmid et al., 2004; Froitzheim et al., 2008). An essential key to reveal the tectonostratigraphy of Austroalpine nappes and the sequence of nappe emplacement was the analysis of the Alpine and pre-Alpine metamorphic evolution of distinct nappes (e.g., Schuster et al., 2004; Handy and Oberhänsli, 2004). Studies on these units, however, are rather unequally distributed. Strong emphasis was given on the investigation of units showing an Eo-Alpine high-grade metamorphic evolution including eclogite facies metamorphism, whereas the pool on structural, metamorphic, and geochronological data from other units is quite blank.

2 Geological setting of the Austroalpine Unit

The Austroalpine Unit forms a complex nappe stack of crustal material which can be subdivided into a Lower Austroalpine and Upper Austroalpine Subunit (Schmid et al., 2004; Froitzheim et al., 2008; Kurz et al., 2024) (Fig. 1). The Lower Austroalpine Subunit derived from the continental margin towards the Piemont-Ligurian Ocean and was affected by extension during the Jurassic opening and by nappe stacking during Upper Cretaceous to Eocene closure of this oceanic realm, respectively. It is overlying the Penninic nappes that derived from the Penninic / Piemont-Ligurian Ocean. The Upper Austroalpine Subunit represents a nappe pile which formed mainly during the Eo-Alpine event in the Early Cretaceous to early Late Cretaceous. Its lowermost part is the Silvretta-Seckau Nappe System consisting of a basement with a dominating pre-Alpine metamorphic imprint and remnants of Permian to Lower Triassic cover sequences (Rannach Formation). The basement is dominated by paragneisses (partly migmatic) and orthogneisses with minor intercalations of micaschists, quartzites, amphibolites, hornblende-bearing gneisses and local occurrences of serpentinites and eclogites. Most of the amphibolites and orthogneisses developed from Cambrian to Ordovician magmatic rocks and are interpreted to reflect pre-Cambrian to Ordovician collision, subduction and rifting processes (Neubauer, 2002). Additionally, some Late Cambrian and Carboniferous intrusions are present (Schermair et al., 1997, Mandl et al., 2018, 2022). The medium to high grade imprint in these basement rocks occurred during the Variscan tectonometamorphic event (Neubauer et al., 1999). In the structurally deepest part of the westernmost element represented by the Silvretta Nappe also a Permian metamorphic overprint can be recognized (Schuster et al., 2004). The post-Variscan cover is best preserved in the Silvretta Nappe which is overlain by un-metamorphosed Permian to Triassic sediments in the Landwasser and Ducan synclines and a more or less stratigraphic contact to the Permomesozoic sequences of the Bajuvaric Nappe System (Nowotny et al., 1992; Nagel, 2006). Further to the east tectonically truncated sequences show an Eo-Alpine greenschist facies metamorphic overprint. They comprise only Permian metaconglomerates and metapelites as well as Lower Triassic quartzites. In the basement units the Eo-Alpine imprint reaches sub-greenschist to epidote-amphibolite facies conditions causing retrograde overprint in most of the Variscan metamorphic rocks (Neubauer et al., 1995; Schuster et al., 2004; Hoinkes et al., 2010). Nappes of the Silvretta-Seckau Nappe System build up antiformal structures in the western (Schladminger Tauern) and eastern part (Seckauer Tauern) of the Niedere Tauern mountain ridge.

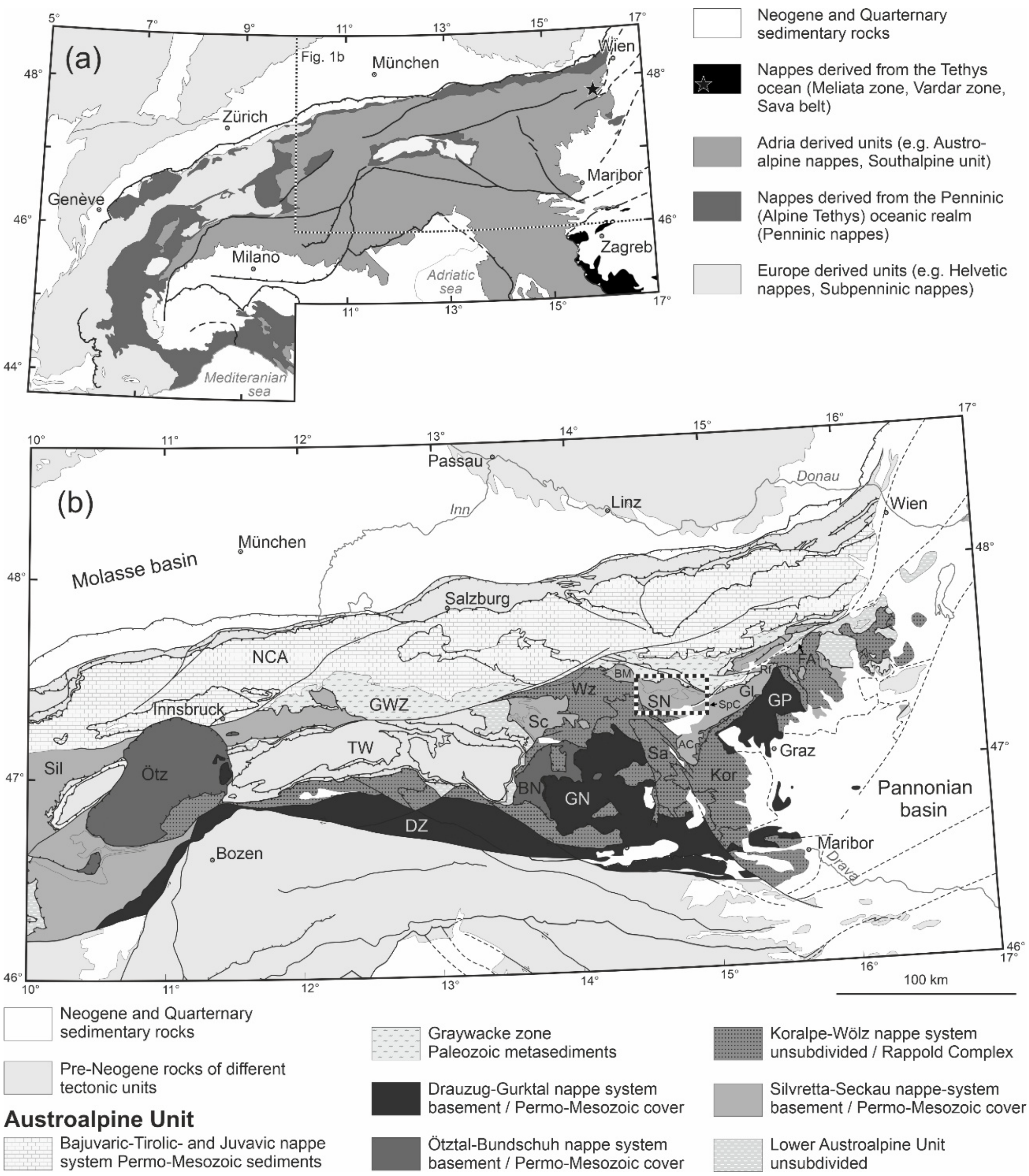

Figure 1: Overview maps (a) showing the paleogeographic origin of the main tectonic units of the Alps, and (b) the tectonic subdivision of the Austroalpine unit based on Schmid et al. (2004). Abbreviations: AC: Amering Complex, BM: Bösenstein Massif, BN: Bundschuh nappe, DZ: Drauzug, FA: Fischbacher Alps, Gl: Gleinalm, GP: Graz Paleozoic, GWZ: Graywacke zone, GN: Gurktal nappe, Kor: Koralpe, NCA: Northern Calcareous Alps, Ötz: Ötztal nappe, Rf: Rennfeld, Sa: Saualpe, Sc: Schladming nappe, Sil: Silvretta nappe, SN: Seckau nappe, SpC: Speik Complex, TW: Tauern Window, Wz: Wölz nappe.

To the north the Silvretta-Seckau Nappe System is overlain by the nappes of the Greywacke zone, which consists of greenschist facies metamorphic Paleozoic sequences, and the Juvavic, Tirolic-Noric and Bajuvaric Nappe Systems. The latter form the Northern Calcareous Alps, mostly comprising un-metamorphosed to lowermost greenschist facies metamorphic Permian to Mesozoic sediments deposited on the shelf facing originally towards the Meliata Ocean, with the sequences of the Juvavic Nappe System representing the most distal shelf towards the oceanic basin.

To the south the Silvretta-Seckau Nappe System is overlain by the Koralpe-Wölz Nappe System which represents an Eo-Alpine metamorphic extrusion wedge (Schmid et al., 2004). Its Permian to Mesozoic cover was completely stripped off during an early phase of the Eo-Alpine orogenic event and it therefore consists exclusively of metamorphic basement nappes. To a various grade the individual nappes are affected by a Variscan, Permian to Triassic HT/LP and an Eo-Alpine HP metamorphic overprint (Neubauer, 1999; Schuster et al., 2004).

The Ötztal-Bundschuh Nappe System shows a similar lithological composition as the Silvretta-Seckau Nappe System but is positioned on top of the Koralpe-Wölz Nappe System. The overlying Drauzug-Gurktal Nappe System is made up of a Variscan metamorphic basement, anchizonal to greenschist facies Paleozoic metasedimentary sequences and by un-metamorphosed Permian to Triassic sediments. Within the Ötztal-Bundschuh and Drauzug-Gurktal Nappe Systems the Eo-Alpine metamorphic grade decreases upwards from epidote-amphibolite facies at the base to diagenetic conditions at the top of the nappe pile. In other words, the high-grade nappes of the Koralpe-Wölz Nappe System are sandwiched between nappes affected by rather medium to low- grade Eo-Alpine metamorphism.

3 Geology of the Seckau Complex

According to Schmid et al. (2004) and Froitzheim et al. (2008), the Seckau Complex forms part of the Seckau Nappe which is part of the Silvretta-Seckau Nappe System (Figs. 1, 2). The Seckau Nappe forms a more or less triangle shaped area extending in the north from the Bösenstein massif and Seckauer Tauern in the eastern part of the Niedere Tauern to the Fischbacher Alps over nearly 100 km. There it is cut off by the sinistral, east-west trending Trofaiach fault. Its continuation is represented by the Troiseck Floning Nappe (Neubauer, 1988). The southern edge is at Ameringkogel in the northern part of the Koralpe mountain ridge (Becker, 1979). The north-south extension is about 50 km.

The nomenclature used in literature for the crustal piece referred as Seckau Nappe in here is quite complicated and confusing. Until the 70ies of the past century it is attributed to the so called Muriden unit in contrast to the overlying Koriden unit. This was, however, a local subdivision which was never extended over the whole Austroalpine Unit.

Names used for the area of the Bösenstein massiv and the Seckauer Tauern, which is dominated by orthogneisses, paragneisses and migmatic paragneisses (Metz, 1976) were "Seckauer Gneis" (Schmidt, 1921, p. 103 ff), „Seckauer Masse", „Seckauer Massiv" (Tollmann, 1977), „Kristallin der Seckauer Tauern" (Metz, 1979) and „Seckauer Kristallin" (Scharbert, 1981; Tollmann, 1977, p. 287). The term Seckau Complex is to favour (Faryad and Hoinkes, 2001, Gaidies et al., 2006) because it matches recent lithostratigraphic standards (GeoSciML).

For the eastern continuation „Mugel-Rennfeldzug" (Schwinner, 1951, p. 110; Metz, 1971, p. 56; Tollmann, 1977, p. 222) and „Rennfeld Mugel Kristallin" (Neubauer, 1988) can be found. In the southern part two units have been distinguished. A lower Amering-Komplex (Flügel and Neubauer, 1984 after „Ameringserie bzw. Gneiskomplex" in Becker, 1979), formed by biotite-plagioclase paragneisses and some orthogneiss intercalations, is overlain by the Speik-Complex (Flügel and Neubauer, 1984, after „Speikserie bzw. Amphibolitkomplex" in Becker, 1979) dominated by amphibolites with some ultramafic rocks and an eclogite at Hochgrößen mountain. However, the individual complexes are not well defined and their boundaries are not clear. The overlying Permian to Lower Triassic metasediments are summarized as Rannach-Formation (Flügel and Neubauer, 1984, after "Rannachserie" from Metz, 1967). It needs to be mentioned that the term Rannach-Formation is problematic because there is a Rannach-Group (Flügel and Neubauer, 1984) defined in the nappes of the Graz Paleozoic just 30 km to the southeast.

In the north the Rannach-Formation is overlying the Seckau Complex with a northward dip, whereas in the south the Speik Komplex is the uppermost element. Further, the Gaal Zone (Metz, 1971, "Gaaler Schuppenzone") mainly composed of the Speik Complex and overlying Permian to Lower Triassic metasediments is tectonically overlying the northwesternmost part of the Seckau Nappe in the Bösenstein area.

As mentioned before the Seckau Complex is formed by orthogneisses, paragneisses and migmatic paragneisses. The orthogneisses and augengneisses derived from tonalites, granodiorites as well as granites. In general these units form a coherent suite of I-type granitoids (Schermaier et al., 1997; Pfingstl, 2013; Pfingst et al., 2015; Mandl et al., 2018, 2022). A-type, and transitional S- and I- type granitoids are represented to minor extent. Based on Rb-Sr whole rock (~ 350 Ma) and white mica ages (~330 Ma) and the contact to the Permomesozoic metasediments the orthogneisses were thought to have formed during the Variscan tectonometamorphic event (Scharbert, 1981). An additional Rb-Sr whole rock age of 432 +/- 16 Ma argues for a pre-Variscan, possibly Ordovician intrusion age.

In the map of Metz (1967) the Rannach-Formation ("Rannach Serie") in the northern part of the Seckauer Tauern comprises Permian metaconglomerates, metapelites derived from fine grained clastic sediments and some carbonatic intercalations. Lower Triassic thin bedded greenish quartzites occur in the north within a window near to the village Wald am Schoberpass below the nappes of the Greywacke Zone.

Permian to early Mesozoic (meta-)sedimentary units except those of the Northern Calcareous Alps and the Drau Range were summarized as Central Austroalpine Mesozoic (CAM) (e.g. Tollmann, 1977; see Kurz et al., 2024 for summary). They are widely dispersed on most of the Austroalpine nappe systems. Prominent examples for CAM are the Brenner Mesozoic in the west and the Stangalm, Thörl and Rannach Permo-Mesozoic units to the east of the Tauern Window, respectively. Most of the clastic Permian to Lower Triassic sequences of CAM have minor thicknesses between few meters (Brenner, Stangalm Mesozoic) to a maximum of 100 meters (Thörl unit) (e.g., Schnabel, 1980). An exception is the Rannach-Formation (Metz, 1976) with up to 1000 meters thickness.

The metamorphic conditions in the Seckau Nappe show a slight increase from north to south. In the north the transgressive Permian to Lower Triassic metasediments (Rannach-Formation) are characterised by the assemblage muscovite + chloritoid + chlorite + quartz, indicating upper greenschist facies conditions (520°C at 0.9 GPa; Faryad and Honikes, 2001). In the Gleinalm area in the south lower amphibolite facies conditions are expected from amphibolite assemblages including garnet + amphibole + plagioclase and intercalated micaschists with garnet, staurolite and kyanite.

Timing of the peak of Eo-Alpine metamorphism in the Seckau nappe is not constrained with data and also for the cooling through greenschist facies conditions the data are scarce. Three Rb-Sr biotite ages are in the range of 70 to 77 Ma (Scharbert, 1981). Unexpected high fission track ages were described by Hejl (1997). Orthogneiss samples from the summit and valley areas of the Seckau Tauern yielded apatite fission track ages of ca. 60 Ma and 44 Ma, respectively. These fission track data indicate that after fast denudation during Late Cretaceous times the Seckau Nappe stayed at nearly constant temperature in the order of 80° C until the late Oligocene, followed by a phase of faster cooling, and a phase of slow cooling during Miocene times. The fission track data exclude any post-Cretaceous metamorphic overprint within the Seckau Nappe. During the whole Cenozoic the highest portions of the Seckau Nappe therefore resided at a depth of less than 3000 meters at temperatures much cooler than the conditions of anchi-metamorphism (Hejl 1997).

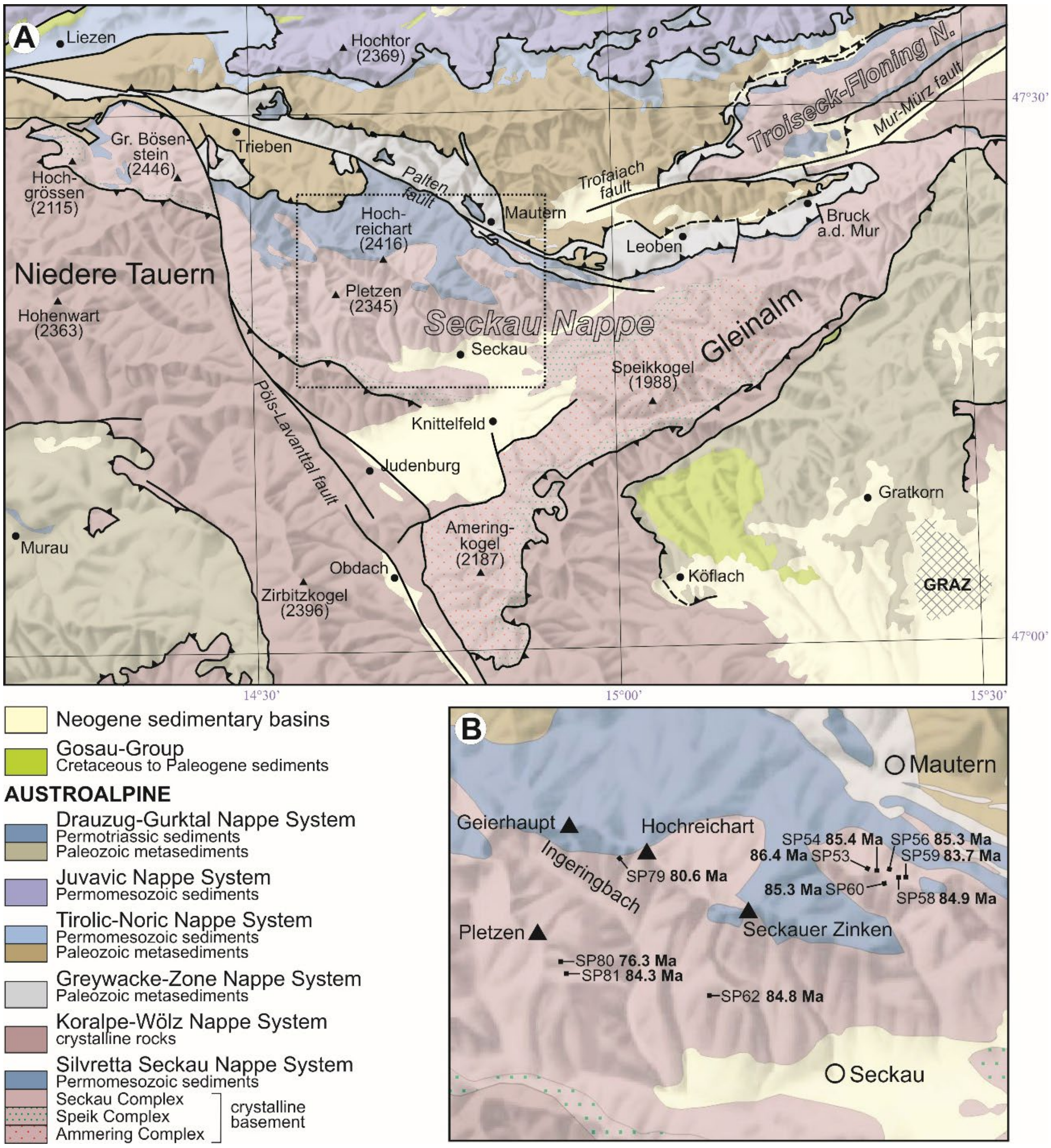

Figure 2: (A) Geological map of the study area in the Seckauer Tauern, based on Metz (1967, 1979), Flügel and Neubauer (1984) and Schubert et al. (2009). (B) Enlargement of the sampling area with sites of samples and the revealed Rb-Sr isochron ages (after Pfingstl et al., 2015)

4 Geochronological data from the study area and subdivision of the Seckau Complex

The magmatic and geochronological evolution of the Seckau Complex in the northwestern part of the Seckau Nappe (as part of the Austroalpine Silvretta-Seckau Nappe System) was investigated by zircon U-Pb dating of paragneisses and metagranitoids coupled with petrological and geochemical data by Mandl et al. (2018, 2022). This revealed the distinction of three newly defined lithostratigraphic/lithodemic sub-units: (1) Glaneck Metamorphic Suite, (2) Hochreichart Plutonic Suite and (3) Hintertal Plutonic Suite (Fig. 3).

The Glaneck Metamorphic Suite is mainly composed of fine-grained paragneisses that yield U-Pb zircon ages in the range between 2.7 Ga and 2.0 Ga, as well as concordia ages from 572 ± 7 Ma to 559 ± 11 Ma. All these ages are interpreted as detrital zircon ages originating from an igneous source. The paragneisses are the host rock for the large volumes of metagranitoids of the Hochreichart Plutonic Suite and the Hintertal Plutonic Suite. The Hochreichart Plutonic Suite comprises highly fractionated melts with mainly S-type characteristics and late Cambrian to Early Ordovician U-Pb zircon ages (508 ± 9 Ma to 486 ± 9 Ma), interpreted as magmatic protolith ages. The Hintertal Plutonic Suite is composed of metagranitoids with Late Devonian to early Carboniferous (365 ± 11 Ma and 331 ± 10 Ma) protolith ages, that intruded during an early phase of the Variscan tectonometamorphic event. The metagranitoids of the Hintertal Plutonic Suites define a magmatic fractionation trend, seen in variable Rb/Sr ratios. On this base they can be further subdivided into (a) the Griessstein Pluton characterized by S-type metagranitoids and (b) the Pletzen Pluton distinguished by intermediate to acidic metagranitoids with I-type affinity.

The detrital zircon age spectra suggest a Neoproterozoic ancestry of the Glaneck Metamorphic Suite, which was located west of the Arabian Nubian Shield, probably next to the Trans-Saharan Belt. The early Paleozoic evolution of the recent Seckau Complex shows similarities to basement units of the Southalpine Unit, parts of the Austroalpine Unit and the Tatric and Veporic units of the Central Western Carpathians.

More recent Rb-Sr biotite ages from the Seckau Tauern were published by Pfingstl et al. (2015). In the eastern part of the Seckau Tauern these ages range from 84.9 to 86.4 Ma. Taking into account the standard deviations, these ages are more or less identical within error. A similar age of 84.8 Ma has also been observed from the southern part of the investigated area. An age from the Hochreichart, yielding 80.6 Ma, is significantly younger. In the western part of the area of investigation, west of the Ingering valley, two different ages were observed. An age of 84.3 Ma is widely identical to the bulk of ages yielded in the eastern part, whereas an age of 76.3 Ma is significantly younger.

Calculation of an isochron including all whole rocks of granitic and granodioritic rocks results in an age value of 517±61 Ma with an initial isotopic ratio of 0.7045±0.0016.

The investigated biotites show brown to yellowish-brown pleochroism. Some separated from orthogneisses show typical rutile exsolutions ("Sagenitgitter"), indicating higher Ti-contents of the primary magmatic biotites.

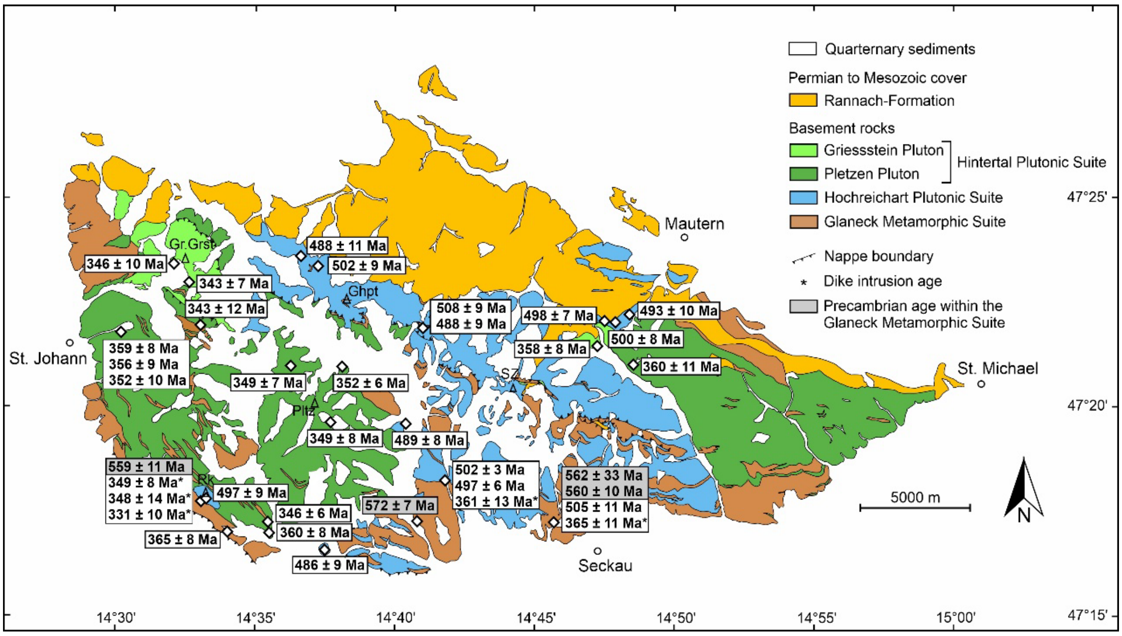

Figure 3: Simplified geological map of the Seckau Complex north (-east) of the Mur valley (compiled from Metz, 1967; Moser, 2015) showing the proposed subdivision into the Glaneck Metamorphic Suite (brownish colored), Hochreichart Plutonic Suite (blue colored) and Hintertal Plutonic Suite (Griessstein- and Pletzen Pluton; green colored) as well as the related U-Pb zircon ages. Dikes are marked with a highlighted star. Abbreviations: Ghpt: Geierhaupt, Gr.Grst: Grosser Griessstein, Pltz: Pletzen, Rk: Rosenkogel, SZ: Seckauer Zinken. (after Mandl et al., 2018)

5 Geochemical data of granitoids

Recent studies by Mandl et al. (2022) revealed that the calc-alkaline metagranitoids of the Seckau Complex comprise both (1) a Late Cambrian to Early Ordovician and (2) a Late Devonian to Early Carboniferous (early Variscan) intrusive complex. The older rocks of the Hochreichart Plutonic Suite reflect I to S-type affinity and are peraluminous and characterized by a general decrease in TiO_2, Al_2O_3, MgO, CaO, P_2O_5, FeOt and MnO with increasing SiO_2. Chondrite-normalized rare earth element (REE) plots display a slight enrichment in light rare earth elements (LREE) relative to heavy rare earth elements (HREE) as well as negative Eu anomalies ($(Eu/Eu^*)_N$ = 0.15- 0.77). The whole-rock initial $^{87}Sr/^{86}Sr$ ratios calculated back to the time of emplacement (~496 Ma) vary between 0.7056 to 0.7061.

The early Variscan rocks of the Hintertal Plutonic Suite can be subdivided into (a) the meta- to peraluminous granodioritic suite of the Pletzen Pluton and (b) the peraluminous granitic suite of the Griessstein Pluton. The Pletzen Pluton shows typical magmatic fractionation trends for most of the major oxides and trace elements plotted against SiO_2. On a chondrite-normalized rare earth element (REE) diagram, metagranitoids are strongly enriched in LREE and show no significant negative Eu anomaly. Metagranitoids of the Griessstein Pluton have a more peraluminous character and similar major and trace element fractionation trends compared to the Pletzen Pluton. However, the contents in SiO_2, major and trace elements clearly point towards a more evolved melt with generally lower TiO_2, Al_2O_3, MgO and CaO values and higher K_2O content. Metagranitoids of the Griessstein Pluton are additionally characterized by a slight negative Eu anomaly of about 0.81 on a chondrite-normalized REE plot. Initial $^{87}Sr/^{86}Sr$ values calculated back to the time of emplacement (~353 Ma) of the Pletzen Pluton and the Griessstein Pluton vary between 0.7051 - 0.7061 and 0.7054 - 0.7063, respectively, and suggest the same magmatic source for both units. Application of rhyolite-MELTS modelling to the Hintertal Plutonic Suite revealed that the Griessstein Pluton formed by fractional crystallization (~30 %) from the more primitive Pletzen Pluton.

Our geochemical data from the Hochreichart Suite granitoids suggest the existence of a Late Cambrian to Early Ordovician active margin with its remnants now exposed in the Seckau Complex. The early Variscan granitoids of the Seckau Complex are inferred as part of a magmatic arc along the southern Bohemian active continental margin that was related to the subduction of differently termed oceanic domains (Galicia-Moldanubian Ocean or Paleotethys), prior to the final collision of Gondwana and Laurussia. The general paleogeographic position of the Seckau Complex during the Variscan orogeny is considered to be south to southeast of the Bohemian Massif, adjacent to the eastern Hohe Tauern, the Schladming Tauern, and the Western Carpathians.

6 Description of Stops

6.1 Site 1: Migmatized basement of the Seckau Complex

Steinmühle near Seckau (47°15’51”N; 14°45’30”E)

The metapelites (garnet-micaschists, biotite-plagioclase gneisses) of the pre-Alpine (probably pre-Variscan) basement of the Seckau Complex is partly migmatized. The migmatites mainly occur as banded gneisses with mm- to cm-thick layers of quartz, plagioclase, muscovite and biotite, and with blasts of garnet.

At this site (Fig. 4), the migmatitic layering and the penetrative foliation is affected by tight folding with an approximately E-W- trending, subhorizontal fold axis. The fold axis is sub-parallel to the stretching lineation. Pegmatite dykes that crosscut the migmatic layering are partly affected by folding. Some pegmatite dykes, however, remain unfolded. All these fabrics are subsequently affected by open folds at a scale of several meters. The related fold axis is subparallel to the stretching lineation, too.

U-Pb zircon ages from an unfolded discordant pegmatite dike are in the range of 365 Ma, whereas ages from migmatized leucosomes are in the range of 505 Ma (Mandl et al., 2018). Another (folded) pegmatite dike revealed an age of 562 Ma.

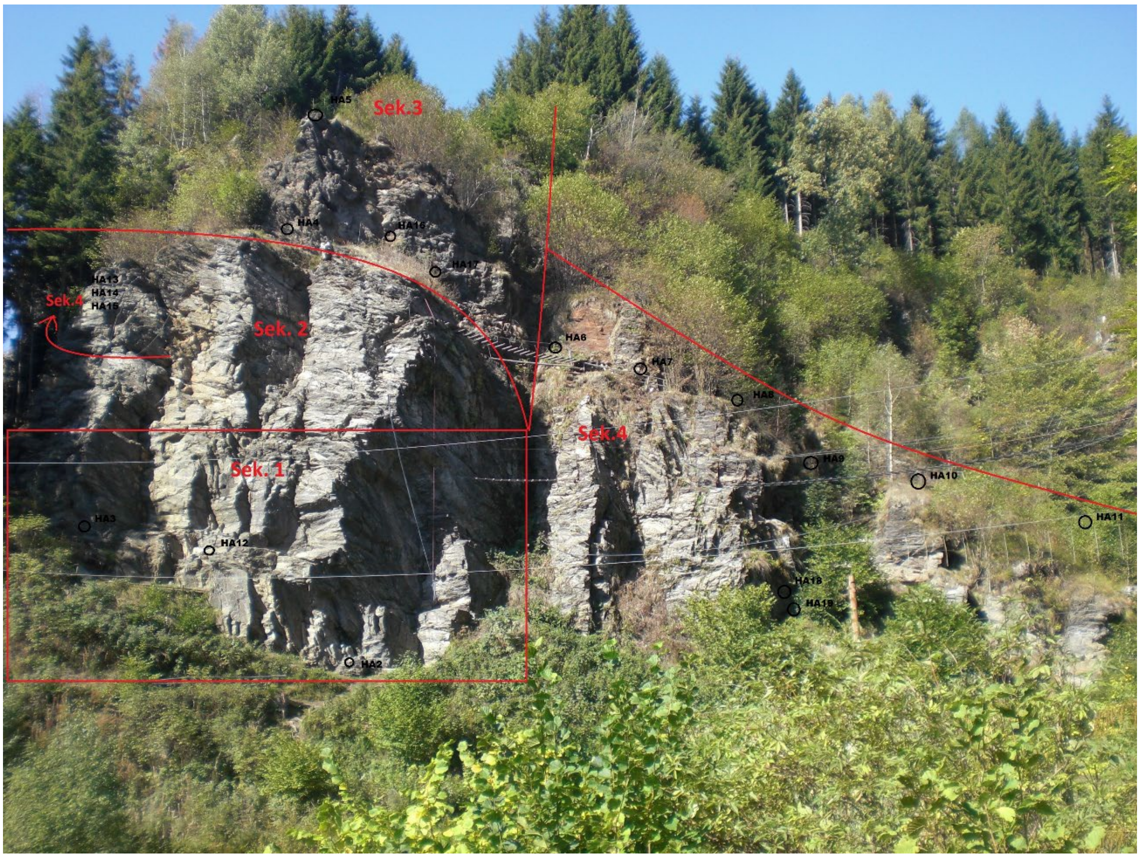

Figure 4: Panoramic view of site 1.

6.2 Site 2: Paragneisses and micaschists of the Seckau Complex

Gaal, Sommertörl - Rosenkogel (47°17’36,84”N; 14°33’08,72”E)

The metapelites of the Seckau complex are highly variable. The lithologies range from biotite-rich (garnet-) micaschists to quartz- and plagioclase- rich paragneisses.

The mineral assemblage within the garnet-micaschists is characterized by quartz, plagioclase, biotite, chlorite and garnet. Commonly, biotite occurs along the penetrative foliation and within strain shadows around garnet. Both garnet and biotite show retrogression to chlorite.

Additionally, biotite and/or chlorite occur as clasts of several millimeters in size, and are asymmetrically deformed to micafish, indicating a top-to-the west sense of shear. Biotite and chlorite are arranged along shear bands as well and define an extensional crenulation cleavage that indicate top-to-the west sense of shear, too.

Detrital zircon ages from the meta-pelites range from 2710 to 559 Ma, with a clear peak around 560 Ma (Mandl et al., 2018).

The metapelites locally host dikes of fine-grained leucocratic granite. The dikes commonly have a thickness of a few centimeters to several decimeters and are sub-parallel to parallel to the micaschist foliation. U-Pb zircon ages from these dikes are in the range of 349 to 348 Ma. These dikes are therefore interpreted to be related to the Hintertal Plutonic Suite.

6.3 Site 3: Granite intrusion of the Hochreichart Pluton

Rosenkogel (47°17’38”N; 14°33’06,50”E; ca. 1810 m)

The fine-grained micaschist host rocks at this site show variable contents of quartz within distinct layers spaced at cm- to dm- scale. The penetrative foliation is gently dipping towards the north to northeast. The micaschists are intruded by coarse grained granites, with K-feldspar up to 5 cm in size. The granites hardly show an internal deformational fabric. The granites are exposed for several tens of meters up to the top of the peak of Rosenkogel (1918 m).

U-Pb zircon ages from this granite are in the range of 497 Ma (Mandl et al., 2018). The granites have I to S-type affinity, are peraluminous, and belong to the Hochreichart Plutonic Suite.

6.4 Site 4: Tonalite and tonalite gneisses of the Pletzen Pluton

A section from the chapel Maria Loretto (1817 m) (47°17’55,66”N; 14°33’22,33”E) towards elevation 1841 (47°17’52,64”N; 14°33’007,10”E) exposes partly migmatized metapelites of the Glaneck Metamorphic Suite that are also intruded by discordant to semi-discordant coarse grained granitic dikes. Towards east, the metapelites are in contact with tonalites and tonalite gneisses of the Pletzen Pluton. The tonalite (gneisses) have a common mineral assemblage of approximately 30% biotite, 30% plagioclase, 30 % quartz and approximately 10 % of K-feldspar. These rocks either appear as isotropic tonalites with a homogenous grain size, or as foliated gneisses with biotite defining the penetrative foliation. U-Pb zircon ages from the tonalite are in the range of 365 to 343 Ma (Mandl et al., 2018).

7 References

Becker, L.P. (1979). Erläuterungen zu Blatt 162 Köflach. - Geologische Karte der Republik Österreich, Geologische Bundesanstalt, Wien.

Becker, L.P. (1979). Geologische Karte der Republik Österreich 1:50.000, Blatt 162 Köflach, Geologische Bundesanstalt, Wien.

Burda, J., Klötzli, U., Majka, J., Chew, D., Li, Q. L., Liu, Y, Gawęda, A. & Wiedenbeck, M. (2021). Tracing proto-Rheic - Qaidam Ocean vestiges into the Western Tatra Mountains and implications for the Palaeozoic palaeogeography of Central Europe. Gondwana Research, 91, 188–204.

Faryad, S. W. & Hoinkes, G. (2001). Alpine Chloritoid and Garnet from the Hochgrössen Massif (Speik Complex, Eastern Alps). Mitt. Österr. Mineral. Ges., 146, 387-396.

Finger F. & Riegler G. (2023). The role of the proto-Alpine Cenerian Orogen in the Avalonian-Cadomian belt. Austrian Journal of Earth Sciences, 116, 109-115. DOI: 10.17738/ajes.2023.0005

Finger F. & Riegler G. (2025). Revisiting the (pre-Variscan) Galatia/Ligeria – Armorica terrane conception from an Austrian perspective. Austrian Journal of Earth Sciences, 118, 175-187, DOI: 10.17738/ajes.2025.0010.

Flügel, H. W. & Neubauer, F. R. (1984). Geologische Karte der Steiermark 1:200.000. Geologische Bundesanstalt, Wien.

Froitzheim, N., Plasienka, D. & Schuster, R. (2008). Alpine tectonics of the Alps and Western Carpathians. In: McCann, T. The Geology of Central Europe. Volume 2: Mesozoic and Cenozoic. 1141-1232.

Handy, M. R. & Oberhänsli, R. (2004). Explanatory notes to the map: metamorphic structure of the Alps: age map of the metamorphic structure of the Alps - tectonic interpretation and outstanding problems. Mitt. Österr. Min. Ges., 149, 201-225.

Hejl, E. (1997). 'Cold spots' during the Cenozoic evolution of the Eastern Alps: thermochronological interpretation of apatite fission-track data. Tectonophysics, 272, 159-173.

Hoinkes, G., Koller, F., Demeny, A., Miller, Ch., Schuster, R., Thöni, M., Kurz, W., Krenn, K. & Walter, F. (2010). Metamorphism in the Eastern Alps.- Acta Mineralogica-Petrographica, Field Guide Series, 1, 1-47, Kurz W., Fritz, H. & Wölfler, A. (2024). Tectonic Evolution of the Eastern Alps. In: Geodynamics of the Alps 1: Present-Structure and Regional Alpine Studies from Extension to Collision, 211-292. iSTE Wiley, London

Mandl, M., Kurz, W., Hauzenberger, C., Fritz, H., Klötzli, U. & Schuster, R. (2018). Pre-Alpine evolution of the Seckau Complex (Austroalpine basement/Eastern Alps): Constraints from in-situ LA-ICP-MS U Pb zircon geochronology. Lithos, 296-299, 412–430.

Mandl, M., Kurz, W., Hauzenberger, C., Fritz, H. & Pfingstl, S. (2022). Geochemistry of granitoids from the Austroalpine Seckau Complex: a key for revealing the pre-Alpine evolution of the Eastern Alps. Mineralogy and Petrology, 116, 251–272.

Metz, K. (1967). Geologische Karte der Republik Österreich 1:50.000, Blatt 130-131 Oberzeiring-Kalwang. Geologische Bundesanstalt, Wien.

Metz, K. (1976). Der geologische Bau der Seckauer und Rottenmanner Tauern. Jahrb. Geol. B.-A., 119, 151-205.

Metz, K. (1976). Der geologische Bau der Wölzer Tauern. Mitt. Naturwiss. Ver. Steiermark, 106, 51-75.

Metz, K. (1979). Geologische Karte der Republik Österreich 1:50.000, Blatt 129 Donnersbach. Geologische Bundesanstalt, Wien.

Moser, M. (2015). GEOFAST Provisorische Karte der Republik Österreich 1:50.000, Blatt 132 Trofaiach. Geologische Bundesanstalt, Wien.

Nagel, T. (2006). Structure of Austroalpine and Penninic units in the Tilisuna area (Eastern Rhätikon, Austria): Implications for the paleogeographic position of the Allgäu and Lechtal nappes. Eclogae.geol. Helv., 99, 223-235.

Neubauer, F. (1988). Bau und Entwicklungsgeschichte des Rennfeld-Mugel- und des Gleinalm-Kristallins (Ostalpen). Abh. Geol. B.-A., 42, 1-137.

Neubauer, F. (2002). Evolution of late Neoproterozoic to early Paleozoic tectonic elements in Central and Southeast European Alpine mountain belts: review and synthesis. Tectonophysics, 352, 87-103.

Neubauer, F., Dallmeyer, R. D., Dunkl, I. & Schirnik, D. (1995). Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: kinematics, cooling history and sedimentary response in a sinistral wrench corridor. Tectonophysics, 242, 79-98.

Neubauer, F., Hoinkes, G., Sassi, F.P., Handler, R., Höck, V., Koller, F. & Frank, W. (1999). Pre-Alpine metamorphism in the Eastern Alps. – Schweiz. Mineral. Petrogr. Mitt., 79, 41-62, Zürich.

Neubauer, F., Liu, Y., Dong, Y., Chang, R., Genser, J. & Yuan, S. (2022). Pre-Alpine tectonic evolution of the Eastern Alps: From Prototethys to Paleotethys. Earth-Science Reviews, 226, 103923.

Nowotny, A., Pestal, G. & Rockenschaub, M.J. (1993). Die Landecker Quarzphyllit- und Phyllitgneiszone als schwächer metamorpher Anteil des Silvrettakristallins. - Jb. Geol. B.-A., 135, 867-872, Wien.

Pfingstl, S. (2013). Tektonische und metamorphe Entwicklung des Seckauer Kristallins. Masterarbeit, Naturwissenschaftliche Fakultät, Universität Graz, 121 pp.

Pfingstl, S., Kurz, W., Schuster, R. and Hauzenberger, C. (2015). Geochronological constraints on the exhumation of the Austroalpine Seckau Nappe (Eastern Alps). Austrian Journal of Earth Sciences, 108, 172-175.

von Raumer, J. F., Stampfli, G., Borel, G. & Bussy, F. (2002). Organization of pre-Variscan basement areas at the north-Gondwanan margin. International Journal of Earth Sciences, 91, 35–52.

von Raumer, J. F., Stampfli, G. M. & Bussy, F. (2003). Gondwana-derived microcontinents — the constituents of the Variscan and Alpine collisional orogens. Tectonophysics, 365, 7–22.

Scharbert, S. (1981). Untersuchungen zum Alter des Seckauer Kristallins. Mitt. Ges. Geol. Bergbaustud. Österr., 27, 173-188.

Schermaier, A., Haunschmid, B. & Finger, F., 1997. Distribution of Variscan I- and S-type granites in the Eastern Alps. a possible clue to unravel pre-Alpine basement structures. Tectonophysics, 272, 315-333.

Schmid, S. M., Fügenschuh, B., Kissling, E. & Schuster, R., 2004. Tectonic map and overall architecture of the Alpine orogen. Eclogae geol. Helv., 97, 93-117.

Schnabel, W. (1980). Permomesozoikum in den zentralen Ostalpen: Zentralalpin (Mittelostalpin), Oberostalpin incl. Zentralalpine Gosau mit Eozän, mittlerer und östlicher Teil . In: Oberhauser, R. (Ed.): Der geologische Aufbau Österreichs. Springer Verlag, Wien New York, 406-407.

Schubert, G., Berka, R. & Philippitsch, R. (2009). Karte der trinkbaren Tiefengrundwässer Österreichs 1:500.000. In: Arbeitstagung 2007 der

Geologischen Bundesanstalt Blatt 67 Grünau im Almtal und Blatt 47 Ried im Innkreis:

Schuster, R., Koller, F., Hoeck, V., Hoinkes, G. & Bousquet, R. (2004). Explanatory notes to the map: Metamorphic structure of the Alps - Metamorphic evolution of the Eastern Alps. - Mitt. Österr. Miner. Ges., 149, 175-199.

Stampfli, G. M., Raumer, J. F. von & Borel, G. D. (2002). Paleozoic evolution of pre-Variscan terranes: From Gondwana to the Variscan collision. Geological Society of America Special Paper, 364, 263–280.

Tollmann, A. (1977). Geologie von Österreich. Band 1. Die Zentralalpen. 766 pp, Deuticke, Wien.

Zurbriggen, R. (2017). The Cenerian orogeny (early Paleozoic) from the perspective of the Alpine region. International Journal of Earth Sciences, 106, 517–529.

21.-25. Sept. 2026

PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Field Trip 2

Die Hebung der Ostalpen:

Neotektonik Evidenz im Grazer Bergland

/

Uplift of the Eastern Alps:

Neotectonic Evidence in the Grazer Bergland

Organizers:
Kurt Stüwe

NAWI Graz
Natural Sciences

Graz

Uplift of the Eastern Alps: *Neotectonic Evidence in the Grazer Bergland Region*

Kurt Stüwe[1)]

[1)] **Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Graz, Austria**

DOI: https://doi.org/10.3217/xxx

Preface

This field guide describes the PANGEO field excursion through the Grazer Bergland on Sept 21st 2026. This field trip is in 2 parts: The morning is a car-trip (with very little walking except for a 30 minutes hike through the Kesselfall) to some overview points and key locations for the evidence to young uplift in the Eastern Alps. In the afternoon we will visit the Drachenhöhle – the “type locality”, where Wagner et al. (2010) first dated the young burial ages as evidence for young uplift of the Alps. This hike involves steep 500 vertical meters to the cave (along a well marked trail) and about 1 hour in the cave.

This guide consists of some figures (including a location map for the field trip but not all stops can be visited because of timing constraints) mainly focusing on the argumentation for the observed evidence for Pliocene uplift. The later part of this guide describes the key-stops of the field trip.

This field trip was done as an annual field trip for about 10 years as part of the course “Neotectonics and Geomorphology” at the KFU. The references in the back are not exclusively those that are cited in the text of this guide, but were selected to provide a good overview on the current literature on the subject.

1. Info about the Drachenhöhle visit:

Aside from a steep 500m vertical hike to the cave you should know/bring the following:

- If the hike to the cave may be a bit much to you, or you want to be a bit slower than the group, I still recommend you go part of the way with us. The entrance itself is worth seeing. It is located on the “Trahütten level” and you can see spectacular evidence for a paleosurface on the same level opposite on the other side of the Mur valley.
- The cave is large and open and easy to access and about 600m long. So you DO need a head-light or similar, but you don’t necessarily need a helmet or other special caving gear.
- There are two ladders inside that are usually full of clay. Bring some gardening or dishwashing gloves for that.
- The place I call the “type locality” where Wagner et al. (2010) first dated the young uplift of the eastern Alps with a 4 Ma burial age of quartz pebbles from the Paleo-Mur, is called the “Ostergang”. This is a 10m long “appendix” near the end of the cave that needs crawling and is usually lined with clay! So you will get dirty! If you want to see this with me, you may want to bring a helmet, and a change of some clothes (gardening pants?, dirty T-Shirt?, gloves?)

The following pages are stop-descriptions (related to numbers on Fig. 1) of the field trip as they were used for the course “Neotectonic and Geomorphology” in the Earth Science curriculum at Graz University. Sorry they are in German ;-)

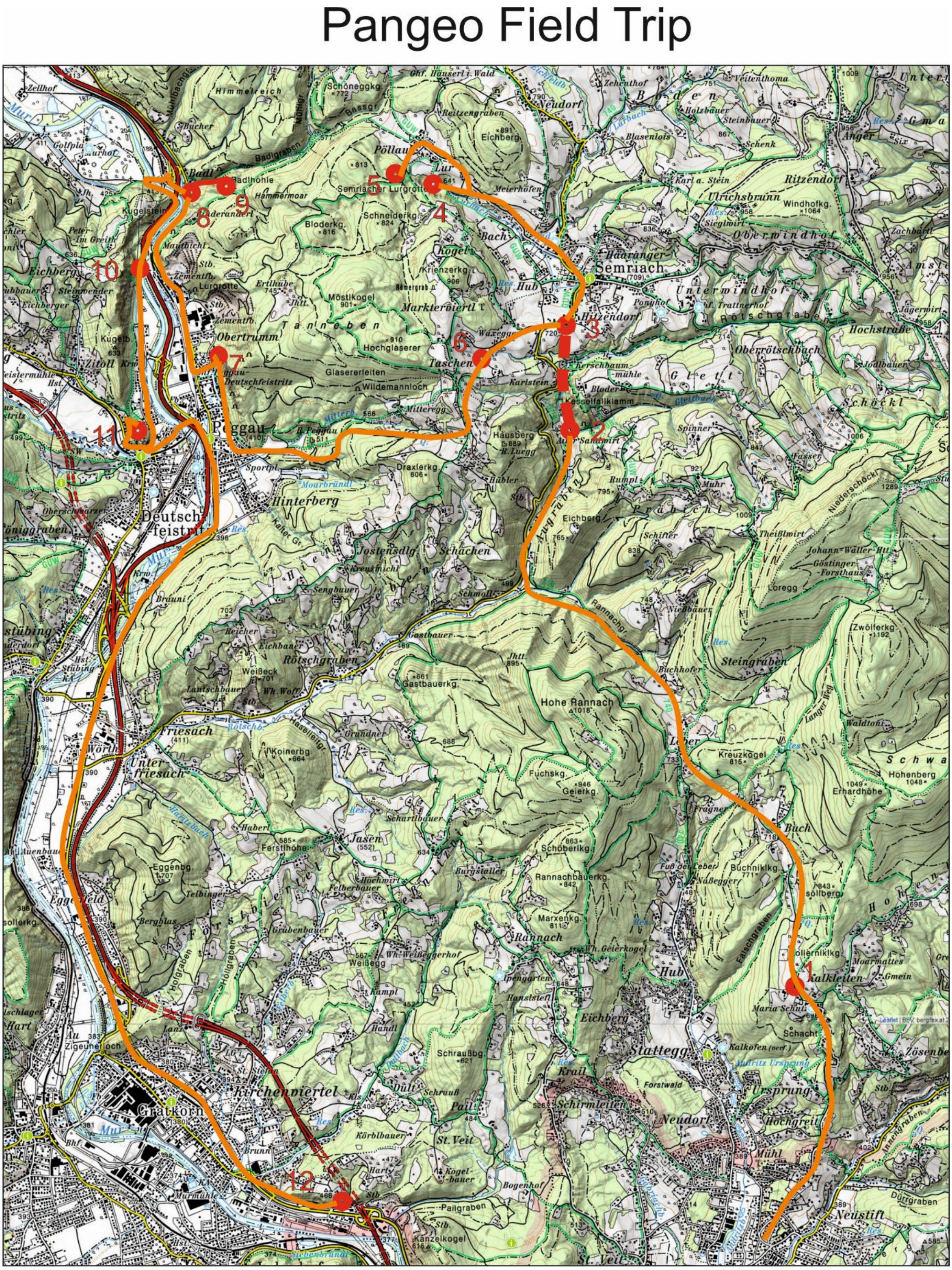

Fig. 1: Routing of the PANGEO26 field trip (morning part). Stop descriptions are in the text part of this guide.

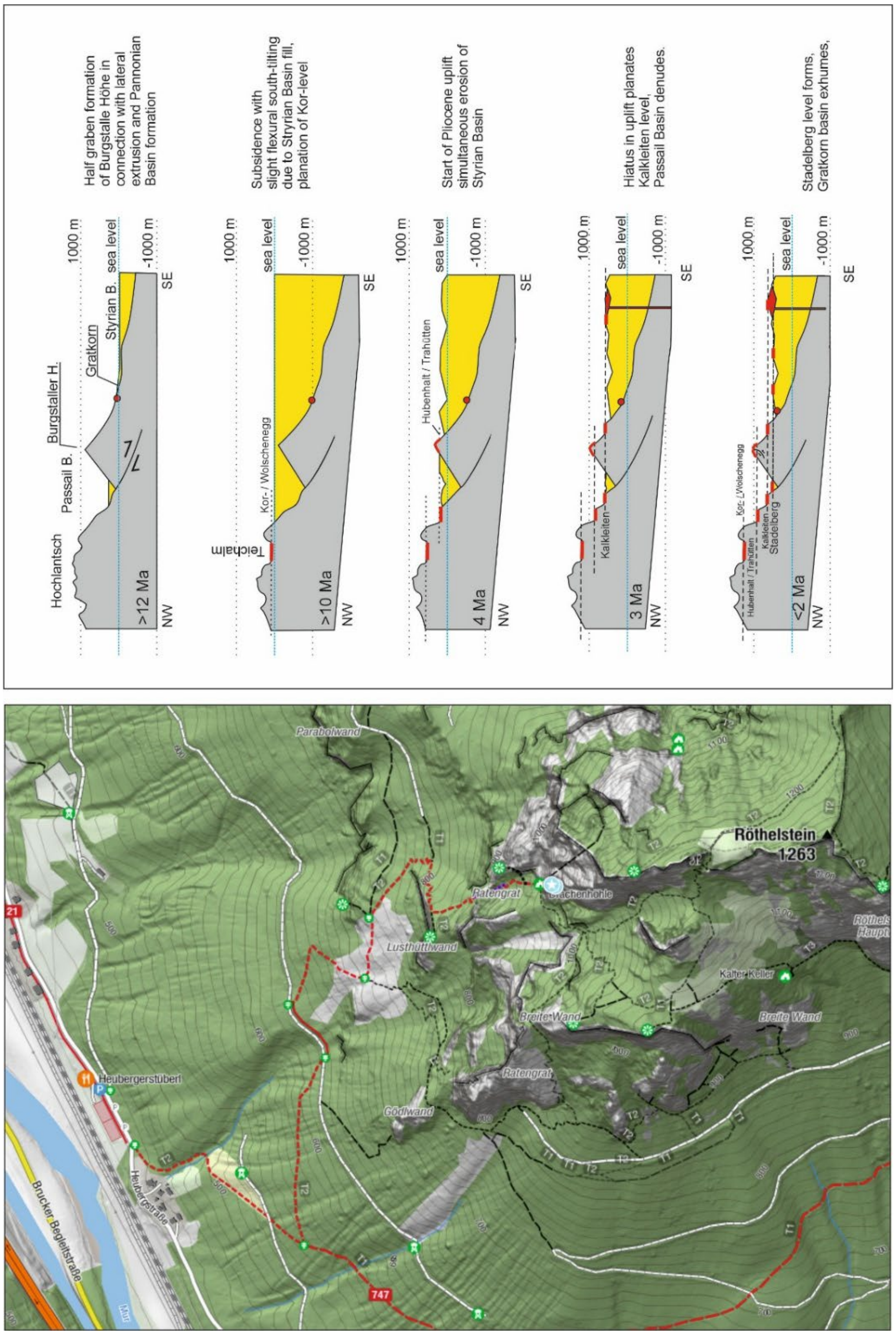

Fig. 2: Hiking map to the Drachenhöhle (PANGEO field trip afternoon part). And: a schematic north south cross section through the Grazer Bergland region illustrating the interpreted uplift history over time (Stüwe and Hohmann, 2021). Note that – because of the erodibility contract between soft basin sediment (yellow) and the hard rocks – erosion keep pace with tectonic uplift in the basins (i.e. NO surface uplift despite significant rock uplift), while surface uplift is almost as large as rock uplift (NO erosion) in the Bergland region. As a consequence, drainage gradients between Bergland and Basin oversteepen through time and erode river headwards leading to knickpoints and substantial river-piracy events in the Mur-Mürz catchment.

1 STOP 1

LOKATION: Marterl wenige Hundert Meter nordwestlich der Schule in Kalkleiten entlang Straße Richtung Semriach: Kalkleiten bei Graz (47°08‘42‘‘N; 15°26‘03‘‘E).

GEOMORPHOLOGISCHE POSITION: Kalkleiten Möstl/Hochstraden Niveau, die wichtigste Verebnungsfläche im Grazer Bergland.

WAS GIBTS ZU SEHEN?: Dieser Aussichtspunkt ist ein geologisches Highlight! Es gibt auf der ganzen Welt kaum einen Punkt von dem man mehr variable Geologie sehen kann als von hier. Nehmen Sie die geologische Karte der Steiermark (1:200.000) zur Hand und machen Sie sich vertraut mit der Geografie und Geologie die man von diesem Punkt sehen kann. An einem schönen Tag sehen sie von hier: Die Eklogit Fazies Gneise der Koralpe, Den Wildoner Berg (invertiertes Steirisches Becken), Sausal (Schwelle des Steirischen Becken Untergrundes aus Gratzer Paläozoikum), den Granitpluton im slowenischen Bachern Gebirge (Plattengrenze in der Periadriatischen Naht), die Gleichenberger Vulkankegel, Gleinalm (Ostalpines Kristallin), eiszeitlichen Terrassen in Graz die den Grazer Schlossberg als Inselberg umgeben und einiges mehr…. Was können Sie selber tun?: Identifizieren Sie diese Punkte!

Wir stehen hier mehrere hundert Höhenmeter über Graz, sind steil heraufgefahren, hinter uns geht es weiter hinauf auf den Schöckl und hier ist es völlig flach. Erosionsprozesse machen allerdings keine flachen Ebenen – außer auf der Talsohle. Daher ist dieses Niveau als Relikt einer Talsohle interpretierbar. Es ist die Talsohle vor 3 Ma. Sie ist auch stark verkarstet. Sie ist unter dem Namen „Kalkleiten-Möstl Niveau“ bekannt aber heißt auch „Hochstraden Niveau“ weil sie den Gipfel des Stradener Kogel im Steirischen Becken abflacht (auf gleicher Höhe wie hier). Wir wissen daher, dass die Hebung der Steiermark sowohl das Grazer Bergland als auch das steirische Becken erfasst, aber im Becken die Erosionsrate viel höher ist und daher die Oberfläche niedriger geblieben ist.

Was können Sie selber tun?: (a) Verinnerlichen Sie sich den Unterschied zwischen Hebung von Gesteinen und Hebung der Oberfläche: Steirisches Becken und Grazer Bergland haben den SELBEN Hebungsbetrag der Gesteine, aber sehr verschiedene Hebungsbeträge der Oberfläche. (b) Nennen sie weiter 4 wichtige Verebnungsflächen im Grazer Bergland die tiefer und höher liegen als das Kalkleiten Niveau (Nehmen Sie dazu Einheit 9 zur Hilfe). (c) Beobachten Sie auf der Weiterfahrt Richtung Semriach die Dolinen und seltsame Morphologie mit Hügeln auf der Talseite der Straße.

2 STOP 2

LOKATION: Von Stopp 1 fahren wir Richtung Semriach beim Gasthof Martinelli vorbei und durch den Rannachgraben hinunter ins Rötschgrabental, das wir bei der „Schule im Augraben“ erreichen. Hier rechts Richtung Richtung Semriach, aber bald schleifende rechts abzweigen zum: Sandwirt am Fuß des Kesselfall (47°12‘06‘‘N; 15°24‘00‘‘E).

GEOMORPHOLOGISCHE POSITION: Am Fuß des Kesselfall - ein dramatischer Knickpunkt im Rötschgraben.

WAS GIBTS ZU SEHEN?: Beobachten Sie, dass wir hier noch fast auf Mur Niveau sind: Die Fahrt hierher war im Wesentlichen ein flaches Tal. Bab hier geht es jedoch steil hinauf in den Kesselfall Klamm. Ein solch dramatischer Knickpunkt kann nur durch plötzliche Absenkung des „Base levels“ entstehen (lithologisch sind wir hier überall in sehr ähnlichen Gesteinen). Diese Absenkung des Base levels ist durch die Absenkung des Murtals vor 3 Ma entstanden und der Kesselfall Knickpunkt ist seither 7-8 km in das Tal bis hier hinein gewandert.

Was können Sie hier selber tun?: Wandern Sie nun zumindest bis zu den Leitern im Kesselfall um ein Gefühl für den Knickpunkt zu bekommen. Wenn Sie 2 Auto haben, können Sie auch eines bei Stopp 3 am Oberende des Kesselfall parken und einmal ganz durch gehen.

3 STOP 3

LOKATION: Fahren Sie von Sandwirt zurück bis zur Semriach Bundesstraße und diese hinauf (den Kesselfall umfahrend) bis zum Supermarkt Hitzendorf am Ortseingang von Semriach. Hier Parken. Gehen Sie auf die gegenüberliegende Straßenseite (dort ein paar Meter nach links) und dann 20 m den Wanderweg Richtung Kesselfall hinein. Rechterhand ist ein Zaun mit einem kleinen Aufschluss im 1 m tiefen Graben wo Schotter aufgeschlossen sind (47°12‘45‘‘N; 15°23‘58‘‘E).

GEOMORPHOLOGISCHE POSITION: Schotter bedeckte trockene Geländeschwelle zwischen Semriach Polje und Kesselfall auf Höhe des Kalkleiten Niveaus.

WAS GIBTS ZU SEHEN? Obwohl wir hier auf einem Gewässerlosen trockenen Sattel stehen, der die Semriach Polje vom Rötschgraben trennt, besteht diese Schwelle aus einer massiven Schotterbank. Wie kommen die Schotter auf diesen Sattel? Flusspiraterie Ereignisse haben diesen Sattel trocken gelegt. Davor floss der Lurbach über diese Schwelle in den Rötschgraben.

Was können Sie hier tun?: Nehmen Sie die topografische Karte zur Hand und schauen Sie nach wie der Lurbach direkt auf den Kesselfall zufließt und dann einen scharfen Knick nach Nordwesten zur Lurgrotte macht. Bis vor 2 Ma floss der Lurbach geradeaus über diese Schwelle ins Rötschbachtal. Etwa zeitgleich fing der zurückwandernde Kesselfall Knickpunkt den oberen Rötschbach ab und leitete denselben in den Kesselfall um. Beobachten Sie auf der Karte und im Gelände wie der obere Rötschbachgraben heute verläuft.

4 STOP 4

LOKATION: Fahren Sie nun vom Stopp 3 in die Ortschaft Semriach und weiter den Schildern zur Lurgrotte folgend bis zum Parkplatz Semriacher Lurgrotte. Gehen Sie um das Haus herum bis zum Eingang der Höhle (47°13‘37‘‘N; 15°22‘47‘‘E).

GEOMORPHOLOGISCHE POSITION: Lurgrotten Eingang Semriach.

WAS GIBT'S ZU SEHEN?: Sie sind jetzt am tiefsten unkt des „Waschbeckens“ beim Abfluss der größten Polje Österreichs. Hier verschwindet der Niederschlag von fast 50 km^2 in die Lurgrotte.

Was können Sie hier tun?: Beobachten Sie die Schotterbank, die (bereits überdacht) wenige Meter im Lurgrotten Eingang liegt. Hier werden kristalline Schotter gerade in die Höhle gespült und beginnen ihr „burial age“. Versuchen Sie einen gerundeten Quarzkiesel zu finden.

5 STOP 5

LOKATION: Fahren Sie nun vom Lurgrotten Eingang zurück zur Bundesstraße, aber nun nicht rechts Richtung Semriach, sondern links bis zur kleinen Siedlung Pöllau. Biegen Sie hier links ab und fahren noch 200 m bis zum Fahrverbotsschild am Waldrand: Straßenende bei Pöllau (47°13‘46‘‘N; 15°22‘31‘‘E).

GEOMORPHOLOGISCHE POSITION: Dolinen Plateaus des Tanneben Massifs auf Kalkleiten Level Niveau.

WAS GIBT'S ZU SEHEN?: Verinnerlichen Sie sich, dass es hier geradeaus nun über die flachen Wiesen von Pöllau in Richtung Badlgraben geht und dort ein weiterer klammartiger Abbruch – also ein Knickpunkt – liegt, der durch die plötzliche Absenkung des Murtals entstanden ist.

Was können Sie hier tun?: Wenn Sie noch kein gutes Gefühl dafür haben warum die Mur vor etwa 4 Ma plötzlich eingeschnitten wurde, dann schauen Sie sich im Bergland Manuskript von Einheit 9 die Abbildung 13 noch einmal sorgfältig an und lesen den Abschnitt „4.2. Geomorphological Evolution“ nochmal. Es ist weil erst vor 4 Ma die Mur von ihrem Verlauf durch das Mürztal ins Wiener Becken auf ihren heutigen Kurs von Bruck nach Graz umgeleitet wurde. Die Wasserscheide, die etwa 300-400 m über der heutigen Badl Enge lag wurde dann dramatische schnell abgetragen und die Mur schnitt sich sehr schnell auf ihr heutiges Niveau ein. Spazieren Sie nach rechts in den Wald (westliche Richtung) und spazieren Sie durch eine oder mehrere der gigantischen Dolinen. Überall werden Sie vereinzelt Schotter finden für das Tanneben Massif so typisch sind.

6 STOP 6

LOKATION: Fahren Sie nun zurück nach Semriach und kurz westlich vom Supermarkt (Stopp 3) geht es rechts ab Richtung Taschen und Peggau. Fahren Sie die Straße hinauf bis zu einem guten Aussichtspunkt über Semriach. Zum Beispiel an der Stelle wo links der Straße ein Sitzbankerl auf der Wiese steht (47°12‘27‘‘N; 15°23‘11‘‘E). Setzten Sie sich aufs Bankerl (oder gehen ein paar Meter vor damit die Bäume nicht im Weg sind) um einen Blick Richtung Kesselfall zu haben.

GEOMORPHOLOGISCHE POSITION: Guter Überblickspunkt über die Fluss-Piraterie Ereignisse des Semriacher Beckens

WAS GIBT'S ZU SEHEN?: Nehmen Sie die Skizzen aus dem Grazer Bergland Paper (von Einheit 9) zur Hand (insbesondere Abb. 7a und Abb. 5) und verinnerlichen Sie sich die morphologische Situation.

Was können Sie hier tun?: Mit den Skizzen und der Topografischen Karte zur Hand, verfolgen Sie die Verläufe von Lurbach, Kesselfall und oberem Rötschbachgraben im Gelände und versuchen Sie die Flusspiraterie Ereignisse nachzuvollziehen (so ähnlich wie bei Stopp 3).

7 STOP 7

LOKATION: Fahren Sie nun weiter bergauf über den Sattel und die Straße hinunter nach Peggau. In Peggau direkt am Wandfuß der Peggauer Wand entlang bis ans Nordende Peggau zum Ende der Straße am Wandfuß der Peggauer Wand (47°12‘35‘‘N; 15°20‘50‘‘E).

GEOMORPHOLOGISCHE POSITION: Hammerbach Austritt.

WAS GIBT'S ZU SEHEN?: Gehen sie ein paar Schritte den Fahrweg hinauf (an den blockierenden Steinen vorbei) bis zur Quelle des Hammerbach. Dieser Bach ist jener der in Semriach in die Lurgrotte hineinfließt und ist unter den Hydrogeologen der Uni Graz gut bekannt und für Tracer Versuche beliebt. Sie sehen auch die Pegel Messstation des Joanneum Research. Historisch interessant sind die Stolleneingänge etwa 50 m weiter, die zum Teil versperrt, zum Teil aber auch offen sind. Hier führen ein paar gut ausgebaute Stollen tief in die Peggauer Wand hinein. Diese Stollen sind unter dem Namen „Stollenanlage Marmor“ bekannt und waren im 2. Weltkrieg Fertigungsanlagen.

Was können Sie hier tun?: Neben der Beobachtung einmal den Hammerbach gesehen zu haben können Sie auch die Stollenanlage besichtigen: Wenn Sie mit Taschenlampe ausgerüstet 100 oder 200 Meter in die Stollen gehen finden Sie auch Relikte von Versuchsanlagen von Joanneum Research.

8 STOP 8

LOKATION: Fahren Sie nun zurück auf die Peggauer Bundesstraße und nun Richtung Norden. (Wenn Sie Lust haben und die Lurgrotte noch nicht kennen, können Sie noch einen kurzen Abstecher zum Peggauer Lurgrotten Eingang machen.) Dann fahren Sie aber weiter Richtung Nord, entlang der historischen Badl Gallerie durch die Badl Enge bis zum Badlgraben etwa 1 km nördlich von Peggau. Hier parken auf dem Parkplatz gegenüber dem Eingang zum Badlgraben (westliche Straßenseite) (47°13'38''N; 15°20'33''E).

GEOMORPHOLOGISCHE POSITION: Kapellenhöhle. Gehen Sie auf die östliche Straßenseite etwa 10-20 m südlich der Kapelle durch die Büsche direkt zum Wandfuß (5 m von der Straße) in die Kapellenhöhle.

WAS GIBT'S ZU SEHEN?: Sie sind jetzt gerad durch die Wasserscheide de rMur vor 4 Ma gefahren! Südlich und nördlich der Badl Enge ist das Tal breit und offen. In die Badl Enge selber hat sich die Mur erst vor knapp 4 Ma eingeschnitten. Steile Felswände und viele Höhlen die sich im Strudel gebildet haben sind die Relikte diese dramatischen Geschichte. Gehen Sie in der Kapellenhöhle etwa 15 m bis zum Höhlenende. Wenn sie hier nach oben schauen sehen Sie 1 m über sich Kalksteinbrocken, die eingesintert sind und eine Art Brekzie bilden. Das Ganze verfüllt einen schönen runden ausgewaschenen senkrechten Erosionskolk.

Was können Sie hier tun?: Wenn Sie genau schauen finden Sie etwa 1 cm große gerundete Kieselsteine in der Brekzie. Diese Kieselsteine sind aber erst NACH der Höhlenbildung von der Oberfläche hineingerieselt und sind daher nicht sehr nützlich um das Höhlenbildungsalter via Burial ages mit kosmogenen Isotopen zu messen.

9 STOP 9

LOKATION: Wie gehen nun zur Badlhöhle. Folgen Sie dazu dem markierten Wanderweg in den Badlgraben, der wenige Meter nördlich vom Parkplatz beginnt und nach Osten in den Graben führt. Es geht auf einem kleinem Fußweg ein paar Mal über den Bach immer weiter in den Graben. Nach 5-10 Minuten geht es nach rechts über eine alte Betonbrücke. Ab hier aufpassen damit Sie den Abzweig nicht verpassen! Es geht noch etwa 50 Meter weiter bis Sie einmal über einen ausgewaschenen Felsaufschluss klettern. 10-20 Meter danach zweigt recht schräg zurück ein Steigerl steil hinauf in den Wald ab. Dieses hinauf! Das Steigerl geht ein paar Mal zick zack und zum Teil ist es aufgrund umgefallener Bäume fast nicht erkennbar, aber steigen Sie nun in der Falllinie etwa 70 (+/- 20 Höhenmeter) direkt hinauf. Kurz vor der Badlhöhle erkennt man große Schutthalden die vom Abbau der Bärenknochen herrühren, die hier vor 100 Jahren aufgrund ihres Phosphorgehalts als Dünger für die Felder von Peggau in der Badlhöhle abgebaut wurden, Der Eingang der Badlhöhle ist 5-6 Meter hoch und 4 Meter breit am Fuß einer kleinen Felswand leicht zu erkennen und vergittert (47°13‘39‘‘N; 15°20‘55‘‘E). Das Gitter ist jedoch an einer Stelle durchbrochen und man kann in die Höhle hinein schlupfen…..

GEOMORPHOLOGISCHE POSITION: Badlhöhle.

WAS GIBT’S ZU SEHEN?: Die Badlhöhle wurde im phreatischen Milieu, also UNTER dem grundwasserspiegel gebildet und besteht daher nicht aus einem horizontalen Tunnel, sondern besteht aus Kugelförmigen Räumen. Gegenüber der Badlhöhle auf der anderen Hangseite ist die Repolusthöhle. Im Sommer können sie diese von hier aus nicht sehen, aber sie ist berühmt für ihre Steinzeitlichen Relikte.

Was können Sie hier tun?: (a) Wenn -sie mutig sind, können Sie die Badlhöhle besuchen. Man kann sich eigentlich nicht darin verlaufen – seien Sie also beruhigt. Schlupfen Sie durch das Gitter und halten Sie sich rechts immer Bergauf den Steigspuren folgend. Nach etwa 100 m kommen Sie an einigen schönen Tropfsteinen vorbei und stehen danach in einem großen Raum von dem auch noch mehrere kleine runde Seitengänge wegführen. Dies ist der letzte große Raum und praktisch das Höhlenende.

(b) Vor der Höhle können Sie versuchen fossile Höhlenbärenzähne auf der Schutthalde zu finden. Am leichtesten findet man die Zähne ohne zu graben, sondern einfach durch sorgfältiges Schauen nach einem Regen. Dann haben die Regentropfen die Zähne vom Lehm freigewaschen und man sieht den fossilen Zahnschmelz in der Erde blitzen.

10 STOP 10

LOKATION: Gehen Sie zurück zum Auto und fahren Sie nun vom Parkplatz kurz (<100 m) Richtung Süden und Richtung Autobahnauffahrt (Hinweistafel zum Golfplatz Murhof) aber nicht auf die Autobahn, sondern über die Holzbrücke über die Mur und dann links entlang dem Wandfuß entlang der Mur Richtung Deutschfeistritz. Hier ist ein Fahrverbotsschild. Für 1 km ist hier Fahrverbot und sie können zu Fuß hinein gehen und wieder zurück. (Die Weiterfahrt geht allerdings dann zur Kirche in Deutschfeistritz bei Stopp 11 und die Straße geht geradeaus weiter genau dort hin. Wenn Sie also keinen großen Umweg fahren wollen und „Mutig sind" könnten sie das Fahrverbot ignorieren und den 1 km durchfahren und direkt zum Stopp 10 fahren ;-), Nach etwa 600 m fahren/gehen Sie ein 2. Mal unter der Bahn und gleich danach unter der Autobahn durch. Danach sehen Sie links Stromschnellen und Aufschlüsse im Murbett (47°13'07''N; 15°20'08''E).

GEOMORPHOLOGISCHE POSITION: Stromschnelle in Mur.

WAS GIBT'S ZU SEHEN?: In diesen Stromschnellen tritt das anstehende Gestein zutage. Der Fluss ist also ganz klar „detachment limitiert".

Was können Sie hier tun?: Verinnerlichen Sie sich, dass die Mur im Peggauer Becken und im Frohleitener Becken auf ihren eigenen eiszeitlichen Terrassen entlang fließt und hier direkt am Bedrock. Die Mur alterniert zwischen Bruck und Graz mehrfach zwischen einem „Bedrock channel" und einem „Alluvial channel". Das liegt daran, dass die Mur in den Eiszeiten ihr eigenes Bett mehrere Zehner Meter mächtig aufgeschottert hat und diese Schotter seit der letzten Würm Eiszeit noch nicht ganz wieder ausgeräumt hat. Beachten Sie außerdem, dass dieser Aufschluss im Mur Bett der letzte anstehende Aufschluss für die nächsten 1000 km ist. Erst nachdem Mur in Drau und Donau geflossen ist, hat die Donau erst bei dem „Iron Gates" wo sie den Karpaten Bogen durchbricht, das nächste Mal anstehendes Gestein in ihrem Bett.

11 STOP 11

LOKATION: Fahren Sie weiter nach Süden bis Deutschfeistritz (oder zurück nach Peggau und südlich von Peggau nach Deutschfeistritz wenn Sie nicht durch das Fahrverbot fahren wollen) und um den Kirchberg herum Richtung Übelbachtal. Nur etwa 100 m nach dem Hauptplatz zweigt rechts die kleine Straße auf den Kirchberg ab (Achtung: leicht zu übersehen!). Hier hinauf bis zum Parkplatz vor der Kirche und zu Fuß durch den Torbogen auf die Westseite der Kirche wo am über eine Brusthohe Mauer einen schöner Überblick über das Tal hat. Kirche Deutschfeistritz (47°12‘07‘‘N; 15°20‘08‘‘E).

GEOMORPHOLOGISCHE POSITION: : Überblick über das Peggauer Becken.

WAS GIBT’S ZU SEHEN?: Diese Punkt ist ein schöner Überblickspunkt um sich das Peggauer Becken und die alte Wasserscheide der Mur in der Badl Enge zu verinnerlichen.

Was können Sie hier tun?: (a) Erkennen sie dass das Peggauer Becken völlig flach ist Solch flache Ebnen können nur durch Sedimentation entstehen: Das ganze Peggauer Becken ist von massiven eiszeitlichen Terrassen gefüllt „Burial Ages“ von Kieseln aus der Lurgrotte sind bis zu einer halben Million Jahre alt. Das ist viel älter als die Durchlauf Geschwindigkeit für Kiesel von Semriach nach Peggau dauern würde und deutet an, dass der Peggauer Lurgrotten Eingang in den Eiszeiten zu geschottert war und die gesamte Lurgrotte voll Sedimente war. (b) Erkennen Sie die höhlen in der Peggauer Wand. Sie sind alle trocken! All diese Höhlen haben sich gebildet während die Mur durch die Badl Enge einschnitt. (c) Erkennen Sie die Badl Enge am Nordrand des Peggauer Beckens. Hier ist der Ursprung der „Paleo Mur“ die nach Süden floss. Nördlich der Badl Enge entwässerte ein andere Fluss nach Norden Richtung Bruck und von dort in Richtung Semmering ins Wiener Becken.

Wenn Sie um die Kirche herumgehen finden Sie auf der Südseite auch einen Karner voller menschlicher Knochen.

12 STOP 12

LOKATION: Hart bei Gratkorn. Fahren Sie nun zurück nach Peggau und auf der Bundesstraße Richtung Graz. Südlich von Gratkorn, wenige hundert Meter vor der Autobahnauffahrt kann man nach links abzweigen und steil hinauf Richtung Hart fahren. Nach wenigen hundert Meter ist auf der linken Seite ein mit Drahtgittern zugehängter Aufschluss. Fahren sie hier noch vorbei, nach der Kurve kann man gut links parken und gehen Sie 100 m zurück zum Aufschluss (47°12‘07“N; 15°20‘08“E).

GEOMORPHOLOGISCHE POSITION: Schottergefüllte Störungszone mit denen die Inversionsgeschichte des Steirischen Beckens messbare wäre….

WAS GIBT'S ZU SEHEN?: Wenn Sie den Aufschluss entlang der Straße nach unten gehen kommen Sie an mehreren Schotter gefüllten Störungszonen vorbei. Die Störungen fallen steil nach Norden ein. Sie sind bis zu 1 m breit und von horizontal gefülltem Quarzschotter gefüllt. Durch das Gitter über dem Aufschluss sind sie nicht leicht zu erkennen aber halten Sie die Augen offen!

Was können Sie hier tun?: Überlegen Sei sich wie diese horizontal geschichteten Schotter in die Störungszone kommen können? Eigentlich müssen Sie von oben hinein gerieselt sein und zwar kurz nachdem die Störungszone sich erdbebenartig geöffnet hat, denn eine so große Kluft würde nicht sehr lange offen bleiben. Dies bietet die Möglichkeit, dass wir ein Sprödbruch Ereignis mittels Burial Ages der Schotter datieren könnten.

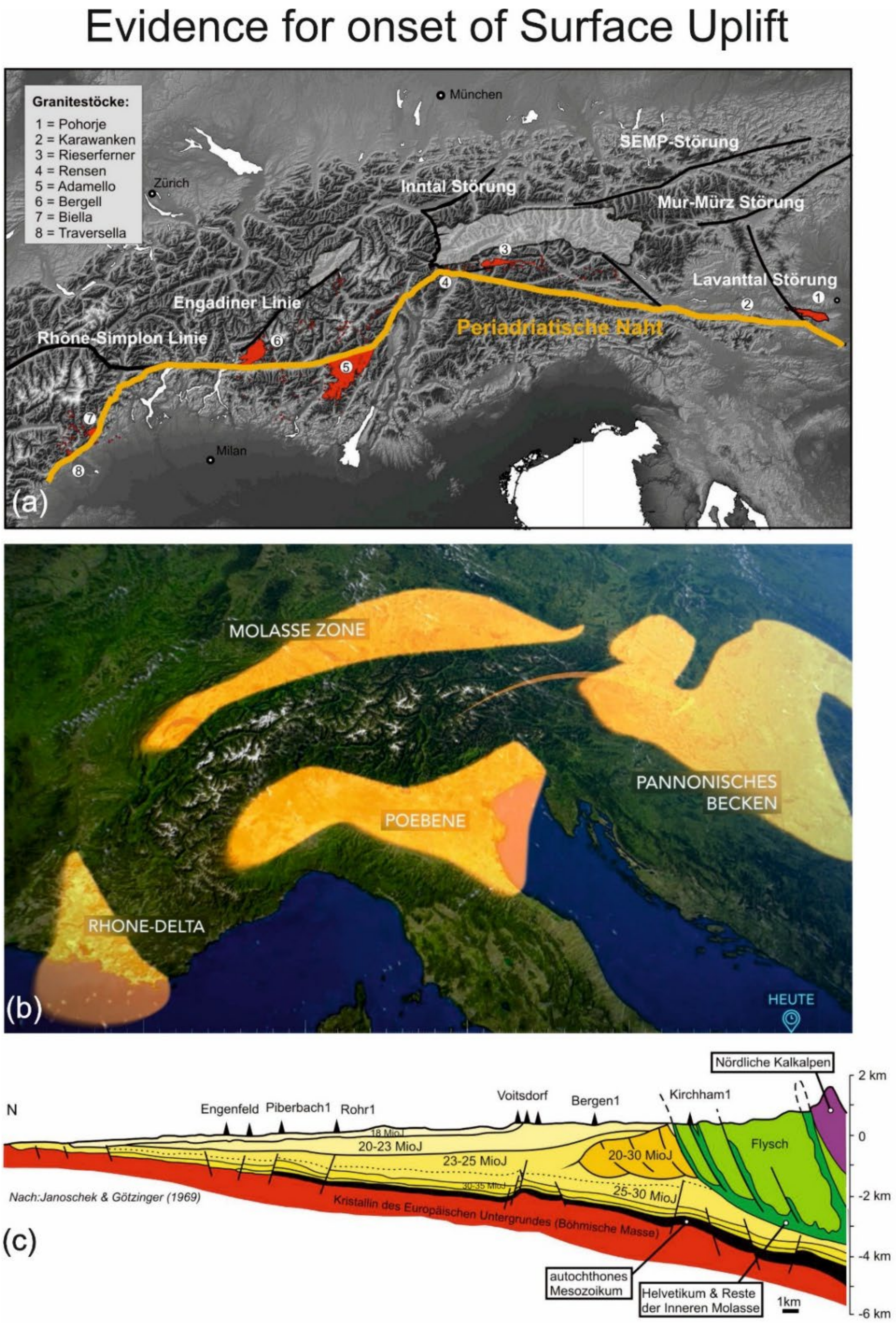

Fig. 3: Classic evidence for onset of surface uplift in the Alps around 30 Ma. (a) The formation of the Periadriatic line around 30 Ma marks the creation of a new plate boundary between the Adriatic and the European plates. It formed in response to the final subduction of the Penninic ocean, the beginning of the head-on collision between the two continental plates and the creation of potential energy (uplift) in the Alps. (b) Five sedimentary basins surrounding the Alps (Danube delta in Black Sea is not shown) accommodate sediments that erode from the range in response to uplift. The oldest sediments in all basins are around 30-35 Ma. (c) The Molasse basins (north and south) are classic foreland basins: they formed due to elastic down-bending of the plate in response to loading by topography. Oldest sediments are 35 Ma.

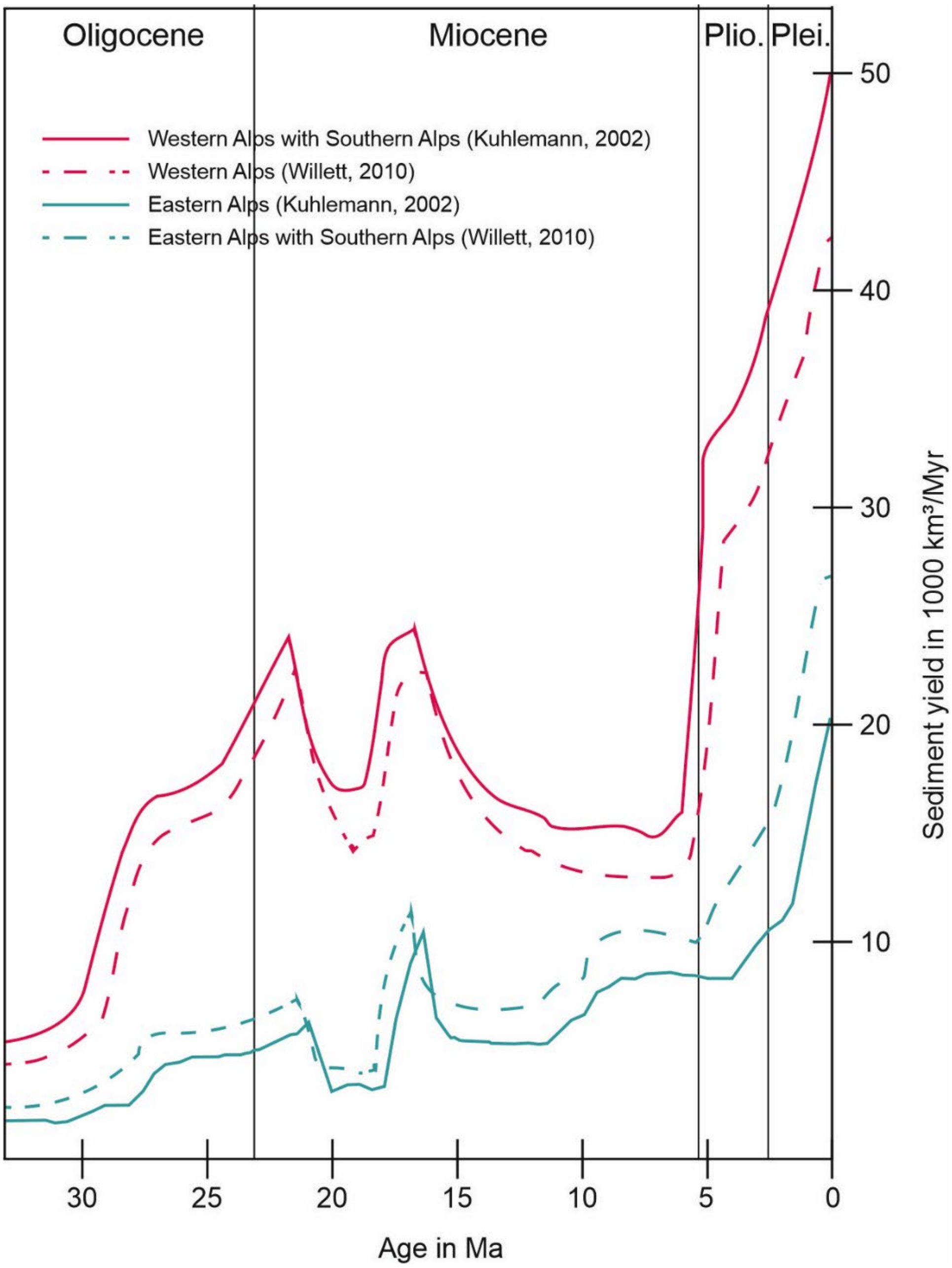

Fig. 4: Kuhlemann et al. (2002) recognized that the sedimentation rates into the basins surrounding the Alps can be used as a proxy for surface uplift. His seminal work showed that the sedimentation rate has not been linear through time. However, the dramatic increase in the last 5 Ma has long not been recognized as evidence for dramatic increase in uplift rates. Instead, it has been interpreted as a sampling artefact (Willenbring and Blanckenburg 2010, Willett 2010) or as a response to glaciation In the Eastern Alps it has only been shown by Wagner et al. (2010) that it may in fact be due to rapid uplift. We will see the first location this was documented in the Drachenhöhle today.

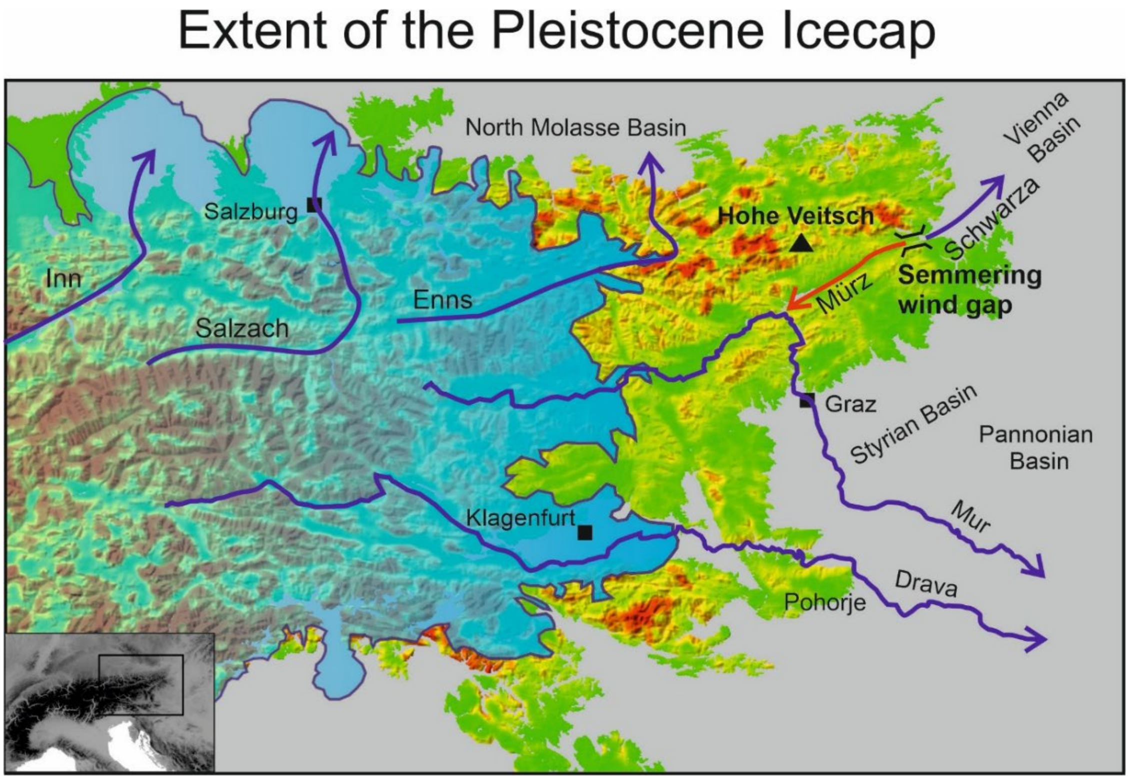

Fig. 5: In order to find geomorphic evidence for surface uplift it is necessary to study regions where the Pleistocene glaciations did not reach. In the entire Alps, the eastern end of the range is the only region with peaks up to 2000 m and above that were never pervasively glaciated. The LGM Ice cap reached in the Drau valley only as far as Völkermarkt, in the Mur valley as far as Judenburg and the Enns glacier reached as far as Admont and Treglwang. East of there Pre-Pleistocene geomorphic evidence is preserved.

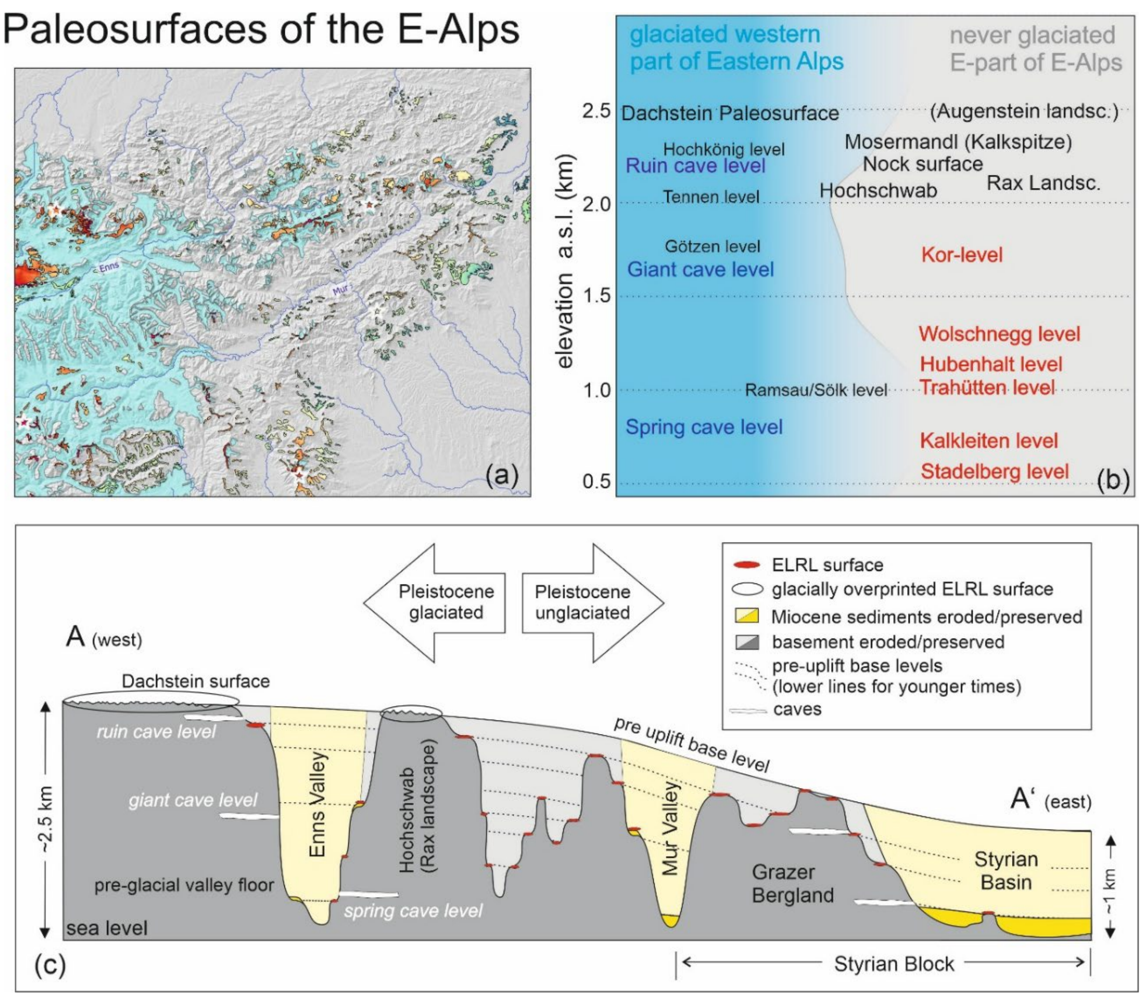

Fig. 6: At the eastern end of the Alps that escaped pervasive Pleistocene glaciation, an interesting landform is preserved: elevated low-relief surfaces that occur at a series of elevations. The highest is well known as the Dachstein Plateau, but these surfaces have been well known (and named) for about 100 years. (a) shows the mapping results of Gradwohl et al. (2024) (b) Some of the named paleosurfaces. Red are those we will see in the Grazer Bergland. (c) These surfaces have been correlated across much of the Eastern Alps (initially by Wagner et al., 2011 and then many other studies summarized by Gradwohl et al., 2024) to show that surface uplift in the Eastern Alps is a broad long wavelength process with a slight increase in uplift rate to the west.

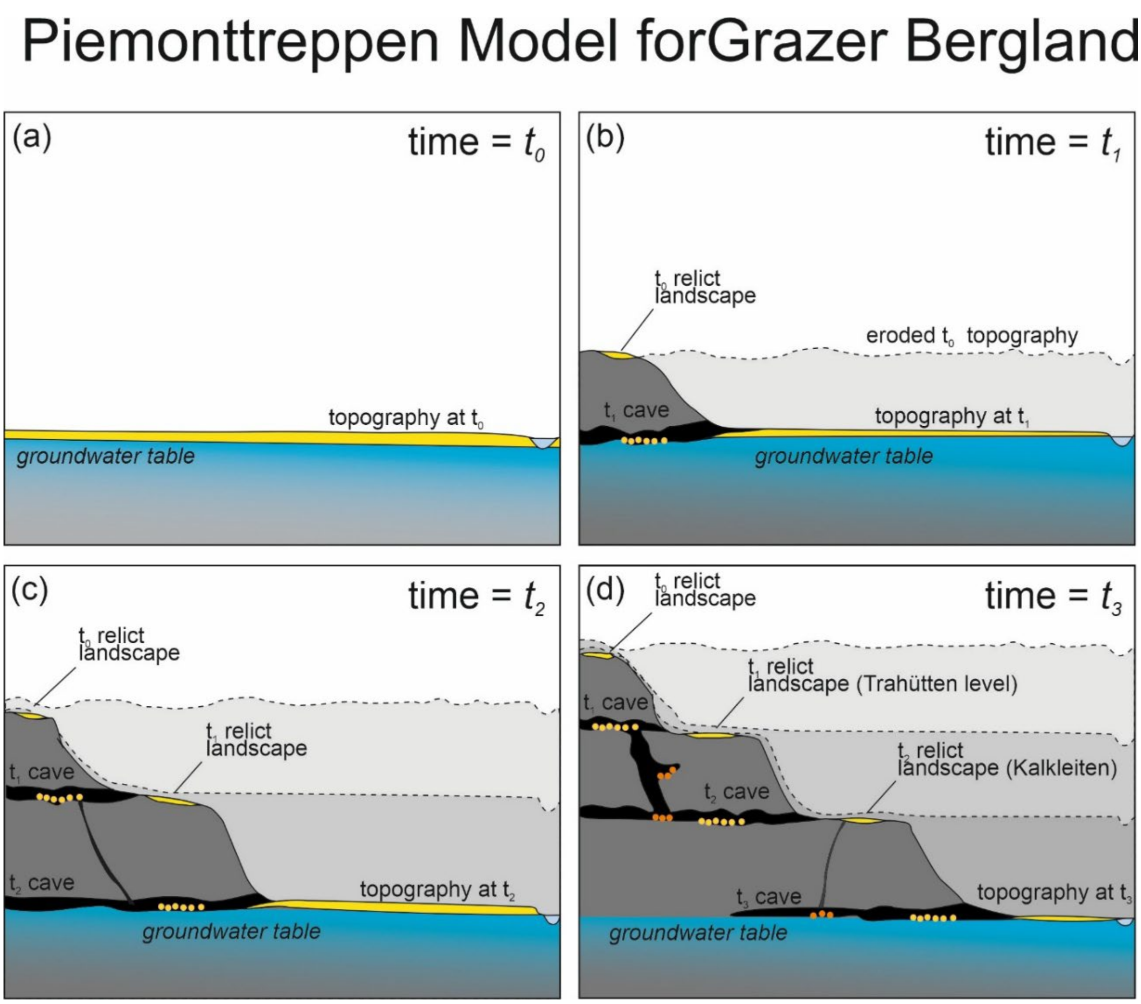

Fig. 7: The elevated low relief surfaces can be interpreted in terms of a “Piedmonttreppe”. This concept was first described in the Black Forrest by Penk (1925) and interprets a series of elevated low relief surfaces as relicts of valley floors (base level) that are preserved on flanks of mountain ranges and record pulses and stagnation phases during a long lived uplift history. During stagnation phases karst caves may form at the same elevation on the phreatic-vadose transition. Dating of cave formation can therefore provide a useful proxy to document uplift history.

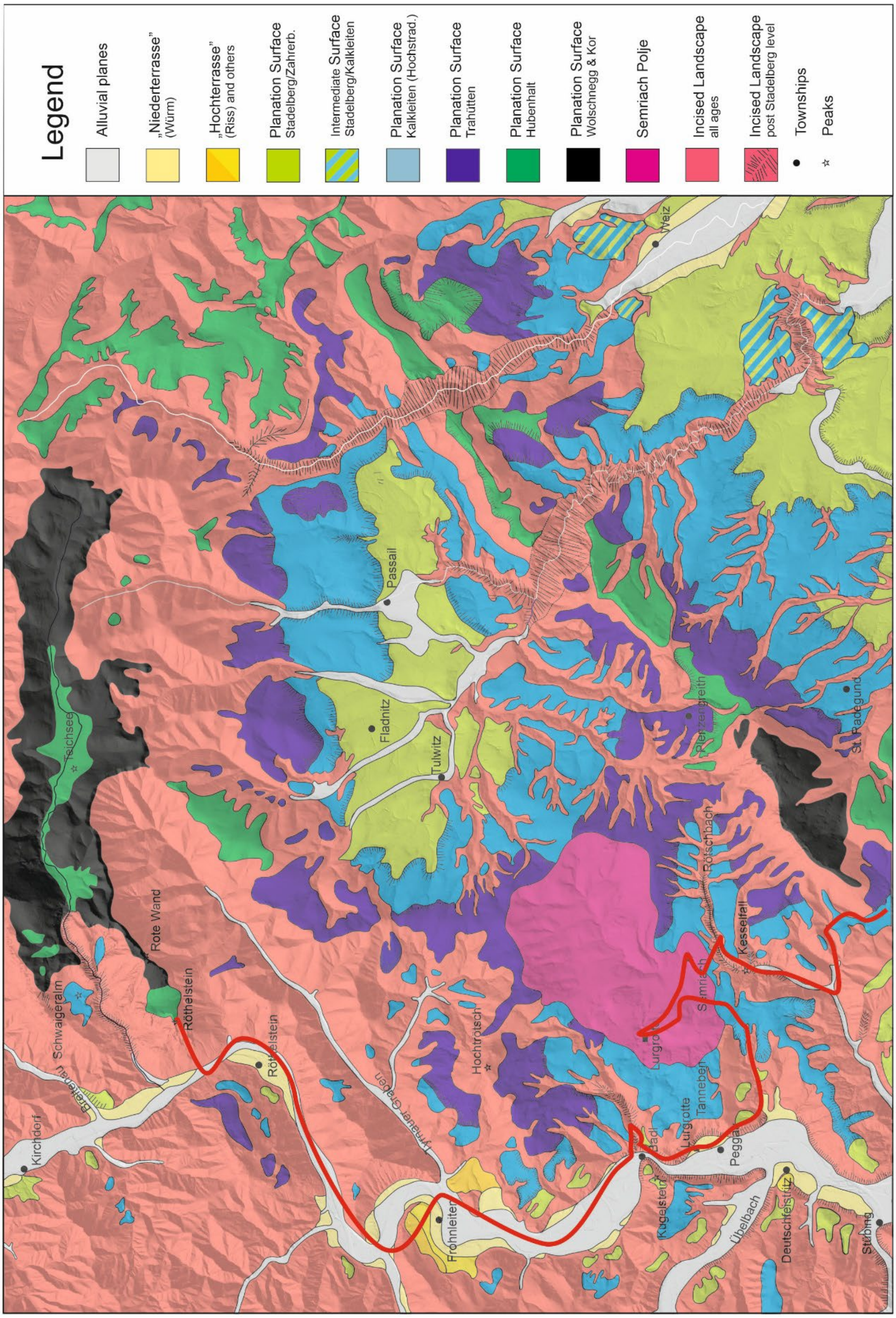

Fig. 8: Geomorphic map of the Grazer Bergland region of Stüwe and Hohmann (2021). The field trip line is marked in red.

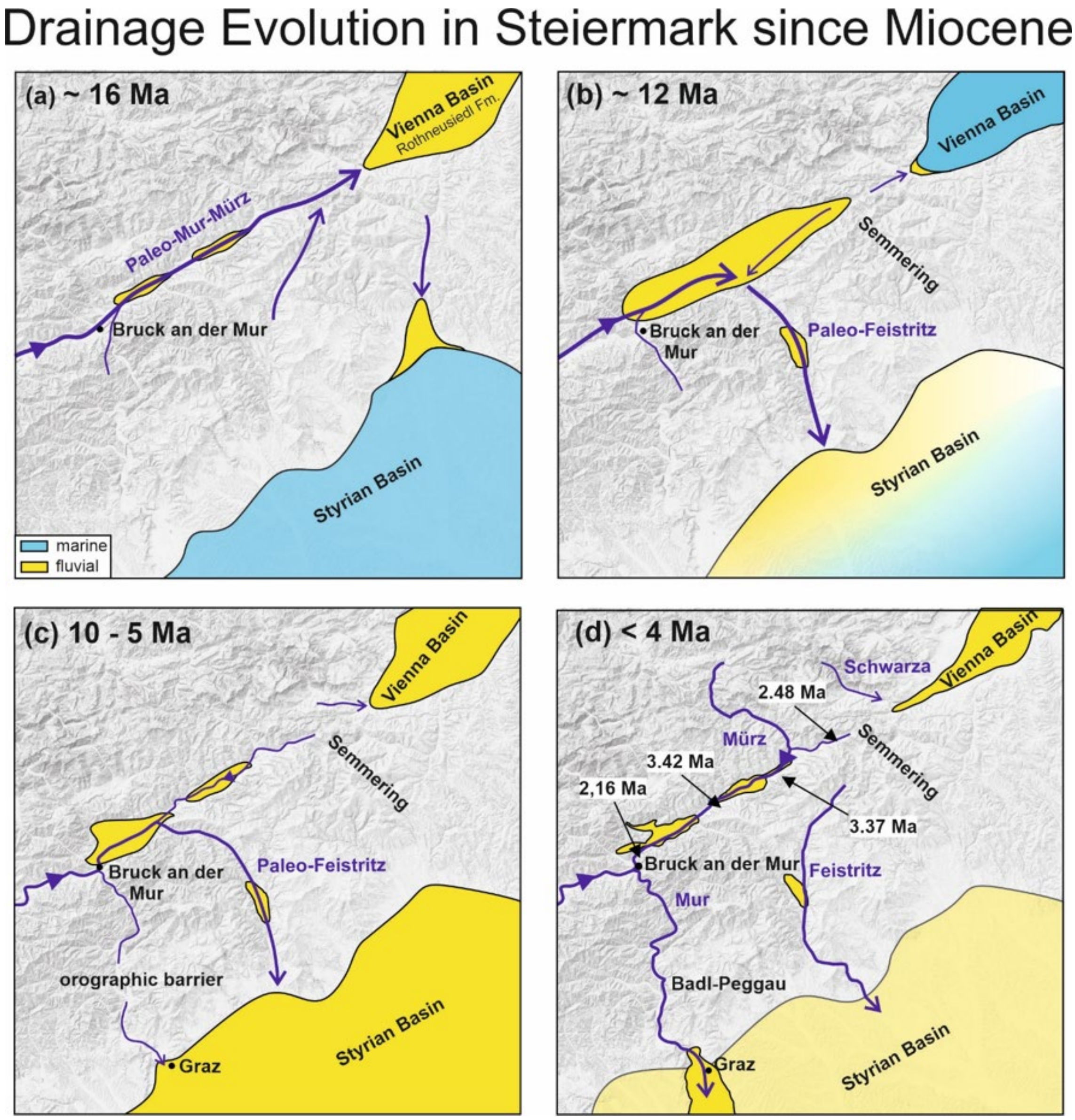

Fig. 9: Drainage evolution of the Eastern End of the Alps since the Miocene. Aspects of this figure were published by Stuimpf and Stüwe (2019), Patscheider and Stüwe (2023) and Hohmann and Stüwe (2024) and are currently being summarized in connection with geochronological dating of the Mürz valley by Del Negro et al., (2026).

13 References

Bartosch, T., Stüwe, K., 2019. Evidence for pre-Pleistocene landforms in the Eastern Alps: Geomorphological constraints from the Gurktal Alps. Austrian J. Earth Sci. 112, 84–112.

Bartosch, T., Stüwe, K., Robl, J., 2017. Topographic evolution of the Eastern Alps: the influence of strike-slip faulting activity. Lithosphere 9, 384–398. https://doi.org/ 10.1130/L594.1.

Dixon, J.L., von Blanckenburg, F., Stüwe, K., Christl, M., 2016. Glaciation's topographic control on Holocene erosion at the eastern edge of the Alps. Earth Surf. Dynam. 4 (895–909), 2016. https://doi.org/10.5194/esurf-4-895-2016.

Dunkl, I., Kuhlemann, J., Reinecker, J., Frisch, W., 2005. Cenozoic relief evolution of the Eastern Alps–constraints from apatite fission track age-provenance of Neogene intramontane sediments. Austrian J. Earth Sci. 98, 92–105.

Frisch, W., Kuhlemann, J., Dunkl, I., Brügel, A., 1998. Palinspastic reconstruction and topographic evolution of the Eastern Alps during late Tertiary tectonic extrusion. Tectonophysics 297, 1–15.

Frisch, W., Kuhlemann, J., Dunkl, I., Szekely, B., 2001. The Dachstein paleosurface and the Augenstein formation in the northern calcareous alps - a mosaic stone in the geomorphological evolution of the eastern Alps. Int. J. Earth Sci. 90, 500–518.

Frisch, H., Kuhlemann, J., Dunkl, I., Szekely, B., Vennemann, T., Rettenbacher, A., 2002. Dachstein-Altfläche, Augenstein-Formation und Höhlenentwicklung – die Geschichte der lezten 35 Millionen Jahre in den zentralen N¨ordlichen Kalkalpen. Die Höhle 53, 1–36.

Gradwohl G., Stüwe K., Robl J., Liebl M. (2023). Topography and landscape evolution of the Alps. In: Rosenberg C. and Bellahsen N., (eds.) Geodynamics of the Alps 1, Wiley, ISBN 978–1–78945-116-0, pp. 115–147.

Gradwohl G., Stüwe K., Liebl M., Robl J., Plan L., Rummler L. (2024). The elevated low-relief landscapes of the Eastern Alps. Geomorphology 458. https://doi.org/ 10.1016/j.geomorph.2024.109264.

Hohmann K., and Stüwe K. (2024). The Fischbach Alps: A Geomorphological Record of late Neogene Uplift at the Eastern Margin of the European Alps. Austrian Journal of Earth Sciences, 117.

Kuhlemann J., Frisch W., Székely B., Dunkl I., Kázmér M. (2002). Post-collisional sediment budget history of the Alps: Tectonic versus climatic control. International Journal of Earth Science, 91, 818–837.

Legrain N., Stüwe K., Wölfler A. (2014). Incised relict landscapes in the eastern Alps. Geomorphology, 221, 124–138. https://doi.org/10.1016/j.geomorph.2014.06.010.

Legrain N., Dixon J., Stüwe K., von Blanckenburg F., Kubik P. (2015). Post-Miocene landscape rejuvenation at the eastern end of the Alps. Lithosphere 7, 3–13. https:// doi.org/10.1130/L391.1.

Patscheider L., Stüwe K. (2023). Entwässerungssystems der Ostalpen im Miozän: Eine Provinienz-Studie an Höhlensedimenten. Die Höhle, 74/1-4, 30-49.

Penck W. (1925). Die Piedmontflächen des südlichen Schwarzwaldes. Zeitschrift der Gesellschaft für Erdkunde zu Berlin, Berlin, pp. 81–108.

Schuster R., Stüwe K. (2022). Geological and tectonic setting of Austria. In: Embleton- , Hamman C. (Ed.), Landscapes and Landforms of Austria. Springer International Publ, 978-3-030-92813-1 (ISBN) 496 pp.

Stumpf S., Stüwe K. (2019). Aspekte der morphologischen Entwicklung des Murtales zwischen Bruck und Graz. Eine Augenstein Provenienz Studie. Mitteilungen des Naturwissenschaftlichen Vereins für Steiermark, 149, 63-81.

Stüwe K., Hohmann K. (2021). The Relic Landscapes of the Grazer Bergland: Revisiting the Piedmonttreppen debate. Austrian Journal of Earth Science 114, 46–65. https://doi.org/ 10.17738/ajes.2021.0003.

Stüwe K., Robl J., Fable D., Stuart F. Plan L., Ruszkiczay Zs. (2026). Surface uplift of the Eastern Alps. Was it much faster than we thought? Earth Science Reviews. https://doi.org/10.1016/j.earscirev.2025.105374

Willenbring J.K., von Blanckenburg F. (2010). Long-term stability of global erosion rates and weathering during late-Cenozoic cooling. Nature, 465, 211–214.

Willett S.D. (2010). Late neogene erosion of the Alps: A climate driver? Annual Reviews of Earth and Planetary Science, 38, 411–437.

Wagner T., Fabel D., Fiebig M., Häuselmann P., Sahy D., Xu S., Stüwe K. (2010). Young uplift in the non-glaciated parts of the Eastern Alps. Earth and Planetary Science Letters 295, 159–169.

Wagner T., Fritz H., Stüwe K., Nestroy O., Rodnight H., Hellstrom J., Benischke R. (2011). Correlations of cave levels, stream terraces and planation surfaces along the river Mur - timing of landscape evolution along the eastern margin of the alps. Geomorphology 134, 62–78.

Winkler-Hermaden A. (1957). Geologisches Kr¨aftespiel und Landformung. Springer Verlag, Wien, p. 822p.

21.-25. Sept. 2026

PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Field Trip 3

Das Neogen des Steirischen Beckens:

Einblicke in seine sedimentäre Evolution, Stratigraphie und Ressourcennutzung

/

The Neogene of the Styrian Basin:

Insights into its sedimentary evolution, stratigraphy and resource utilisation

Organizers:
Gerald Auer, Nikolaus Petschacher, Arthur Borzi,
Martin Gross, Gerfried Winkler & Werner Piller

NAWI Graz Natural Sciences

TU Graz

UNI GRAZ

The Neogene of the Styrian Basin: *Insights into its Sedimentary Evolution, Stratigraphy and Resource Utilisation*

Gerald Auer[1), Nikolaus Petschacher[2), Arthur Borzi[1), Martin Gross[3), Gerfried Winkler[1), Werner E. Piller[1)

[1)University of Graz, Departement of Earth Sciences, NAWI Graz Geocenter, Heinrichstraße 26, 8010 Graz, Austria
[2) Hydro GmbH, Ingenieurbüro für Hydrogeologie und Geothermie, Naglergasse 10, 8010 Graz, Austria
[3) Universalmuseum Joanneum, Department for Geology & Palaeontology, Weinzöttlstraße 16, 8045 Graz, Austria

DOI: https://doi.org/10.3217/xxx

1 The Styrian Basin – an overview

The Styrian Basin lies at the southeastern margin of the Alps and forms the westernmost extent of the Pannonian Basin in Austria. Crystalline Austroalpine units of the Koralpe–Wölz Complex bound it to the west and southwest, while its north-eastern extent is defined by the Graz Palaeozoic and, further north-east, the Penninic Güns Mountains. To the east and south-east, the basin is separated from the Pannonian basin system by the NE-SW striking South Burgenland High (Kröll, 1988). The basin is ~100 km long and ~60 km wide and covers an area of approximately 2500 km^2.

Geomorphologically, the landscape is characterised by a range of gentle hills separated by a predominantly south-east-draining river system. The Styrian Basin is internally divided into a Western and an Eastern Styrian Basin by outcropping basement units of the Sausal Mountains, which form the Middle Styrian High. Additional basement spurs and subordinate highs further differentiate bays and sub-basins (Fig. 2). Apart from the Sausal Mountains, the Miocene and Plio-Pleistocene volcanic "cones" (e.g., Gleichenberg, Kapfenstein) are a defining feature of the basin landscape.

Fig. 1: Aerial photographs of the Styrian Basin showing a view of the typical landscape in the basin south-east of Graz with the Middle Miocene (Badenian) volcanic Gleichenberg Kogel in the distance (**left image**) and (**right image**) an aerial view of the Riegersburg volcanic diatreme (photos courtesy of Kurt Stüwe; © Kurt Stüwe and Ruedi Homberger; https://luftbildsteiermark.at/, all rights reserved).

The Styrian Basin has been the subject of extensive study since the early 19th century. Arthur Winkler-Hermaden published an extensive body of scientific work in the early 20th century on the basin's stratigraphy and hydrogeology. He later summarised the state of knowledge in his monograph "Geologisches Kräftespiel" [Geological dynamics] in 1957 (Winkler-Hermaden, 1957). Winkler-Hermaden's work laid the foundation for subsequent hydrogeological and geothermal resource utilisation of the basin. Later hydrocarbon exploration by the Austrian Rohöl-Aufsuchgs AG [RAG; crude oil mining company] was published by Kurt Kollmann (Kollmann, 1965), which remains one of the seminal summaries of the subsurface geology of the Styrian Basin to date.

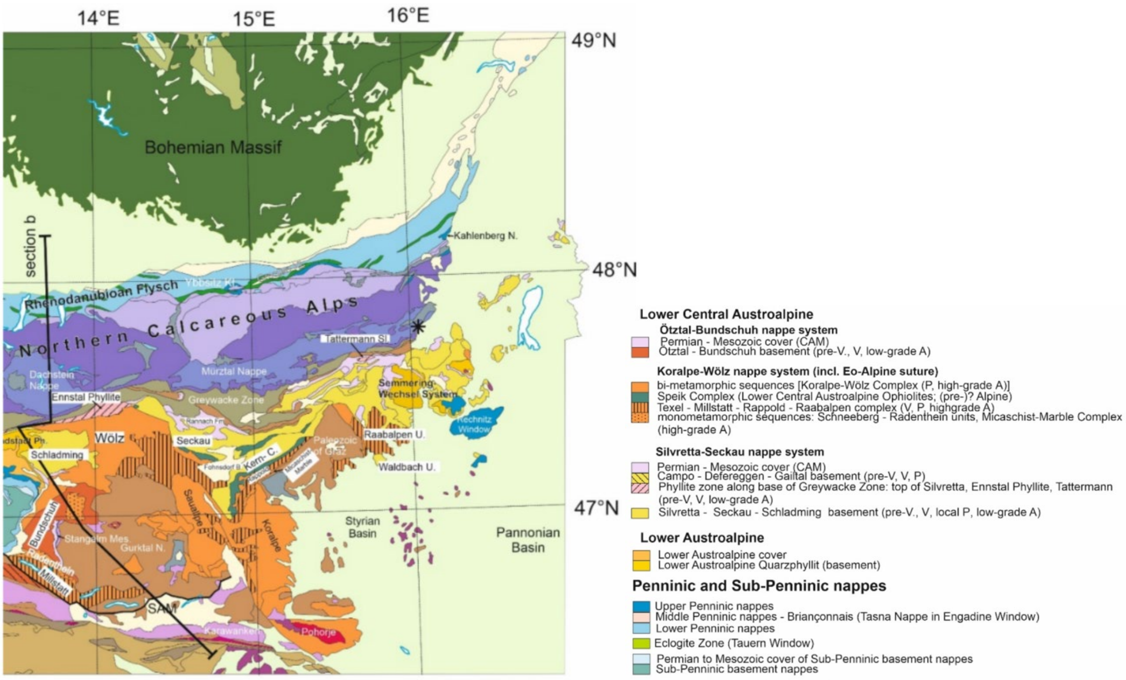

Fig. 2: Geotectonic map of the Eastern Alps showing the Styrian Basin and its bounding Austroalpine and Penninic units (from Kurz et al., 2024). Note the volcanics (dark purple) in the Styrian Basin.

2 Genesis and paleogeographic evolution of the Styrian Basin

Basin formation began in the late Oligocene to Miocene and was linked to continental escape tectonics of Alpine crustal wedges during the latest collision stage of the Alps (Neubauer & Genser, 1990; Kurz et al., 2024). The formation of the Styrian Basin is therefore intimately connected to the history of the wider Pannonian Basin, and consequently the now-vanished Paratethyan Sea, with lateral escape due to subduction towards the Carpathian realm as a result of the northward movement of the Adriatic Plate against the European Plate. Rapid rollback of a Carpathian slab attached to a 'stable Europe' (Fodor et al., 1999; Matenco and Radivojevic, 2012) in the east controlled the extensional regime responsible for basin subsidence, leading to diapiric uplift of the asthenosphere beneath the Pannonian Basin system (Konečný et al., 2002; Kováč et al., 2017). Lateral escape was accommodated along extensive E–W-trending strike-slip faults, which generated small pull-apart basins (Noric Line). At the same time, isostatic uplift of the thickened continental crust, together with gravitational sliding of elevated parts of the lithosphere along flow-thrust faults, led to the exhumation of deeper Penninic units. Associated downthrow along normal faults is considered responsible for horizontal block tilting, which in turn produced asymmetric, N–S-striking extensional structures such as the Styrian Basin (Neubauer and Genser, 1990; Neubauer et al., 2020; Dax et al., 2024; Kurz et al., 2024; Schreilechner et al., 2024). The formation of the Pannonian Basin and associated crustal thinning produced a varied magmatic suite throughout the basin system, including the Neogene to Plio-Pleistocene Styrian volcanic phases (Kollmann, 1965; Bräuer et al., 2016).

The Paratethys represents a remnant of the Tethys Ocean, which formed as a marginal sea during the collision of Eurasia, India, and Africa around the Eocene/Oligocene boundary (Rögl, 1998; Schulz et al., 2005; Piller et al., 2007). While the (Proto-)Mediterranean formed to the south from the rising Alpine orogen, the Paratethys formed to the north and east, with a maximum extent from the Rhône Basin in France and into Inner Asia (Piller et al., 2007; Sant et al., 2019). During the Miocene, ongoing geodynamic processes, including the opening of the Pannonian back-arc system, exhumation of the Alps–Carpathians–Dinarides orogens and associated volcanic episodes and opening/closure of sea straits, resulted in a dynamic palaeogeography, resulting in a unique biogeographic entity (e.g. Piller et al., 2007). Internally, the Paratethys is divided into three distinct paleogeographic and geotectonic units: the larger Eastern Paratethys and the smaller Western and Central Paratethys. Paleogeographically, the Styrian Basin lies within the Central Paratethys. The Central Paratethys spans the region from the Bavarian Molasse zone in the west to the Carpathian arc in Moldova to the east (Rögl et al., 1998; Popov et al., 2004).

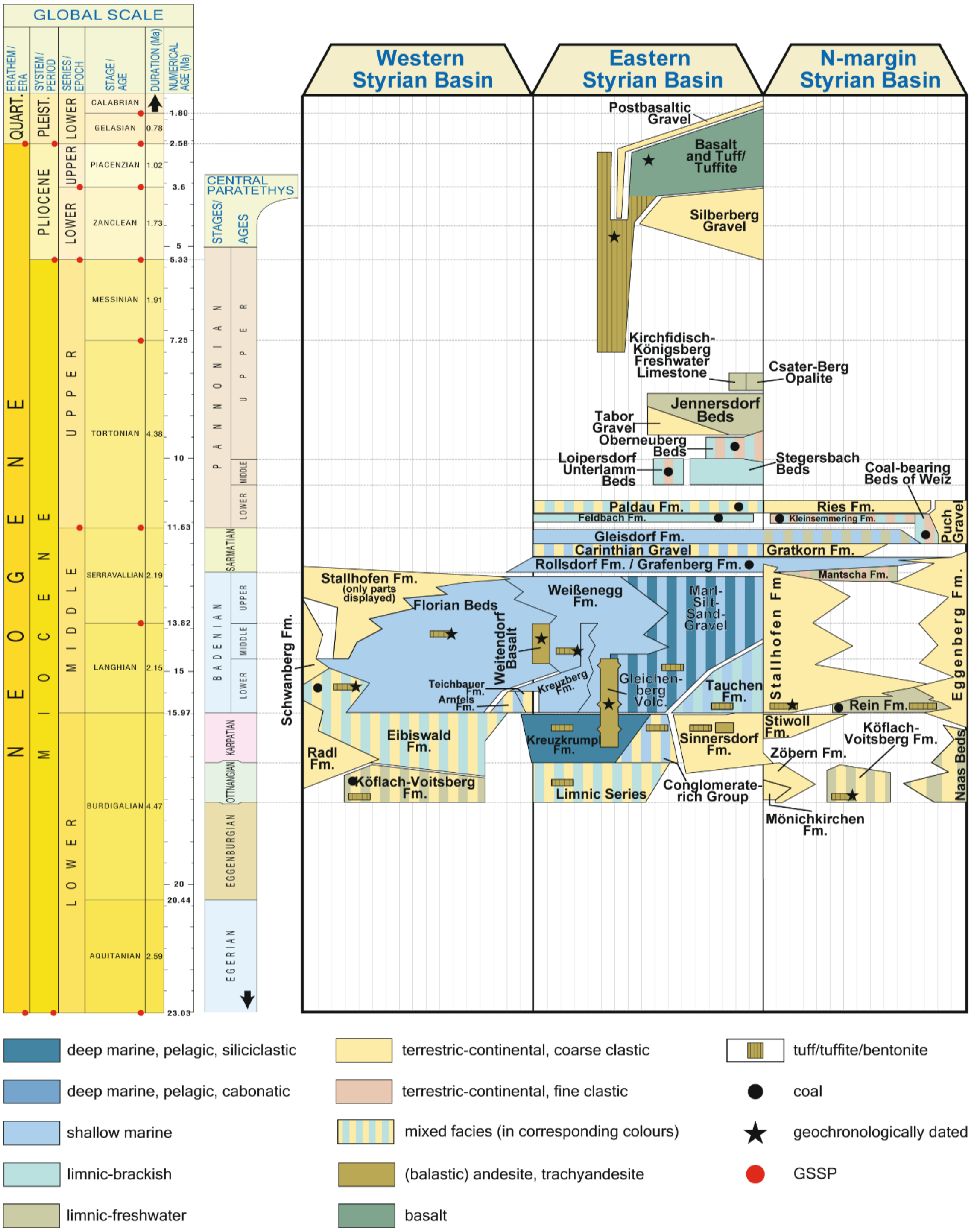

Fig. 3: Chronostratigraphic chart of the Neogene to Pleistocene basin infill of the Styrian Basin (modified after Piller, 2022).

This geodynamically controlled paleogeographic differentiation resulted in a complex pattern of changing seaways and land bridges between the Paratethys, the North Sea and the Mediterranean as well as the western Indo-Pacific (Rögl 1998; Popov et al., 2004; Bialik et al., 2019; Sant et al., 2019; Piller et al., 2024). The resulting unique biogeography of the Paratethys caused major difficulties in stratigraphic correlation between the Paratethys and the Mediterranean, and with global (chrono-)stratigraphy.

Because of its resulting unique biogeography and a large number of endemic species, chronostratigraphic correlation of the Paratethys with the Mediterranean and global stratigraphy remains challenging. As a result, regional chronostratigraphic and geochronologic scales were established for each subunit of the Paratethys, including the Central Paratethys (see Piller et al., 2007 and Piller et al., 2022 for comprehensive reviews and updates). In the following section, we provide a short overview of basin infill (Figure 3) and the resulting lithological and paleobiological changes in the Styrian Basin within the context of the geodynamics and eustatic sea-level fluctuations affecting the larger Central Paratethys.

2.1 The Pre-Neogene basement of the Styrian Basin

Kollmann (1965) subdivided the Styrian Basin into three distinct depocentres: the Western Styrian Basin and the Eastern Styrian Basin, the latter subdivided into the Gnas sub-basin and the Fürstenfeld sub-basin, which together form the Eastern Styrian Basin. The variable relief across the Styrian (sub-)basins, with elevation differences over 3000 m, developed independently of the basement's structure and composition and its pre-Neogene erosional history (Flügel et al., 1988). Knowledge of the basement underlying the Neogene sediments largely relies on deep wells, supplemented by geophysical research campaigns and rare isolated outcrops (Kollmann, 1965; Kröll et al., 1988; Schreilechner et al., 2024). Two distinctive highs strongly influence basement topography and have also shaped the depositional history of the (sub-)basins of the Styrian Basin. The "Middle Styrian High" [Mittelsteirische Schwelle], which forms topographic rises in Remschnigg and Poßruck, Sausal, Seggauberg, and Keuzkogel, exposes part of the Palaeozoic basement including phyllites and greenschists in the lower part and overlying (mostly Devonian) carbonates (Schönlaub, 1979). The Middle Styrian High separates the Western from the Eastern Styrian Basin (including the Gnas and Fürstenfeld sub-basins). Similarly, the South Burgenland High [Südburgenländische Schwelle] represents another uplift of Palaeozoic phyllites (Schönlaub, 2000) and possibly the Carboniferous Radochen Beds (Kröll et al., 1988), separating the Eastern Styrian Basin from the rest of the Pannonian Basin. Outcrops of the South Burgenland High are found around St. Anna am Aigen, Rotterberg/Sotinski Breg (southern Burgenland and northern Slovenia), and

Kohfidisch, Hannersdorf, and Hohensteinmaißberg (Kirchfidisch). The sediments outcropping in the highs have undergone at least greenschist metamorphosis. Despite the potential for detailed outcrop-based study of the basement in these upraises, the poor outcrop situation limits non-drilling base knowledge to only anecdotal evidence, as no continuous successions are known (Heritsch, 1963; Gross et al., 2007a). The known exposures are generally monotonous, fossil-poor, extensively folded and fractured internally, and tectonically cut. These conditions also hamper meaningful comparisons with outcropping metamorphic Austroalpine units around the northern and (North-)western edges of the Styrian Basin. Based on compilations of Kröll et al. (1988) and most recently updated by Schreilechner et al. (2024) using material recovered from deep boreholes, the underground can be subdivided into four larger tectonic units (Figure 4): (1) Austroalpine Crystalline Units, (2) Upper-Austroalpine Units including Palaeozoic Carbonates of the Graz Palaeozoic, (3) the "Permo-Mesozoic carbonates" of the Radkersburg Group and (4) Penninic Units of the Rechnitz Window.

The Austro-Alpine Crystalline Units form the largest portions of the pre-Neogene basement. These successions represent a continuation of the units outcropping in the west and (north-)west of the basin and are assumed to primarily represent the continuation of the Koralpe-Wölz Komplex in the west and the Semmering-Wechsel System to the North (Kurz et al., 2024; Schreilechner et al., 2024). However, the tectonic position of the phyllitic-to-greenschist successions in the Middle Styrian High, including the associated volcanoclastic and carbonate units, is not well constrained. Orographically, they represent the continuation of the Plabutsch-Buchkogel-Range of the Graz Palaeozoic, but have little in common with the outcropping lithology in this region. An upper Ordovician age is assumed for the acidic volcanits (similar to the Graywacke zone) found in the Sausal area. Associated sandy to clayey slates with occasional interbeds of green schists and diabases are tentatively assigned a Silurian to Devonian age. However, biostratigraphic constraints are lacking because carbonates occur rarely in these successions. Flaser limestones and crinoidal limestones of Lochkovian to Pragian age are known from Burgstall-Grillkogel and tectonically overlie the older units outcropping in the Sausal area.

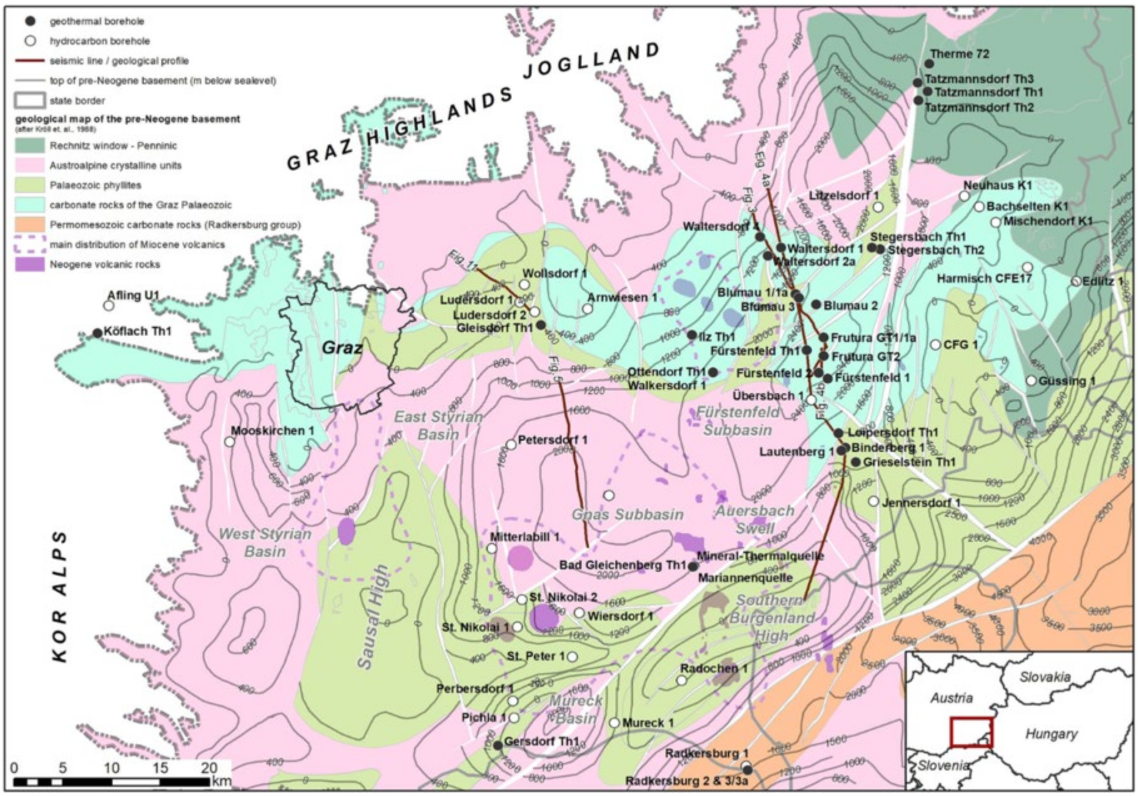

Fig. 4: Structural map of the Styrian Basin with lithology of the pre-Neogene basement (Schreilechner et al., 2024). Depths are given in metres below sea level. The location of key boreholes, depth measurements, and isohypses are shown after Kröll (1988).

In the Poßruck and Remschnigg region, at the border of Slovenia, volcanic tuffs, green schists, and diabase form the stratigraphically oldest outcropping units (South of Oberhaag). Argillaceous shales and shists interbedded with platy limestones, flaser-limestones, and crinoidal limestones overlie these units. The age of this succession remains debated, although limited conodont evidence indicates Llandoverian/Wenlockian to Emsian and Frasnian ages. Deep wells to the North of the Styrian Basin show a continuation of the Graz Palaeozoic into the pre-Neogene basement of the Styrian Basin, yielding significant (up to 1000 m thick) successions of carbonates of the Graz Palaeozoic including the Plabutsch Formation as far east as Fürstenfeld and further into the Pannonian Basin (Schreilechner et al., 2024; Flügel et al., 1988).

The Radkersburg Group (sensu Schreilechner et al., 2024) is primarily described from subsurface samples from deep wells. It is commonly described as Permo-Mesozoic, indicating that further lithological and biostratigraphic analyses are needed to disentangle the stratigraphic placement of these units. Limited potential evidence for corresponding outcropings of these successions comes from isolated occurrences of quartzitic sandstones and argillaceous shales, marls and platey limestones with *Cidaris*. These successions are interpreted as equivalent to the Lower Triassic Werfen Formation and the "Raibl Level" (Karnian) of the Northern Calcareous Alps. Succeeding dolomites and cellular dolomites are assumed to be equivalent to the Norian "Hauptdolomit", which reach a maximum thickness of up to 100 metres in the area. This succession terminates with Cretaceous becciated limestones, containing rudists and marls with coccoliths (Ebner, 1974; Flügel, 1984). Flügel (1988) first described samples recovered from the Radkersburg-1 drill core as potential evidence that these units continued eastward into the Styrian Basin. In the South Burgenland High near St. Anna am Aigen (southern Styria) and Rotterberg/ Sotinski breg (southern Burgenland and Slovenia), quartzitic and carbonatic phyllite successions are exposed. Metatuffs and pyrite-rich "banded limestones" occur in small outcrops. To date, these successions of the Blumau Formation have not been successfully integrated into the stratigraphy of the basement of the Styrian Basin (Schönlaub, 2000; Suttner and Lukeneder 2004).

While the Penninic units outcrop extensively in western Burgenland, no evidence (even from deep drillings) indicates their presence in the Styrian Basin (Schreilechner et al., 2024).

2.2 The Neogene Basin infill and erosion of the Styrian Basin

Figure 5 depicts the distribution of exposed Neogene sediments within the Styrian Basin. Their stratigraphic age decreases from the Western to the Eastern Styrian Basin due to basin infill history and subsequent basin inversion, which resulted in uplift during the Pliocene. The Pliocene uplift led to the erosion of several hundred meters of sediment in the Basin (Ebner and Sachsenhofer, 1995). The uplift extended throughout the Pannonian Basin toward the Carpathians and was likely caused by detachment of the subducted slab (e.g., Tari et al., 1992).

2.2.1 Ottnangian and Karpatian – Early Miocene inception and early basin sedimentation

Infill of the Styrian Basin began in the Early Miocene syn-rift phase, with limnic-fluvial sediments deposited in the Limnic Series (Fig. 3; Kollmann, 1965; Piller, 2022), following a long period of non-deposition and the formation of red palaeosoils. The limnic series is restricted to the Eastern Styrian Basin, with bituminous, marly sediments containing thin coaly layers of roughly 300 m thickness. Unpublished RAG data also suggest shallow marine successions up to 1000 m thick in the Gnas basin of Ottnangian age (Ebner and Sachenshofer, 1995). Alluvial fan and delta sediments dominate the proximal areas of the basin in the West and North during the Ottnangian. Areas include the Bay of Eibiswald, Weiz, and Friedberg Pinkafeld, encompassing the Köflach-Voitsberg Formation, the Mönichkirchen Fm., and the Naas Beds (Fig. 3). Bio-/magnetostratigraphic age constraints are provided for the coal-bearing Köflach-Voitsberg Formation (Haas et al., 1998; Steininger et al., 1998; Ebner et al., 2002). The formation includes a diverse warm-temperate subtropical plant flora and weathered tuffs, which are the oldest in the Styrian Basin (Kovar-Eder et al., 2001). The three major coal seams in the Köflach-Voitsberg Formation are up to 70 m thick and are interbedded in up to 300 m-thick fine-grained limnic-freshwater to terrestrial sediments (Ebner and Sachsenhofer, 1995; Steininger et al., 1998).

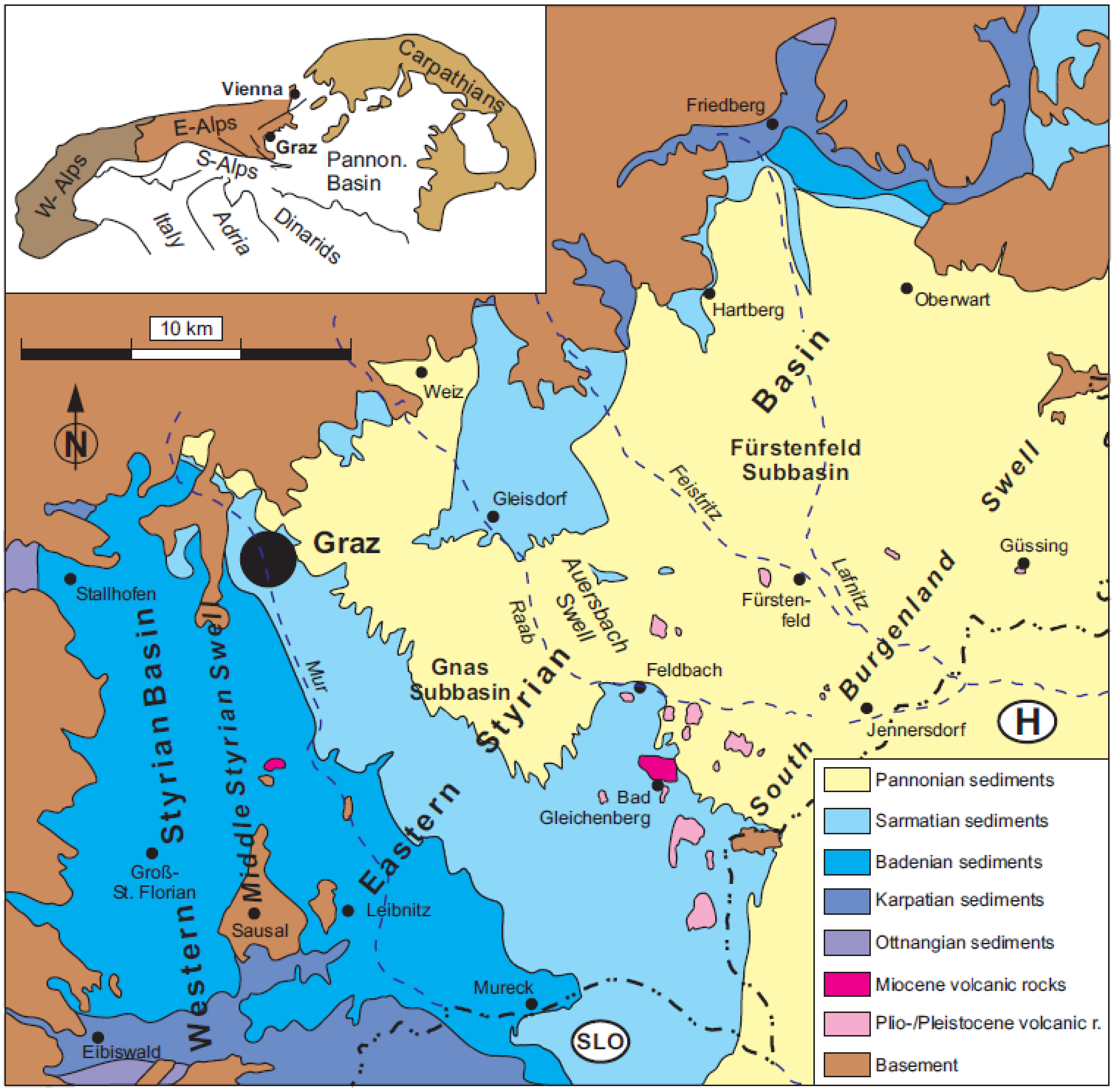

Fig. 5: Overview of the geology of the Styrian Basin (adapted from Gross et al., 2007a).

In the Karpatian, high basin subsidence continued, which resulted in intense syn-sedimentary fault tectonics. Due to a marine ingression from the south, the palaeoenvironment became more marine (Ebner and Sachsenhofer, 1995). These sediments were deposited at depths of 100 to 600 m and are summarised in the Kreuzkrumpl Formation (also known as the "Styrian Schlier"), with several well-studied sections such as the abandoned brickyard in Wagna/Leibnitz. These deeper-marine sediments are fossil-rich, containing plant remains, nannofossils, ostracods, dinoflagellates, foraminifers, gastropods, bivalves, echinoids, and trace fossils (see Hohenegger et al., 2009; Hohenegger et al., 2014; Piller, 2022 for further details and references). Sedimentation at the margins of the basin also became more marine-influenced, including proximal delta sediments of the Radl

Formation, as well as the sub-aquatic deltaic mass flows summarised in the Eibiswald Formation in the Western Styrian Basin.

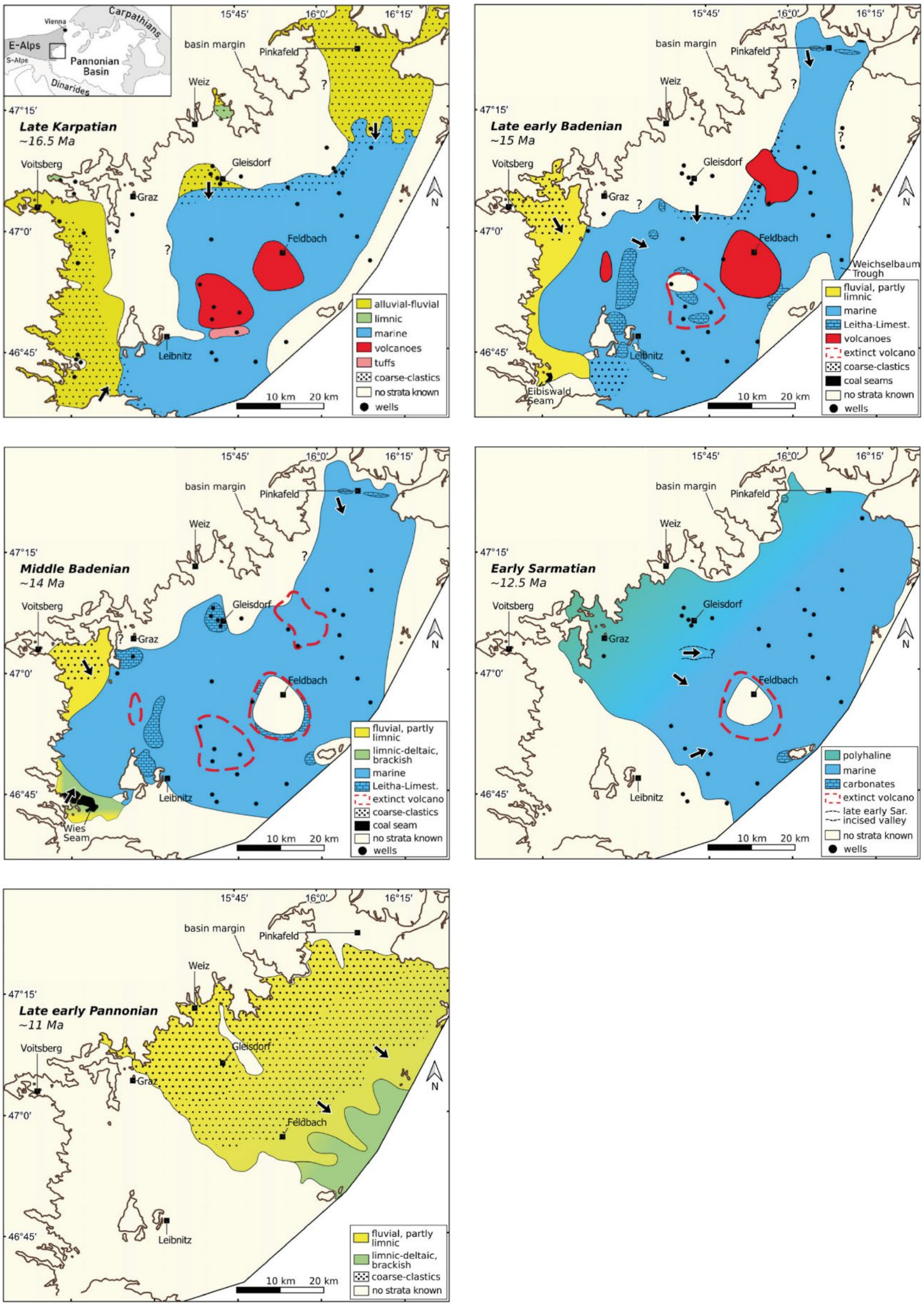

Fig. 6: Palaeogeography and facies maps of the Styrian Basin during its main depositional intervals from the Karpatian to the Pannonian (adapted from Dax et al., 2024)

In the Eastern Styrian Basin, carbonate conglomerate-rich sandy marl-/clay stones and sandstones are recorded in outcrops as well as in the deep wells of Fürstenfeld Thermal-1 and Blumau-1 and are summarised in the Conglomerate-rich Group, interpreted as an alluvial to submarine fan system originating from the northern margin of the basin (Goldbrunner 1988; Piller, 2022). At the northern margin of the basin, terrestrial sedimentation continued in the Naas Beds and the deltaic Stiwoll Formation, interpreted as the northern extent of the Conglomerate-rich Group encountered in the deep wells of the Eastern Styrian Basin (Goldbrunner 1988; Piller, 2022).

Strong crustal and subcrustal extension during the Karpatian resulted in the development of large andesitic shield volcanoes in the Eastern Styrian Basin, summarised as the Gleichenberg Volcanites (Fig. 3; Ebner and Sachsenhofer, 1995; Piller, 2022). These volcanoes formed islands in the marine Eastern Styrian Basin (Fig. 6) and increased heat flow, helping explain the Eastern Styrian Basin's current geothermal resource potential (see section 2.3). Eruptions occurred within two volcanic cones, which are the St. Nikolai and Gleichenberg palaeo-volcanoes (Dax 2021)

At the end of the Karpatian, a tectonic event, the "Styrian Tectonic Phase" (coined by Stille, 1924), led to tilting of crustal blocks and uplift of the western hinterland, as well as uplift of the Sausal Mountains (= Middle Styrian High). In addition, the Styrian Tectonic Phase led to the formation of major normal faults along the western border of the South Burgenland High, as well as within the internal structure of the Eastern Styrian Basin. This event therefore defined the structure and palaeogeography of the Styrian Basin until the upper Pannonian, establishing the South Burgenland High as a stable block that separated the Styrian Basin from the rest of the Central Paratethys (Ebner and Sachsenhofer 1991). The culmination of the Styrian Tectonic Phase is recognised as a distinct hiatus that extends from the Styrian Basin into the Vienna and Molasse Basin and is linked to a global sea-level fall (Kovac et al., 2004; Hohenegger et al., 2009).

2.2.2 Badenian – Middle Miocene establishment of fully marine sedimentation

At the base of the Badenian (Middle Miocene), the tectonic activity of the Styrian Tectonic Phase reopened marine seaways, which, together with a large marine transgression that flooded the entire Central Paratethys as far as the Carpathian Foredeep and into the Dacian and Transylvanian Basins, and further into the Eastern Paratethys (Rögl 1998; Kovac et al., 2004). A seaway across Slovenia (the "Slovenian Corridor" or "Transtethyan Corridor") allowed the migration of significant marine subtropical and tropical faunal elements from the proto-

Mediterranean into the Styrian basin (Harzhauser et al., 2003; Harzhauser and Piller, 2007; Piller et al., 2007; Ivančič et al., 2025).

Biostratigraphic subdivision of the Badenian has historically followed the benthic foraminiferal ecostratigraphy established in the Vienna Basin (Papp, 1963). More recent work has focused on integrated bio-, magneto-, and chemostratigraphic approaches to improve correlation with (Proto-)Mediterranean and global stratigraphic zonations (e.g., Hohenegger et al., 2009; Piller et al., 2007). Nevertheless, original ecostratigraphy remains a crucial part of deep well stratigraphy in the region (Hohenegger et al., 2014; Schreilechner et al., 2024). The Karpatian/Badenian boundary corresponds to the Burdigalian/Langhian boundary in the Mediterranean/global chronostratigraphy. The Badenian is subdivided into the lower, middle, and upper Badenian (Fig. 3; e.g. Piller et al., 2022).

Following the lower Badenian transgression after the Karpatian/Badenian lowstand, marine sedimentation in the Styrian Basin reached its largest extent. The palaeogeography of the Lower Badenian was defined by a distinct relief formed by the now-uplifted Middle Styrian and South Burgenland highs, as well as the Karpatian to Badenian shield volcanoes in the Eastern Styrian Basin (Fig.6; Dax et al., 2024). The St. Nikolai volcano had already gone extinct (and was subsequently buried by marine sediments) in the uppermost Karpatian to Lower Badenian, and volcanic activity shifted to new eruption centres in the now more active Gleichenberg paleo-volcano. Additional volcanic activity (K-rich basaltic andesites) is also exposed near Weitendorf along the Middle Styrian High (Serri et al., 1998; Sant et al., 2020).

Around topographic highs of the Styrian Basin, such as the Middle Styrian and South Burgenland High and the Gleichberg shield volcanoes, tropical to subtropical shallow marine carbonates developed. These carbonates of the classical "Leitha Limestone" type (Dullo 1983; Reuter et al., 2012; Piller, 2022) are formed by variegated corallinacean-coral patch reefs and rodolith platforms. The Leitha Limestones and associated shallow- and deeper-marine siliciclastics within the Eastern Styrian Basin are summarised in the Weißenegg Formation (Piller, 2022). These limestones have been used as important building stones and for cement production since Roman times, with large surface quarries such as Weißenegg and Retznei (Reuter et al., 2012), as well as the subsurface "Roman Quarry" near Aflenz, documenting their economic importance (Figs. 3, 6).

The Badenian of the Western Styrian Basin is characterised by the marginal shallow-lagoonal deposits of the Florian Beds (sensu Piller, 2022). These deposits have been known for over one hundred fifty years because of their exceptionally rich and well-preserved fossil assemblage including gastropods, bivalves, foraminifera, ostracods, fishes, decapods, echinoids and cephalopods (e.g. Rolle, 1855; Hilber, 1878; Hiden, 1997; Messner and Bernhard, 2016). The Weitendorf basalt quarry represents the best-exposed outcrop of the Florian Beds; other known outcrops are generally small and dispersed. The Weitendorf basalts have been geochronologically dated to ~14 Ma (Balogh et al., 1994), a date confirmed by recently dated tuff layers in the Florian Beds that show similar ages (Sant et al., 2020). Terrigenous influx into the lagoonal Florian Beds is associated with the coal-bearing middle to upper Eibiswald Formation. Geochronological data of the proximal Eibiswald Formation provide evidence for an early Badenian (Early Langhian) age of 15.52 ± 0.18 Ma. (Gruber et al., 2003; Sant et al., 2020; Piller et al, 2022). The Schwanberg Formation at the western margin contains coarse clastics interpreted to relate to the uplift of the basement due to its lithology containing badly sorted, coarse boulder debris/gravel (including >3 m-sized, rounded clasts including large gneiss but also pegmatite and eclogite pebbles) with partially crossbedded, grey to yellowish sand and grey, sandy clay interlayers forming rhythmical successions (Piller, 2022).

The Stallhofen Formation (and its members) represents fluvial (braided river) and limnic deposition, partly influenced by volcanic fallout in the Badenian. It occurs at the western and northern margins of the Styrian Basin (Gross, 2015). Its lithology contains silt and clay with paleosol horizons, coarse gravel/conglomerate to boulder gravel, subordinate sand and pelite, and rare plant and gastropod remains. It overlies the Köflach-Voitsberg Formation.

Volcanism in the Styrian Basin became progressively reduced from its main phase in the Karpatian/lower Badenian into the middle Badenian. The Miocene Styrian volcanic phase had ceased by the upper Badenian (Piller, 2022; Dax et al., 2024).

A major global eustatic regression marks the end of the Badenian (Piller et al., 2007). The Styrian Basin is assumed to have fallen largely dry, leading to extensive erosion and the progradation of large fluvial and deltaic systems (Dillach Member and parts of the Stallhofen Formation), which mark the hiatus at the Badenian/Sarmatian boundary (Friebe 1990; Gross 2015; Piller, 2022).

2.2.3 Sarmatian – a restricted Paratethyan Sea

Although a transgression reestablished marine conditions in the Central Paratethys and thus the Styrian Basin after the major Badenian/Sarmatian regression (Fig. 6), it remained nearly completely isolated from the (Proto-)Mediterranean and Indopacific bioprovinces. Despite long debates, recent studies have put to rest the notion that the Sarmatian was a brackish sea, with multiple lines of evidence from the Styrian Basin and indeed the wider Central and Eastern Paratethys demonstrating fully marine and possibly even hypersaline conditions. The disappearance of common euhaline taxa, such as radiolaria, planktonic foraminifera, corals and echinoids, can be fully explained by the pelogeographic reorganisation of the Paratethys (Rögl, 1998; Harzhauser et al., 2002; Piller and Harzhauser, 2005; Harzhauser et al., 2024).

Similar to the Badenian, biostratigraphic zonations of the Sarmatian of the Styrian Basin follow the benthic foraminiferal ecostratigraphy of the Vienna Basin (Papp, 1956, 1963).

Sarmatian sediments are restricted to Eastern Styria and the northern margins of the Styrian Basin. The Rollsdorf and Grafenberg Formations mark the return of marine sedimentation. The Rollsdorf Formation consists of predominantly fine clastics: yellowish to grey, massive or laminated clay–silt–fine sand alternations, including partly ripple- and cross-bedded intervals. Fossil assemblages reflect its shallow marine (sub- to supratidal), possibly brackish character, with the presence of foraminifers, molluscs, bryozoans, ostracods, and crabs (Gross, 2015; Piller, 2022).

The contemporary Grafenberg Formation shows marginal marine tidal flats and carbonate buildups. These Sarmatian carbonate buildups are well preserved in the Klapping outcrop (Stankt Anna am Aigen) and are primarily built by serpulids and bryozoa. Common fossils within the Grafenberg Fm. include gastropods (*Mohrensternia*), bivalves (oysters), serpulids (*Hydroides*), foraminifers (*Nubecularia*, miliolids, elphidiids), and ostracods (Harzhauser and Piller, 2004a; Piller and Harzhauser, 2024). Seismic data indicate that, despite only a few tens of meters of outcropping sediment, the Grafenberg Formation could be more than 100 m thick, based on seismic and well-log interpretations of deep wells in the Eastern Styrian Basin (Schreilechner and Sachsenhofer, 2007; Schreilechner et al., 2024).

A major regressive event separates the lower from the upper Sarmatian units in the Styrian Basin. Sediments deposited within this event are represented by the Carinthian Gravel and the Gratkorn Formation (Piller, 2022). The Carinthian Gravel remains elusive, and its regional correlation, especially in deep wells of the Eastern Styrian Basin, is difficult. A gravel pit near Trössing (Stop 4) may serve as the type locality pending formalisation (Piller, 2022). The "Gravels of Gratkorn" are considered to be another tongue of sediment of this "Carinthian phase” from the north-west into the Styrian Basin (Gross et al., 2007b). The Carinthian Gravels are of special interest for hydrogeological and water resource management in the basin, as they are considered one of the major deep aquifers within the basin. The components of the Carinthian Gravel are manifold and include crystalline, Eocene (limestones), Mesozoic (carbonates, cherts), and Palaeozoic (limestones, sandstones) clasts, indicating a South Alpine source area (Winkler 1927). The progradation direction was mainly towards the east-northeast (Skala 1967), although Kollmann (1965) and Hanselmayer (1967a; 1967b) argued for a (north)-eastern catchment area. The thickness of the Carinthian Gravel decreases significantly in marginal areas (Kollmann 1965).

The cyclic silt/sand/oolite-mixed, fine-grained carbonate-siliciclastic Gleisdorf Formation defines the upper Sarmatian sediments in the Eastern Styrian Basin. Its northern margin shows a more proximal mixed limnic-marine expression of the Gleisdorf Formation. Continental sedimentation at the northern margin of the basin is represented by limnic-fluvial ("Lower" Coal-bearing Beds of Weiz) and alluvial fan (Puch Gravel) deposits (Flügel 1975; Gross et al., 2007b; Piller, 2022).

2.2.4 Pannonian – Isolation of the Paratethys and birth of the brackish Lake Pannon

The complete isolation of the Central Paratethyan Sea around the Middle to Late Miocene boundary resulted in the development of Lake Pannon and was accompanied by significant erosion. Within the Styrian Basin, repeated alternations of lacustrine, deltaic, and fluvial environments controlled sedimentation throughout the Late Miocene (Pannonian) interval. The increasing freshening of the relict Lake Pannon led to the gradual extinction of many marine species that were widespread during the Sarmatian. Some mollusc taxa (Dreissenidae, Lymnocardiidae) and ostracods (Cytherideidae, Hemicytheridae), however, radiated and evolved in the brackish Lake Pannon. This has provided the basis for a biostratigraphic zonation scheme for Lake Pannon, including the Pannonian sediments preserved in the Eastern Styrian Basin (Magyar et al., 1999; Harzhauser et al., 2004; Müller et al., 2007).

The lower Pannonian is represented by the Feldbach Formation and the Paldau Formation in the Eastern Styrian Basin, while the northern margin of the Basin includes the "Upper" Coal-bearing Beds of Weiz, the Puch Gravel, Kleinsemmering Formation, and the Ries Formation (Piller, 2022). The Feldbach (regional mollusc Zone "B"; *Mytilopsis ornithopsis* Zone) and Paldau Formations (Zone "C"; *Mytilopsis hoernesi* Zone) show a progression from limnic-brackish to mixed limnic to terrestrial facies (Gross, 2003). The Feldbach Formation is interpreted as a deltaic limnic-brackish sequence that contains grey, massive or laminated silt/clay to marl, frequently with mass occurrences of dreissenid bivalves; upsection, it successively increases in ripple-, cross- or horizontal bedded (fine-)sand layers, leading to dm-thick pelite-sand alternations; sporadically stub horizons and thin lignite seams. Fossils recorded include plant remains (pollen, diaspores, leaves), calcareous nannoplankton, dinoflagellates, gastropods (e.g., melanopsids), bivalves (i.e., *Mytilopsis ornithopsis*), ostracods, insects, vertebrates (fish remains, amphibians, reptilians, birds, and mammals (Kollmann, 1965; Gross, 2003; Gross et al., 2011; Kern et al., 2012; Soliman et al., 2013; Gitter et al., 2015; Piller, 2022). Similarly, the Paldau Formation contains a complex suite of laterally and vertically variable, variegated, quartz-dominated, well-rounded siliciclastics that show massive or cross- or horizontal-bedded, or cross-, ripple-, or horizontal-bedded successions of variable grain size and colouring. Overall, members of fluvial and limnic-deltaic genesis can be differentiated within the formation. Fossil content includes plant remains, characean gyrogonites, gastropods, bivalves (e.g., *Mytilopsis hoernesi*), insects, ostracods, vertebrates such as fishes, reptiles, and various mammals. Towards the northern margin of the Styrian basin, the meandering river systems grade into braided river (Ries Formation) and alluvial fan (Puch Gravel) deposits, where a clear separation from the Paldau Formation is not possible. The complex interplay and interfingering of formations is related to a major regression of Lake Pannon during the early Pannonian, interspersed with a short-term ingression of limnic sedimentation within the Paldau Formation (Gross, 2003; Piller, 2022). The occurrence of *Hippotherium* (three-toed horse) in the upper Paldau Formation is of supra-regional importance (Mottl, 1970).

The middle Pannonian encompasses the Loipersdorf-Unterlamm Beds and the Stegersbach Beds and is restricted to the Eastern Styrian Basin close to the border of Burgenland (Sauerzopf, 1952; Kollmann, 1965; Piller, 2022). The lithology of these two units comprises sand, pelite, and gravel, with subordinate gravel and occasionally thin (up to about 1 m thick) coal seams in the Lopersdorf-Unterlamm Beds, with rare fossils including gastropods (melanopsids), bivalves (dreissenids), ostracods, and mammals (Piller, 2022). Both units correspond to Zone “D–E” (*Lymnocardium conjugens* Zone) of the regional mollusc zonation of Lake Pannon (Kollmann, 1965).

Finally, the upper Pannonian is represented by the Oberneuberg Beds, Tabor Gravel, Jennersdorf Beds, Kirchfidisch-Königsberg Freshwater Limestone, and the Csater-Berg Opalite, which are all restricted to the (south-)eastern portions of the Eastern Styrian Basin. The fluvial, limnic (in part slightly brackish) and swamp deposits of the Oberneuberg Beds are dated to the regional mollusc Zone “F”; but possibly also the upper part of Zone “E” and/or the lower part of Zone “G” may occur (Sauerzopf, 1952). The overlying fluvial Tabor Gravel, questionably dated to regional mollusc Zone “G” (Kollmann, 1965), represents another erosive episode in the Pannonian of the Styrian Basin, which interfingers with the limnic Jennersdorf Beds of similarly uncertain stratigraphic placement.

The upper Pannonian Csater-Berg Opalite is correlated to Pannonian Zone H (Harzhauser et al., 2019), and the nearby mammal fossil site of Kirchfidisch (Kirchfidisch-Königsberg Freshwater Limestone) is correlated with the lower Turolian European Mammal Zone MN11 (Daxner-Höck & Höck, 2015; Piller, 2022).

Subsequent basin inversion (Peresson and Decker, 1997) caused considerable erosion, producing an extensive erosive boundary (peneplain, sometimes with red loam) and a hiatus of up to 3.5 Ma, extending into the Early Pliocene. Fluvial clastics are observed below or adjacent (Silberberg Gravel) as well as on top (Postbasaltic Gravel), containing variegated alkali basaltic rocks of largely Plio-/ Pleistocene age (Piller, 2022).

2.2.5 Plio-Pleistocene – Maar Volcanism in a Terrestrial Environment

Effusive alkali basaltic and phreatomagmatic volcanism was widespread in the Pannonian Basin during the Late Miocene to Middle Pleistocene (Ali et al., 2013; Harangi et al., 2015). In general, four major monogenetic volcanic fields are recognised in the Pannonian Basin: the Styrian, Bakony–Balaton Upland, Nógrád–Gemer, and Perșani volcanic fields. In addition, isolated basaltic centres occur in several areas, including Pauliberg–Oberpullendorf in Burgenland and Lucaret–Sânovita in Banat, where neither precursor nor subsequent volcanism has been identified (Harangi et al., 2015). The alkaline volcanism in the Pannonian Basin represents small-volume magmas erupted through transtensional faults and indicates a shift from lithospheric to asthenospheric melting of an upwelled, slowly cooling asthenospheric dome (Seghedi and Dowes, 2011). Data from xenoliths within the often explosive Plio-Pleistocene volcanism suggest that their depth of origin was within the subcontinental lithospheric mantle from a depth of 50-80 km (Bojar et al., 2013; Aradi et al., 2020). Within the Styrian Basin, four xenolith types can be distinguished: (1) granites and gneisses, (2) andesites (related to the older Lower to Middle Miocene volcanism), (3) ultramafic xenoliths (peridotite, lherzolite, websterite, harzburgite, hornblendites), (4) hornblende, augite and olivine phenocrysts (Fritz, 1996; Bojar et al., 2013).

During the Pliocene, another phase of effusive basaltic volcanism started within the Eastern Styrian Basin, which formed the lava fields of Neuhaus (~3.71 – 3.11 Ma), Mühldorf (~3.05 – 2.64 Ma), Klöch (~2.56 Ma), Unterweissenbach (~2.27 Ma), Tieschen (~2.17 Ma) and Wilhelmsdorf (~1.71 Ma). The composition of these basalts is alkaline basaltic (Seghedi et al., 2004; Ali et al., 2013; Bojar et al., 2013). These lava flows are partly underlain or adjacent to the fluvial Silberberg Gravels (Fig. 3; Piller, 2022).

In addition to the effusive volcanic activity, the Plio-Pleistocene of the Styrian Basin, phreatomagmatic explosions of e.g., Kapfenstein, Riegersburg, Güssing, and Grad led to the formation of expansive xenocryst-bearing volcanoclastic fields and diatrems, which became filled by meteoric and groundwater, forming characteristic fine siliclastic maar-lake deposits of the region (i.e. Burgfeld/Fehring; Fritz, 1996; Kralj 2011).

After volcanic activity ceased, the lava fields were covered by fluvial Postbasaltic Gravel that integrates with the Pleistocene periglacial and loess deposits. In the Quaternary, erosion, terraces, alluvial cones and landslides formed the diverse present-day topography of the Styrian Basin (Winkler-Hermaden, 1957; Flügel and Neubauer, 1984; Ebner and Sachsenhofer, 1991)

3 Resource potential of the Styrian Basin and its current uses.

Like the Vienna Basin to the northeast, the Styrian Basin was considered early on for its oil and gas resource potential. The first extensive surveys of the Styrian Basin's resource potential were conducted in the mid-20th century by explorative campaigns of RAG (Kollmann, 1965). Despite these extensive resource economic endeavours, the basin has not yielded any significant hydrocarbon resources to date. Despite the lack of economically viable hydrocarbon reservoirs, these early prospectation efforts by the RAG have been highly beneficial for understanding the basin's geology. The only two productive but not economically viable gas wells are located in the western Styrian basin ("Ludersdorf 1" and "Wollsdorf 1"). Resource exploration in the Styrian Basin ended after well Petersdorf-1, drilled in 1995/96, also proved dry (Malzer and Sperl, 1993; Schreilechner et al., 2024).

In addition, the discovery of several geothermal aquifers through deep drilling between 1972 and 2021 has established the Eastern Styrian Basin as a high-potential region for geothermal energy usage in Austria (e.g. Götzl et al., 2007; Schreilechner et al., 2024). For instance, several non-productive exploration wells from the original RAG campaign now serve as geothermal wells for the spas in Bad Loipersdorf, Bald Waltersdorf, and Blumau, as well as for Austria's first geothermal heating system (Malzer und Sperl, 1993). At Frutura GT1 and GT2, groundwater temperatures reach up to ~125°C at a depth of 3188 m below the surface (Zotter, 2026). Upwelling deep groundwater likewise reflects positive thermal anomalies in structural highs, including the South Burgenland High and the shallow portion of the Fürstenfeld sub-basin north of the Blumau Fault. Overall, the geothermal gradient in the Styrian Basin is approximately 4°C/100 m, with some regions reaching thermal gradients over 6°C/100 m (Fig. 7; Schreilechner et al., 2024).

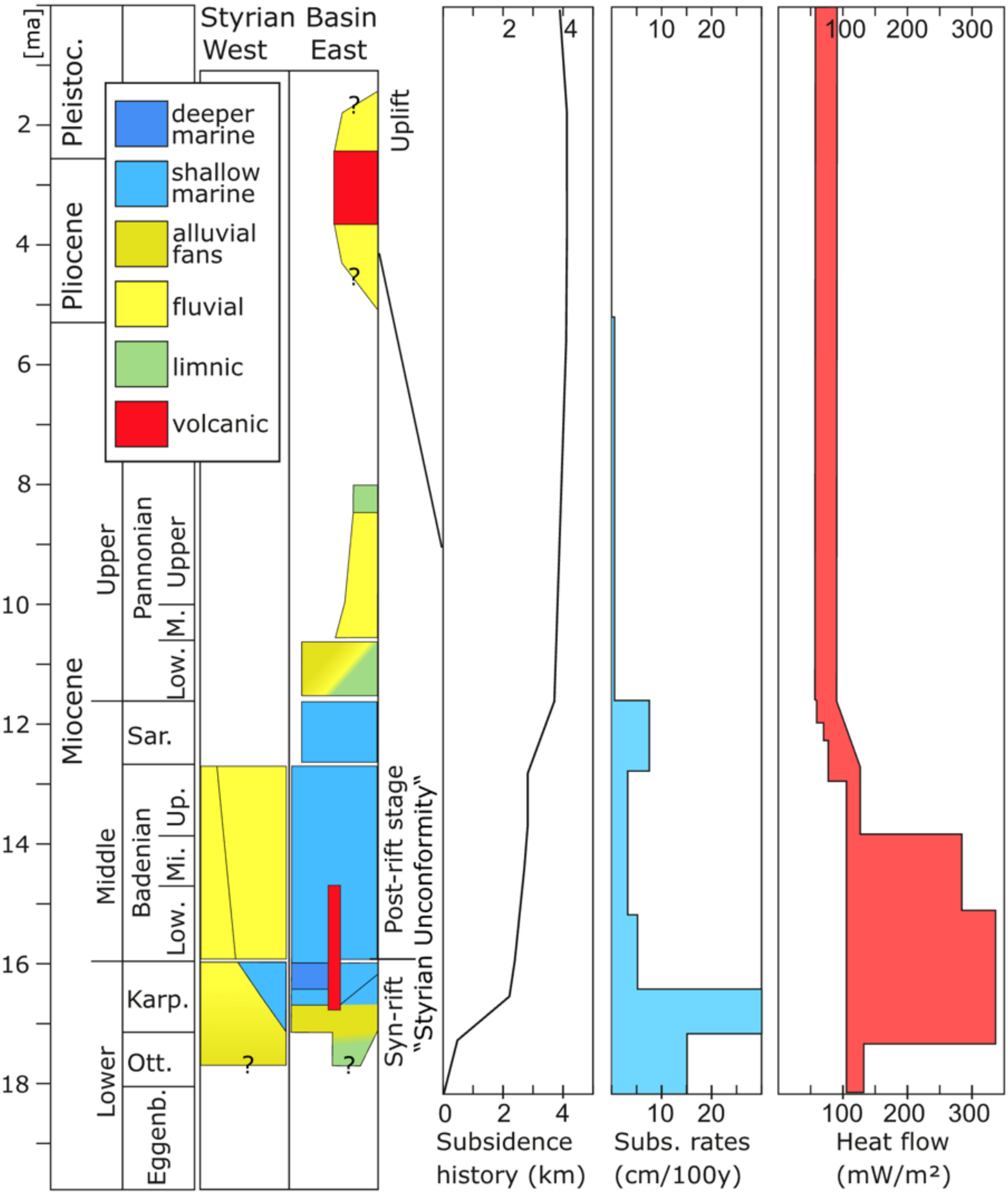

Fig. 7: Subsidence curves and heat flow history of the Styrian Basin. Source: after Sachsenhofer (1994) and Sachsenhofer et al. (1996) (Dax et al., 2024: Fig. 9).

In addition, the basin contains a wealth of deep aquifers, which are gaining increasing socio-economic importance as a freshwater source unaffected by recent weather extremes and climate change (e.g., Gold and Kriegl, 2023). Goldbrunner & Schubert (1993) published a comprehensive hydrochemical analysis of waters from geothermal springs and wells in the Styrian Basin. The aim was to understand how Neogene volcanic activity in the eastern Styrian Basin influenced aquifer parameters, especially its potential impact on the basin's deep aquifer system as a whole. Their findings show that dissolved CO_2 in the carbonated waters (both in mofettes and in wells) in the Styrian Basin is primarily associated with the younger Plio-Pleistocene volcanism. All carbonated waters in the basin show isotopic (δ^2H and $\delta^{18}O$) values indicative of meteoric waters. These meteoric waters interact with subcontinental lithospheric mantle-derived or crust-derived CO_2 at various depths (Bräuer et al., 2016; Goldbrunner & Schubert, 1993; Gostencnik & Winkler, 2021). Mantle-derived volcanogenic CO_2 may also bypass deeper aquifers and reach the surface; these exhalations can escape into the atmosphere and can also carbonate shallow meteoric aquifers, as exemplified by the „Brodelsulz" near Gleichenberg (Gostencnik & Winkler, 2021). Changes in sodium (Na) and potassium (K) content are assumed to reflect fluid-rock-interactions of the acidic CO_2-rich waters with the aquifer host rock. Na-enriched waters are generally derived from the Na-rich Plio-Pleistocene volcanism, whereas K-enriched waters are generally associated with the more K-rich Middle Miocene volcanic phase. Indeed, all known deep aquifers in the Styrian Basin are fed by Holocene to Late Pleistocene meteoric waters, which closely follow the local meteoric water line (Gold and Kriegl, 2023; Fig. 8).

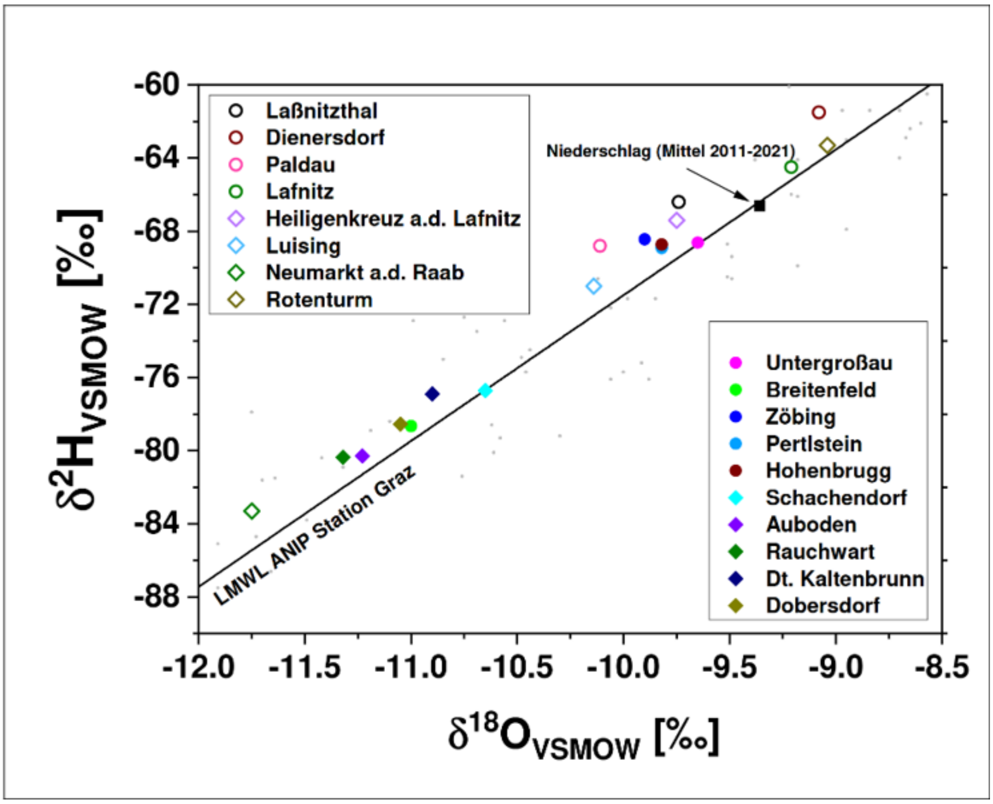

Fig. 8: Summary of δ^2H and $\delta^{18}O$ results of the deep aquifer monitoring wells in Styria (circles) and Burgenland (diamonds) compared to the local mean water line (LMWL) in Graz (black line). Figure adapted from Gold and Kriegl (2023).

Radiocarbon dating of dissolved inorganic carbon ($^{13}C_{DIC}/^{14}C_{DIC}$) in deep aquifers in the basin shows ages ranging from c. 8,500 to >30,000 years, which remain constant over the monitoring period from 1997 to 2023. In addition, isotopic signatures are unchanged, indicating that the water masses transported in the deep aquifers remained unchanged over the last quarter of a century (Fig. 9). Another observation is the increasing age of water masses from the north-west to the south-east, indicating the potential recharge areas and general flow direction within the aquifers.

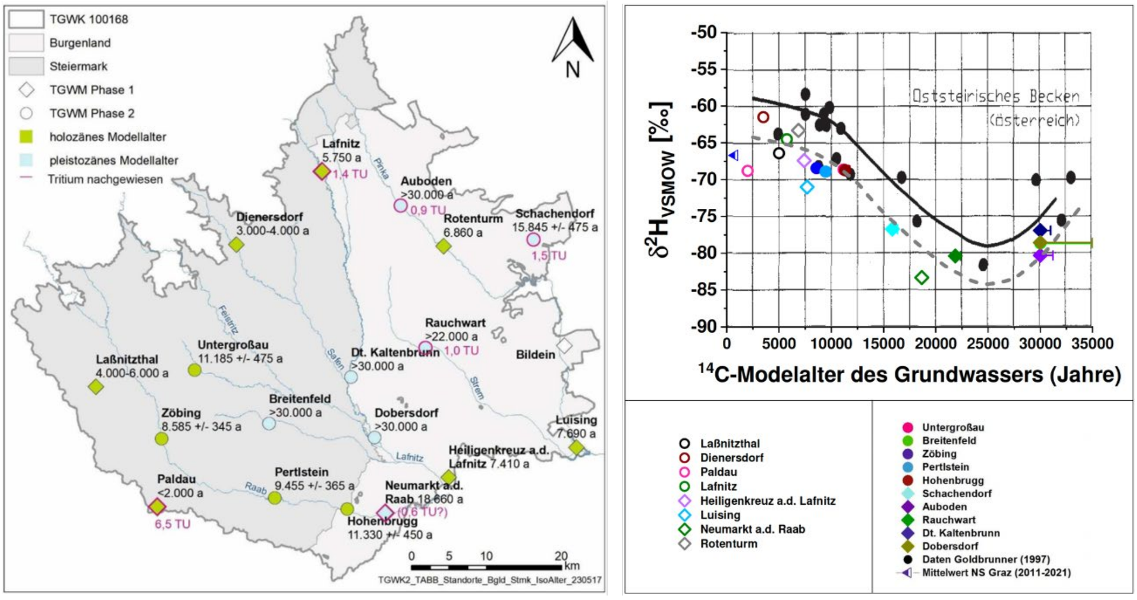

Fig. 9: Figure adapted from Gold and Kriegl (2023), showing the deep water monitoring stations of the Styrian (grey) and the age of waters (**left panel**). Interpretation of the age distribution in the climatic context of the Pleistocene-Holocene transition indicates that δ²H signatures (**right panel**) of the well waters mirror the climatic transition from the last glacial maximum into the Holocene warm period, with values remaining consistent through a monitoring period of ~25 years (1997 to 2023).

4 Field Trip Stops

4.1 Stop 1: Frutura

Topic: Geothermal energy utilisation and sustainable carbon-neutral food industry

Locality: Modern sustainable geothermal greenhouse project specialised in the production of vegetables in Bierbaum 108, 8283 Bad Blumau (Fig. 10). Contact: Frutura Obst & Gemüse Kompetenzzentrum GmbH, Fruturastraße 1, 8224 Hartl, Österreich

Coordinates: 47°05'48.43"N, 16°04'56.53"E

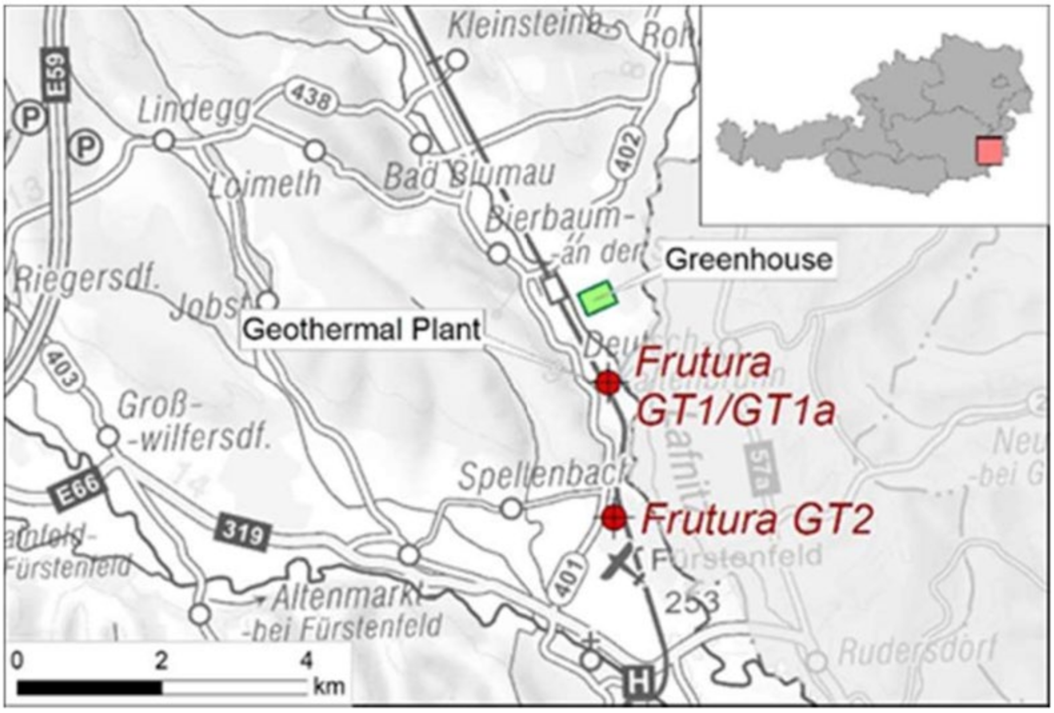

Fig. 10: Location of the deep wells Frutura GT1/GT1a and Frutura GT2 in relation to the Frutura greenhouse project (from Goldbrunner and Goetzl, 2019).

Lithology: Exposures of the Neogene sediments around the Frutura plant in the Fürstenfeld sub-basin are dominated by lower Pannonian limnic-brackish to limnic-fluvial freshwater and terrestrial successions composed of variegated clay, silt, sand, and gravel successions. Schreilechner et al. (2024) describe the stratigraphy of the deep wells Frutura GT1 and GT2 in detail. It represents one of the key stratigraphic reference sites for interpreting the Neogene basin infill of the Eastern Styrian Basin and its pre-Neogene basement (carbonates of the Graz Palaeozoic), including the interpretation and regional correlation of seismic reflection lines (Fig. 11).

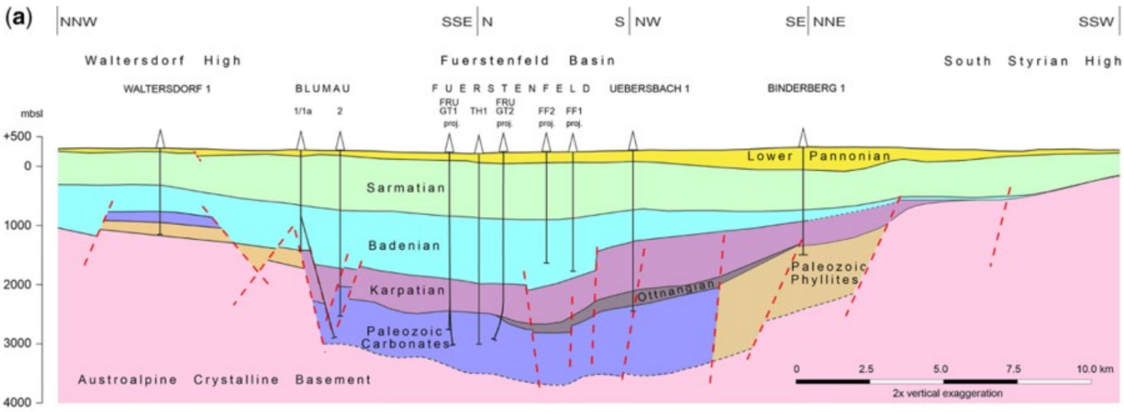

Fig. 11: Interpreted geological profile through the subsurface of the Fürstenfeld sub-basin (adapted from Schreilechner et al., 2024; based on seismic interpretations of Goldbrunner, 2007).

Description: The Frutura plant near the town of Fürstenfeld was the first large-scale plant to use geothermal energy for greenhouse heating in Austria (Schreilechner et al., 2024). The greenhouse project utilises geothermal energy from two deep wells in the Fürstenfeld sub-basin (Frutura GT1 and GT2), which were initially drilled to target the Palaeozoic dolomites of the pre-Neogene Basement of the Styrian Basin.). Thermal waters for spas in the region generally come from Neogene artesian aquifers in Badenian to Sarmatian sediments and volcanic rocks. Waters utilised for geothermal heating are recovered from aquifers in the fractured Graz Palaeozoic carbonates in the pre-Neogene Basement (Schreilechner et al., 2024). Furtura GT2 (true vertical depth of 3,188 m; Fig. 11), for instance, provides up to 60l/s of 124.5°C hot saline thermal water – currently the highest temperature for a geothermal well in Austria (Goldbrunner and Goetzl, 2019; Zotter, 2026).

The well produces gas and water at an 8:1 (gas/water) ratio. The gas phase is dominated by CO_2 (>98% of the accompanying gas), which the greenhouse project uses to fertilise crops (Zotter, 2026). Excess CO_2 is reinjected into the subsurface through well GT1a (Goldbrunner and Goetzl, 2019). Geochemical analyses of the thermal water show NaCl concentrations of 78 g/l. Stable isotopic analyses of the waters of GT2 show typical characteristics of a deep aquifer in the Eastern Styrian Basin with enriched $\delta^{18}O$ values. The enriched $\delta^{18}O$ values indicate significant isotopic exchange between the fluid and the aquifer's carbonate host rocks (Goldbrunner and Goetzl, 2019; Zotter, 2026).

As of 2026, the current heated greenhouse area has extended to 28 ha. The high heating demand for plant cultivation requires an average annual geothermal heat production of ~100 GWh, which is significantly higher than the thermal energy required for a typical Austrian district heating system. With a thermal capacity of 16 MW_{th} and an annual vegetable production of over 9.000.000 kg, the Frutura plant and greenhouse project remains one of Austria's flagship projects for sustainable, large-scale industrial utilisation of deep geothermal energy (Zotter, 2026).

4.2 Stop 2: Wasserwerk Gleichenberg/Bairisch Köllsdorf

Topic: Utilisation of drinking water sources from aquifers in the Sarmatian "Carinthian Gravels"

Locality: Recently refurbished water plant in Bad Gleichenberg/Bairisch Köllsdorf.

Coordinates: 46° 52'19.435"N / 15° 55'37.015"E

Description: The Bad Gleichenberg water supply project began with the recognition that the existing wells I–IV no longer met current technical standards and regulatory requirements. These older wells had operated for many years but did not meet modern criteria for construction, safety, and monitoring. As part of a comprehensive restoration and modernisation program, they have been or are being gradually and permanently decommissioned and backfilled, and the water supply is being transferred to new deep production wells designed according to present-day hydrogeological and technical guidelines. In 2021, well BK1 was drilled, constructed, and tested. At the same time, wells I and II were permanently sealed and taken out of service. In 2022, well BK4 was added as a second deep production well within the same well field, further securing the supply and improving redundancy.

The well field's ongoing operation is monitored through continuous data acquisition. Since the water rights adjustment of 28.08.2025, the maximum permitted drinking water extraction for BK1 has been limited to 8.7 l/s, corresponding to 752 m^3/d. In addition, minimum permissible piezometric levels have been defined to protect the aquifer. For BK1, the minimum pressure head is fixed at 260.0 m above sea level, and for BK4, at 210.09 m above sea level. In 2025, extraction from BK1 amounted to approximately 6.06 l/s. Throughout this period, the specified minimum piezometric levels were maintained, indicating that the current operating regime remains within sustainable limits for the aquifer. This demonstrates that modern well design, careful hydrogeological characterisation, and continuous monitoring allow a secure and sustainable drinking water supply for Bad Gleichenberg.

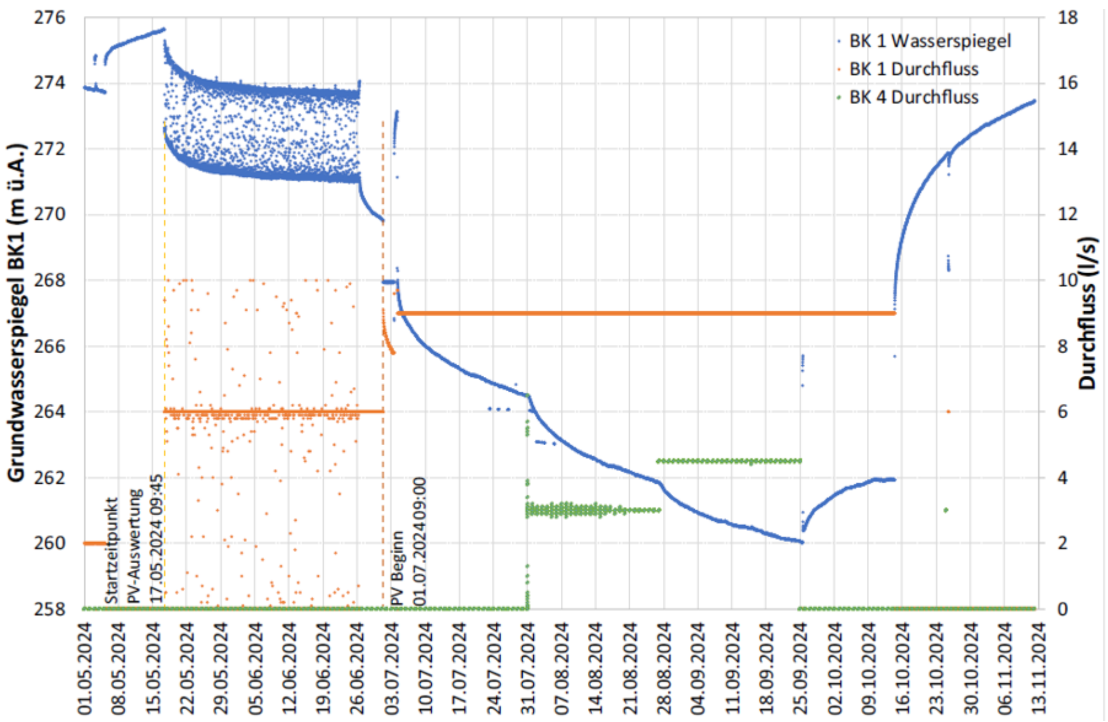

Fig. 12: Results of the combined pumping test in 2024 with the following test regime: BK1 at 9 l/s (constant from 04.07. to 14.10.2024); BK4 at 3.0 l/s from 31.07., then 4.5 l/s from 27.08. to 25.09.2024; recovery phase until 13.11.2024. (Petschacher, 2026; pers. comm.)

Lithology and Hydrogeology: The refurbished well field that supplies Bad Gleichenberg with drinking water is situated in the Eastern Styrian Basin, specifically in the southeastern part of the Gnas sub-basin. The production wells tap a significant Neogene gravel aquifer correlated to the Carinthian Gravel of lower Sarmatian age (compare to Stop 4: Trössing). Regionally, the Carinthian Gravel may reach a thickness of about 30 m (e.g. Winkler, 1927; Hanselmayer 1967a) and forms a laterally extensive, hydraulically continuous aquifer within the Sarmatian of the Eastern Styrian Basin. The overlying upper Sarmatian and Pannonian fine-grained cover sediments act as aquitards or aquicludes, effectively protecting the aquifer from shallow, near-surface influences. As a result, the deep groundwater is confined (artesian), well shielded from recent recharge, and of high chemical and microbiological quality (see Table 1).

Isotope investigations further clarify the origin and age of the groundwater in the Carinthian Gravel. Both BK1 and BK4 yielded tritium-free water, with measured values below 0.5 TU. This absence of tritium indicates that the groundwater contains little to no post-1950s recharge, meaning these wells contain little to no modern, young groundwater.

Stable isotope analyses of δ^2H and δ^{18}O confirm a meteoric origin of the groundwater, consistent with recharge from precipitation. Additionally, the relatively strongly depleted δ^2H and δ^{18}O values point to a contribution from cold-climate (Pleistocene) recharge (compare to Fig. 8). These signatures suggest that a large portion of the water infiltrated during glacial periods, under cooler climatic conditions than today, and has been stored in the confined aquifer over long timescales. No evidence of a relevant admixture of young, shallow groundwater was found, confirming the effectiveness of the overlying Neogene cover sediments in protecting the deep aquifer. Overall, the deep groundwater aquifer tapped by BK1 and BK4 can be interpreted as old, cold-climate meteoric water stored in a well-protected, confined Neogene gravel aquifer.

Table 1: Chemical characteristics of water based on ongoing quality monitoring of the new wells BK1 and BK4 (Petschacher, 2026; pers. comm.; unpubl. lab report).

Parameters	**BK1 (2021)**	**BK4 (2022)**	**Units**
pH	8,1	7,6	-
Conductivity	701	858	µS/cm
Sodium	184	205*	mg/L
HCO3	500	625	mg/L
Calcium	8,85	23,4	mg/L
Magnesium	3,10	9,63	mg/L
Chloride	4,9	11,4	mg/L
Sulfate	5,7	<1	mg/L
Ammonia	1,13	1,40	mg/L

Hydrogeologically, the hydraulic relationship between BK1 and BK4 is particularly instructive. The wells are separated by approximately 689 m. Despite this spacing, the individual pumping steps applied at BK4 produced clearly discernible pressure responses in BK1. These responses were observed in the piezometric head (pressure level) recorded at BK1 and followed the timing and magnitude of discharge changes at BK4. This behaviour confirms a direct hydraulic connection within the Carinthian Gravel at a distance of at least 689 m. These results demonstrate that the aquifer is laterally continuous and connected within the area of Bad Gleichenberg, allowing drawdown effects from one well to propagate to another over distance. This provides an excellent opportunity to discuss regional-scale transmissivity, aquifer continuity, and interference between production wells.

4.3 Stop 3: Quarry Klapping near Stankt Anna am Aigen

Topic: Badenian/Sarmatian boundary, early Sarmatian transgression, marine *Hydroides*/bryozoan bioconstructions.

Locality: Abandoned quarry in the forest close to Klapping, c. 2 km south of St. Anna am Aigen in southeastern Styria. The quarry is a reference section of the Grafenberg Formation and lies on ÖK50-UTM map sheet 4106 Feldbach (ÖK50-BMN sheet 192 Feldbach) (Winkler 1913; Winkler 1927b; Kollmann 1965; Harzhauser and Piller 2004a; Gross et al. 2007).

Coordinates: 46°48′44″ N / 15°58′25″ E

Lithostratigraphy: Grafenberg Formation. Kollmann (1965) used the now-historical local name 'Schichten von Klapping'. At this locality, the formation comprises the Lower Sarmatian transgressive deposits and *Hydroides*/bryozoan limestones above an erosional surface cut into Badenian corallinacean limestone (Harzhauser and Piller 2004a, b; Gross et al. 2007).

Chrono-/biostratigraphy: Middle Miocene, Serravallian; early (lower) Sarmatian. *Elphidium reginum* Zone and *Mohrensternia* Zone. The basal unit following the Sarmatian transgression contains a biostratigraphically indicative mollusc fauna with *Mohrensternia sarmatica* and *Mohrensternia pseudoangulata*, which allows placement within the lower Sarmatian *Mohrensternia* Zone (Kollmann, 1965; Harzhauser and Piller, 2004a, b; Gross et al., 2007).

Description: Badenian corallinacean limestones form the substrate of the Sarmatian succession at Klapping. Their upper surface is an irregular palaeorelief with rounded hummocks up to 70 cm high, but no sharp ridges. Immediately below this discontinuity, *Microcodium* is very abundant. Above the surface, a thin clay layer containing lignite and scattered oysters marks the base of the Sarmatian transgression. Pebbles of 3–4 cm indicate only limited reworking of the underlying Badenian limestone; large limestone boulders of the underlying Badenian corallinacean limestones are absent.

Above this surface, approximately 3 m of thick-bedded marly limestone follows. These beds are composed mainly of *Hydroides*, *Cryptosula*, *Schizoporella* and nodular bryozoans (celleporids?). A few thin clay and marl interbeds contain pebbles of reworked Sarmatian limestone and scattered small archaeogastropods (*Gibbula* spp.). The tops of the limestone beds show only low relief. The uppermost carbonate bed of this lower unit is strongly altered to an unstructured, white layer and is overlain by a laterally traceable, 20 cm thick clay bed. A second unit, about 2 m thick, of indistinctly bedded *Hydroides*–bryozoan limestone forms the top of the exposed section. Two weathered, whitish layers of altered limestone subdivide this unit. Within the limestone beds, irregular *Hydroides*–bryozoan bioconstructions reach roughly 40 cm in diameter and 30 cm in height. Their stacked growth, together with small cavities and caverns, produces a very uneven surface that locally obscures the bedding (Harzhauser and Piller 2004b; Gross et al. 2007).

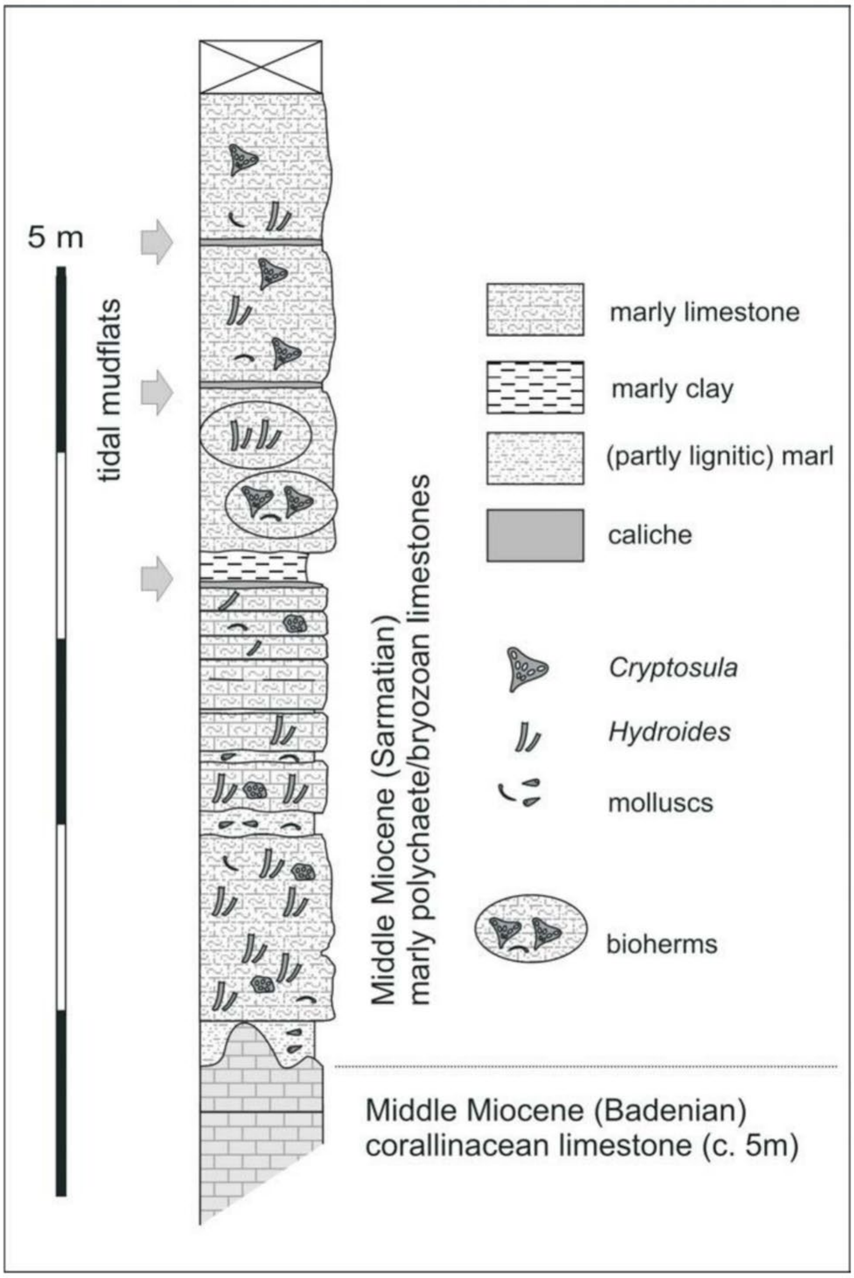

Fig. 13: Klapping section near St. Anna am Aigen, with polychaete/bryozoan bioconstructions characteristic of the lower Sarmatian in the Central Paratethys. Source: Gross et al. (2007: 154, fig. 24).

Interpretation: The palaeorelief at the top of the Badenian corallinacean limestone most likely formed during the lowstand systems tract at the Badenian/Sarmatian boundary. The abundance of *Microcodium*, interpreted here as calcified roots, indicates subaerial exposure. During the early Sarmatian, the sea transgressed across this landscape. Clay, lignites, and limited reworking of the Badenian substrate indicate a low-energy coastal setting. A small colony of *Crassostrea gryphoides*, scarce *Terebralia bidentata*, and numerous *Granulolabium bicinctum* provide evidence for a littoral mudflat. *Hydroides* and bryozoan buildups quickly sealed the relief. A bituminous odour released from the sediment indicates abundant organic matter in the highly porous framestone (Harzhauser and Piller, 2004b; Gross et al., 2007).

The overlying succession records a fluctuating coastline. Phases of extensive *Hydroides*/bryozoan colonies were interrupted at least two to three times by tidal-flat development (see arrows in Fig. 13). Low-relief limestone tops and weathered limestone chips at the bases of overlying beds indicate erosion during emersion. The 20 cm clay bed marks a major interruption. Three strongly altered, unstructured crusts, one at the top of the lower unit and two within the upper unit, are interpreted as caliche formed during aerial exposure due to short-term sea-level fall. The lower Sarmatian deposits at Klapping therefore represent at least four to five parasequences (Harzhauser and Piller 2004; Gross et al., 2007).

4.4 Stop 4: Sand and Gravel Pit Trössing

Topic: Sarmatian fluvial–deltaic gravels of the "Caranthian Gravel"

Locality: Historical sand and gravel pit approximately 5 km SSE of Gnas, east of the Gnasbach valley (owned by Pock Ges.m.b.H. | Dachdecker & Spengler - Gnas)

Coordinates: 46°49'41.9"N 15°50'20.1"E

Lithostratigraphy: 'Carinthian Gravel' ('Carinthian Delta' of Winkler-Hermaden 1951). Kollmann (1965) correlated the up to approximately 30 m thick basal gravel package at Trössing with the '(sarmato-)Carinthian Gravel', at the base of the lower, fossil-poor *Nonion granosum* interval. Its regional progradation is interpreted to follow a regression at the top of the Lower Sarmatian (Gross et al. 2007b; Piller, 2022).

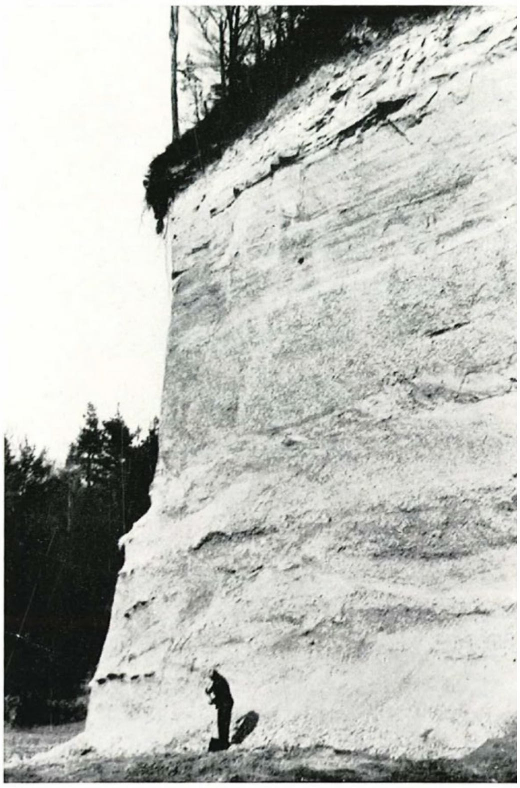

Fig. 14: Historical wall of the sand and gravel pit at Trössing near Gnas. Source: Hanselmayer, 1969 (**left image**). More recent image of the basal gravels in the rear part of the sand and gravel pit Trössing (**right image**, © M. Gross).

Chrono-/biostratigraphy: Sarmatian (Middle Miocene), near the lower/upper Sarmatian transition. Historical assignments differ: Winkler v. Hermaden (1951) placed the delta at the base of the Styrian 'middle Sarmatian', while noting that its lower part may correspond to a higher interval of the Vienna Basin 'lower Sarmatian'. Kollmann (1965) later assigned the basal gravel to the *Nonion granosum* Zone. These historical subdivisions do not match the modern two-part Sarmatian scheme (Gross et al. 2007b).

Outcrop Description: At the time of the classic investigations, Trössing was one of the largest gravel pits in southeastern Styria. The exposed wall was about 72 m long and reached up to 19.5 m in height (Fig. 14). Hanselmayer recorded an 18.60 m section in 1965; subsequent sediment extraction had already destroyed much of this nearly vertical wall by the time of publication (Hanselmayer 1969)

The published section is dominated by 12.00 m of gravel beneath 6.20 m of sand and a 0.40 m surface cover. Sand beds are nearly parallel and alternate between pale yellow-grey and deep ochre tones; elongated thin sand lenses occur locally. The lower gravel interval alternates between coarser and finer beds, contains irregular outsized clasts up to 22 cm and includes weakly cemented red sand horizons known locally as 'Sommergfrer'. Cross-bedding was not observed in the documented wall (Table 2; Hanselmayer 1969). The section has recently been noted as a potential type section to formalise the Carinthian Gravel based on state-of-the-art stratigraphic principles (e.g. Piller, 2022).

Table 2: Published profile at Trössing, from top to base. Source: Hanselmayer (1969: pl. 3, fig. 6).

Unit	Lithology / sedimentary features	Thickness (m)	Base depth (m)
Surface cover	Grass cover	0.40	0.40
Sand 1	Brown-grey, clayey sand	1.80	2.20
Sand 2	Nearly parallel-bedded pale yellow-grey and deep ochre sand; thin elongate sand lenses	3.90	6.10
Sand 3	Light-grey, concordant sand	0.50	6.60
Gravel 1	Medium-coarse, nearly homogeneous gravel package	4.10	10.70
Gravel 2	Alternating coarse and fine gravel; outsized clasts to 22 cm; weakly cemented red sand horizons	7.90	18.60

Clast spectrum: Two counts of clasts larger than 30 mm (104 and 200 pebbles) show quartz as the dominant component, followed by limestones and a diverse suite of Alpine crystalline, sedimentary and ultramafic rocks. Selected large clasts include a 220 mm quartz cobble, a 168 mm chromite-bearing antigorite cobble, as well as gneisses, pegmatite, greywacke sandstone, Mesozoic limestone and chert-bearing limestone (Table 3; Hanselmayer 1967a; Hanselmayer 1969).

Table 3: Selected components in two >30 mm clast counts (range of piece percentages). Sources: Hanselmayer (1967a: 31–32; 1969: 315–316).

Component	**Piece %**
Quartz	37.5–50.0
Limestone	12.4–29.0
Gneiss	5.5–8.6
Quartzite	2.9–6.0
Pegmatite	3.5–5.7
Sandstone/conglomeratic sandstone	5.0–5.7
Antigorite	2.5–2.9
Dolomite	2.0–3.0
Chert-bearing limestone/chert	2.0–3.9
Lydite	1.5–3.9
Quartz rocks	37.5–50.0

The wider petrographic inventory includes rare granitoids, pegmatites, and gneisses; quartzites, lydites, and cherts; diverse sandstones; dolomite; several limestone types; more than twenty volcanic rock varieties; pale chromite-bearing antigorites; and abundant quartz rocks. Especially diagnostic are upper Eocene *Lithothamnion* limestones with *Discocyclina* and *Borelis*. The antigorite pebbles are usually well rounded and mostly up to about 5 cm, although larger specimens occur; their chromite, bastite and weathering textures are petrographically distinctive (Hanselmayer 1967a; Hanselmayer 1969).

Interpretation: The Carinthian Gravel records progradation of coarse continental sediment following regression near the top of the lower Sarmatian (Gross et al. 2007b). At Trössing, the gravel-dominated lower part of the section shows outsized clasts, strong rounding, and a wide-ranging grain-size distribution, consistent with high-energy fluvial to deltaic transport. The preserved section shows little cross-bedding, so the historical wall description alone cannot infer channel geometry or flow direction (Hanselmayer 1969).

Winkler von Hermaden (1951) interpreted the regional gravel body as the delta cone of a Sarmatian precursor of the Drau River advancing eastwards into the Graz Bay. He traced the “intrasarmatian” delta over approximately 40 km north–south and 30 km east–west and related it to a phase of complete terrestrialisation of the Sarmatian basin. East of the limestone-rich gravel belt, he recognised quartz- and schist-rich time-equivalent sediments supplied from the north or north-east. Trössing itself is not named in the 1951 paper; its inclusion in this regional unit rests on Kollmann's (1965) later correlation.

Provenance therefore remains debated. Kollmann (1965) considered an eastern source in the Bakony region, whereas Hanselmayer's pebble petrography demonstrates a mixed source assemblage. In particular, upper Eocene *Lithothamnion* limestones comparable to rocks at Wimpassing and Sieggraben indicate at least partial transport from the north to north-east. The source of the characteristic antigorites remains unresolved (Hanselmayer 1967a; Hanselmayer 1969).

Comparable Sarmatian gravels at Pöllauberg near Jagerberg contain a closely related clast suite and similar chromite-bearing antigorites. These data support the assumption that a regional gravel system exists but do not, by themselves, identify a single catchment or transport direction (Hanselmayer 1967b; Hanselmayer 1969).

4.5 Stop 5: Basalt Quarry Weitendorf and Fossillagerstätte

Topic: Middle Miocene (Badenian) volcanism of the Middle Styrian High, fossils of the lagoonal Florian Beds [Florianer Schichten] and adaptation of an existing quarry as a thermal energy storage facility.

Location: Basalt Quarry Weitendorf (Fig. 15) near Wildon, 1.6 km W of the village Weitendorf, c. 4.9 km WNW of the market town Wildon.

Coordinates: 46°53'43.88"N, 15°26'44.24"E

Fig. 15: Overview of the active quarry area of Weitendorf, with the exposed Florian Beds at the base, followed by the basalts and the Kaiserwald Terrace on top (source: https://www.meinbezirk.at/graz-umgebung/c-lokales/ein-waermespeicher-fuer-die-stadt-graz_a6820635, © Alois Lipp).

Lithostratigraphy: The base of the quarry exposes fossiliferous lagoonal marls of the Florian Beds, which the Weitendorf Basalt concordantly overlies. The Weitendorf basalt is composed of Latite (hawaiite/shoshonite) with xenoliths and was formed by a volcanic intrusion (sill) close to the sediment-/(sea-)water interface of the Badenian Sea along the Middle Styrian High. Some features in the basalt indicate possible, in part, submarine eruptions and the presence of pillow lavas (Balogh et al., 1994). On top of the Weitendorf shoshonites, ~3 m of Badenian sediments are overlain by up to 15m of Pleistocene gravels of the Kaiserwald Terrace. These successions represent Chibanian (possibly MIS 16) alluvial gravels and braided river deposits of the Mur and Kainach rivers. They are followed by up to 10 m of weathered loess sediments (Fig. 16; Flügel et al., 1952; Krainer, 1987; van Husen and Reitner, 2022, p. 248 in Piller, 2022).

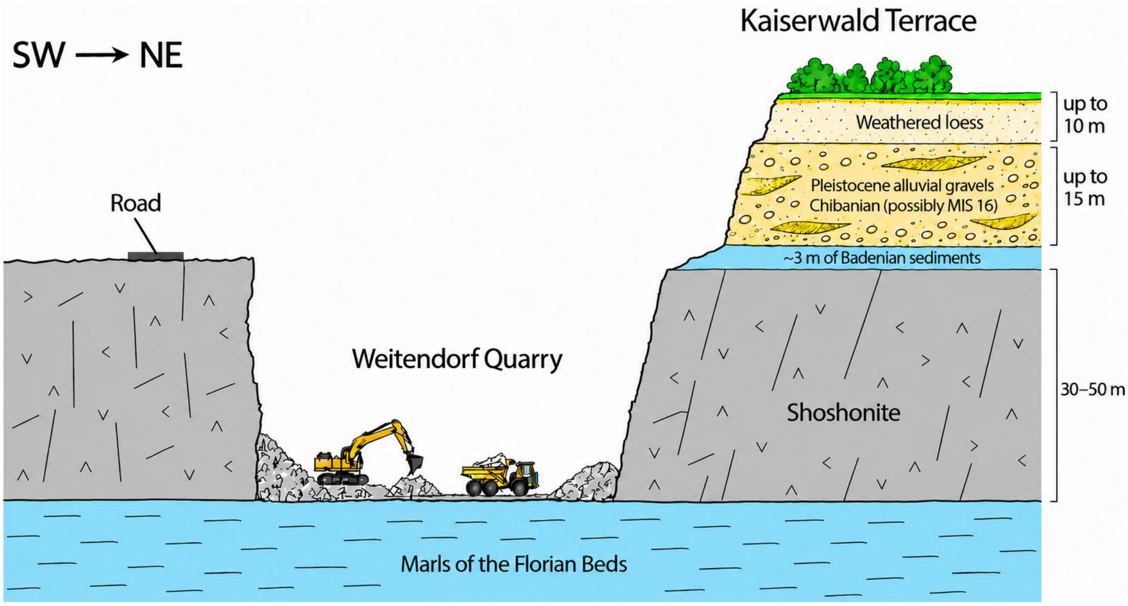

Fig. 16: Sketch (not to scale) of the Weitendorf quarry showing its primary features including the basal marls of the Florian Beds, the ~40 m thick shononitic basalts of middle Badenian Age (~14 Ma) and the overlying ~3 m thick Badenian marine sediments, followed by the Pleistocene fluvial gravels (up to 15m) and weathered loess (up to 10 m) of the “Kaiserwald Terrace”.

Bio-/Chronostratigraphy: The fossil content of the florian beds indicates a Middle Badenian age, based on a diverse fossil assemblage including foraminifers, corals, gastropods, bivalves, cephalopods, ostracods, cirripeds, decapods, echinoids, bryozoans, fishes (elasmobranchii, teleostei), and plant remains. Radiometric investigations (K/Ar dating) of the overlying Weitendorf Basalts yielded an age of 14.0 ± 0.7 Ma, confirming the Middle Badenian Age of the eruption of the Weitendorf paleo-volcano (Balogh et al., 1994).

Outcrop Description: The outcrop is subject to frequent topographic changes due to the ongoing mining activity of the Weitendorf shoshonites. However, the entry road into the quarry provides a stable outcrop situation where the contact between the Badenian basalt flow and the shallow subtropical/tropical lagoon of the Florian Beds can be examined in some detail. On the walk downward, there is a good view of the Pleistocene Kaiserwald Terrace on top of the shoshonites. At the lower base, the basalts give way to the marls of the Florian Beds, which contain a staggeringly abundant and diverse fossil assemblage (Ebner and Gräf, 1977). The Weitendorf fossils are known regionally and globally and are prized by collectors (Fig. 17).

Fig. 17: Weitendorf fossils (*Turritella turris var. badensis* Sacco, 1895) in the Ryugado Cave Museum (Shikoku, Japan), illustrating the global importance of the fossils found within the Florian Beds in the Weitendorf Quarry (© G. Auer, 2026).

Adaptation as a solar energy storage facility: The quarry owners (Unternehmensgruppe Ecker-Eckhofen) plan to convert the site into a thermal solar energy storage facility, with project implementation expected to begin between 2029 and 2030. "Sonnenspeicher Süd" is Austria's largest district-heating decarbonisation project currently under development. Plans are underway to transform the existing basalt quarry pit in Weitendorf into a seasonal heat storage facility with a capacity of 1.5 × 10^6 m^3. The plan is to use Solar energy from around 28 ha of collector area as the main heat source, coupled to high-temperature heat pumps to increase the efficiency of the storage system. The plan is to heat the water in the flooded quarry to around 90 °C. The heat is stored there until winter. When needed, the stored thermal energy is extracted and fed into the district-heating network. Finally, a low-carbon-emission biomass heating plant is envisioned to reheat the stored water to the temperature needed for transfer into Graz's district heating system.

Once in operation, solar heat stored during the summer is expected to supply up to 30% of Graz's total district-heating demand from renewable energy. Integrating this renewable energy storage system into Graz's district-heating network is projected to reduce CO_2 emissions by approximately 100,000 tonnes per year.

One concern for the project's realisation is the uniquely exposed, highly fossiliferous Florian Beds below the Weitendorf Basalt, which were designated a protected natural monument (Naturdenkmal) in the 1980s. To safeguard these fossil-bearing layers, the affected area will be covered. In addition, selected specimens are planned to be stored under ideal climatic conditions at the Roman quarry in Aflenz (Wagna). An exhibition in the former crusher house adjacent to the quarry is also being considered.

5 References

Ali, S., Ntaflos, T., & Upton, B. G. J. (2013). Petrogenesis and mantle source characteristics of Quaternary alkaline mafic lavas in the western Carpathian–Pannonian Region, Styria, Austria. Chemical Geology, 337, 99–113. https://doi.org/10.1016/j.chemgeo.2012.12.001

Aradi, L. E., Bali, E., Patkó, L., Hidas, K., Kovács, I. J., Zanetti, A., et al. (2020). Geochemical evolution of the lithospheric mantle beneath the Styrian Basin (Western Pannonian Basin). Lithos, 378, 105831. https://doi.org/10.1016/j.lithos.2020.105831

Balogh, K., Ebner, F. & Ravasz, C. (1994): K/Ar-Alter tertiärer Vulkanite der südöstlichen Steiermark und des südlichen Burgenlandes. In: Lobitzer, H., Császár, G. & Daurer, A. (Eds.): Jubiläumsschrift 20 Jahre Geologische Zusammenarbeit Österreich-Ungarn, Teil 2, 55–72.

Bialik, O. M., Frank, M., Betzler, C., Zammit, R., & Waldmann, N. D. (2019). Two-step closure of the Miocene Indian Ocean Gateway to the Mediterranean. Scientific Reports, 9(1), 8842–8852. https://doi.org/10.1038/s41598-019-45308-7

Bojar, H.-P., Bojar, A.-V., Hałas, S., & Wójtowicz, A. (2013). K/Ar geochronology of igneous amphibole phenocrysts in Miocene to Pliocene volcaniclastics, Styrian Basin, Austria. Geological Quarterly, 57(3). https://doi.org/10.7306/gq.1102

Bräuer, K., Geissler, W. H., Kämpf, H., Niedermannn, S., & Rman, N. (2016). Helium and carbon isotope signatures of gas exhalations in the westernmost part of the Pannonian Basin (SE Austria/NE Slovenia): Evidence for active lithospheric mantle degassing. Chemical Geology, 422, 60–70. https://doi.org/10.1016/j.chemgeo.2015.12.016

Dax, F. (2021). The Central Styrian Basin (Gnas Sub-basin): Structure and Stratigraphy Revealed by Seismic and Borehole Data. Master's thesis, Montanuniversität Leoben.

Dax, F., Sachsenhofer, R. F., Schreilechner, M. G., & Tari, G. (2024). The Styrian Basin: an overview with new insights from seismic data. Geological Society, London, Special Publications, 554(1), SP554-2023–194. https://doi.org/10.1144/sp554-2023-194

Daxner-Höck, G., and Höck, E. (2015). Rodentia neogenica. In: Piller, W.E. (Ed.): Catalogus Fossilium Austriae, 4, XXVI, 158 pp.

Dullo, W.-C. (1983). Fossildiagenese im miozänen Leitha-Kalk der Paratethys von Österreich: Ein Beispiel für Faunenverschiebungen durch Diageneseunterschiede. Facies, 8(1), 1–111. https://doi.org/10.1007/bf02536740

Ebner, F. (1974). Ein Beitrag zum Altpaläozoikum des Remschnigg (Steiermark). Verhandlungen der Geologischen Bundesanstalt, 1974, 281–287.

Ebner, F. & Gräf, W. (1977). Die Fauna von Weitendorf. – Landesmuseum Joanneum, Jahresbericht 1976, Neue Folge 6, 157–183.

Ebner, F. & Sachsenhofer, R.F. (1991). Die Entwicklungsgeschichte des Steirischen Tertiärbeckens. Mitteilungen der Abteilung für Geologie und Paläontologie am Landesmuseum Joanneum, 49, 1–96.

Ebner, F., & Sachsenhofer, R. F. (1995). Palaeogeography, subsidence and thermal history of the Neogene Styrian Basin (Pannonian basin system, Austria). Tectonophysics, 242(1–2), 133–150. https://doi.org/10.1016/0040-1951(94)00155-3

Ebner, F., Dunkl, I., Mali, H. & Sachsenhofer, R.F. (2002). Stratigraphic evidence of pyroclastic layers in Miocene basins of the Eastern Alps (Austria). – Proceedings of the XVII. Congress of the Carpathian-Balkan Geological Association, Bratislava, September 1st–4th 2002. Geologica Carpathica, 53 (special issue), 1–5.

Flügel, H.W. (1975). Die Geologie des Grazer Berglandes. Mitteilungen der Abteilung für Geologie, Paläontologie und Bergbau am Landesmuseum Joanneum, Sonderheft 1: 1-288.

Flügel, H.W. & Neubauer, F. (1984). Steiermark. Erläuterungen zur Geologischen Karte der Steiermark 1:200.000. Geologie der Österreichischen Bundesländer in kurzgefaßten Einzeldarstellungen. Österreichische Geologische Bundesanstalt, 127 pp.

Flügel, H.W. (1988). Steirisches Becken – Südburgenländi-sche Schwelle. Geologische Karte des prätertiären Untergrundes. *Geologische Bundesanstalt*.

Flügel, H., Hauser, A. & Papp , A. (1952). Neue Beobachtungen am Basaltvorkommen von Weitendorf bei Graz. – Sitzungsberichte der mathematisch-naturwissenschaftlichen Klasse der Österreichischen Akademie der Wissenschaften, Abteilung I, 161/2–3, 173–184.

Fodor L., Csontos L., Bada G., Gyorfi I., & Benkovics L. (1999). Tertiary tectonic evolution of the Pannonian Basin system and neighbouring orogens: a new synthesis of palaeostress data. GeolSoc Lond Spec Publ 156:295–334. https://doi.org/10.1144/gsl.sp.1999.156.01.15

Friebe, J.G. (1990): Lithostratigraphische Neugliederung und Sedimentologie der Ablagerungen des Badeniens (Miozan) um die Mittelsteirische Schwelle (Steirisches Becken, Osterreich). – Jahrbuch der Geologischen Bundesanstalt, 133/2, 223–257.

Fritz I. (1996). Notes on the Plio-/Pleistocene volcanism of the Styrian Basin. Mitteilungen der Gesellschaft der Geologie- und Bergbaustudenten Österreichs, 41, 87–100.

Gitter, F., Gross, M., & Piller, W. E. (2015). Sub-decadal resolution in sediments of late miocene lake pannon reveals speciation of Cyprideis (crustacea, ostracoda). PLOS ONE, 10(4), e0109360. https://doi.org/10.1371/journal.pone.0109360

Gold. M., Kriegl. C., (2023). Tiefengrundwasserkörper GK100168 Steirisches und Pannonisches Becken – Tiefengrundwassermonitoring Ausbaustufen 1 und 2 – Interpretation und Einbindung der Ergebnisse. Hydrogeologischer Bericht and das Land Steiermark. 67 pp., https://www.wasserwirtschaft.steiermark.at/cms/dokumente/11910979_102332494/1b29ed91/TGW_MO~1.PDF

Goldbrunner, J.E. (1988). Tiefengrundwässer im Oberösterreichischen Molassebecken und im Steirischen Becken. Steirische Beiträge zur Hydrogeologie, 39, 5–94.

Goldbrunner, J. (2007). Thermalwassererschließungen –wissenschaftliche Begleitung von Bohrungen einschließlich Bohrlochuntersuchungen. Bbr, 11, 25–33.

Goldbrunner, J. & Schubert, A. (1993). Aquifereigenschaften jungtertiärer Vulkanite im Oststeirischen Becken*). In: Kollmann, W., & Daurer, A. (eds.): Ergebnisse österreichischer Aktivitäten im Internatiplan Hydrogeologischen Programm (IHP) 1981 – 1990. Arch. f. Lagerst.forsch. Geol.B.-A., 14, 81-91.

Goldbrunner, J. and Götzl, G. (2019). Geothermal energy use, country update for Austria. Conference Proceedings of European Geothermal Congress. Den Haag, The Netherlands, 11-14 June 2019, 10 pp.

Gostencnik, M., Winkler, G. (2021). Grundlagenerhebung der Säuerlinge in der östlichen Steiermark. Project Report, 31 pp. https://www.wasserwirtschaft.steiermark.at/cms/dokumente/11910979_102332494/538b59da/Grundlagenerhebung%20der%20S%C3%A4uerli nge%20in%20der%20%C3%B6stlichen%20Steiermark%20GOSTENCNIK%20%26%20WINKLER%202021.pdf

Götzl G., Poltnig W., Domberger G., Lipiarski P. (2007). Projekt TRANSTHERMAL, Geothermie der Ostalpen – Erfassung und zusammenfassende Darstellung des geothermischen Potenzials in Datenbanken, in einem Geothermieatlas und in GIS – basierten Kartenwerken im Bereich von Kärnten, Steiermark und Slowenien. Nationaler Abschlussbericht, INTERREG IIIA Austria – Slovenia, 173 pp. https://www.wasserwirtschaft.steiermark.at/cms/dokumente/11910976_102332494/aa66eb4d/Transthermal-Geothermie%20der%20Ostalpen%20JR-GBA%202007.pdf

Gross, M. (2003). Beitrag zur Lithostratigraphie des Oststeirischen Beckens (Neogen/Pannonium; Österreich).In: Piller, W.E. (ed.): Stratigraphia Austriaca. Schriftenreihe der Erdwissenschaftlichen Kommissionen (Österreichische Akademie der Wissenschaften), 16, 11–62.

Gross, M. (2015). Die neogenen Formationen auf der geologischen Karte GÖK50 164 Graz (Steiermark, SE-Österreich). Mitteilungen des Naturwissenschaftlichen Vereines für Steiermark,144, 105–132.

Gross, M., Fritz, I., Piller, W.E., Soliman, A., Harzhauser, M., Hubmann, B., Moser, B., Scholger, R., Suttner, T.J., & Bojar, H.-P. (2007a). The Neogene of the Styrian Basin - Guide to Exkursions. Joannea Geol. Paläont. 9. 117-193.

Gross , M., Harzhauser, M., Mandic, O., Piller, W.E. & Rögl, F. (2007b): A Stratigraphic Enigma: The Age of the Neogene Deposits of Graz (Styrian Basin; Austria). – Joannea Geologie und Paläontologie, 9, 195–220

Gruber, W., Hermann, S., Sachsenhofer, R. F., & Stingl, K. (2003). Kohlefazies und Sedimentologie der Eibiswalder Bucht (Miozän, Steirisches Becken). Mitteilungen der Österreichischen Geologischen Gesellschaft, 93, 15-29.

Haas, M., Daxner-Höck , G., Decker, K., Kolcon, I., Kovar-Eder, J., Meller, B. & Sachsenhofer, R.F. (1998): Palaeoenvironmental Studies in the Early Miocene Lignite Opencast Mine Oberdorf (N Voitsberg, Styria, Austria). Jahrbuch der Geologischen Bundesanstalt, 140(4), 483–490.

Hanselmayer, J. (1967a). Beiträge zur Sedimentpetrographie der Grazer Umgebung XXVI. Antigoritit mit besonderen Chromitformen aus den Sarmatschottern. Mitteilungen der Abteilung für Mineralogie am Landesmuseum Joanneum, 1–2, 31–39.

Hanselmayer, J. (1967b). Die Sarmat-Schotter von Pöllauberg bei Jagerberg. – Mitteilungen des Naturwissenschaftlichen Vereines für Steier-mark, 97, 17–27.

Hanselmayer J. (1969). Beiträge zur Sedimentpetrographie der Grazer Umgebung XXX. Erster Einblick in die Petrographie oststeirischer Sarmat-Schotter, spez. Trössing bei Gnas. Sitzungsberichte der Österreichischen Akademie der Wissenschaften, mathematisch-naturwissenschaftliche Klasse, Abt. I, 178, 295–321

Harangi, S., Jankovics, M. É., Sági, T., Kiss, B., Lukács, R., & Soós, I. (2015). Origin and geodynamic relationships of the Late Miocene to Quaternary alkaline basalt volcanism in the Pannonian basin, eastern–central Europe. International Journal of Earth Sciences, 104(8), 2007–2032. https://doi.org/10.1007/s00531-014-1105-7

Harzhauser, M., Piller, W. E., & Steininger, F. F. (2002). Circum-Mediterranean Oligo–Miocene biogeographic evolution – the gastropods' point of view. Palaeogeography, Palaeoclimatology, Palaeoecology, 183(1–2), 103–133. https://doi.org/10.1016/s0031-0182(01)00464-3

Harzhauser, M., & Piller, W. E. (2004a). Integrated stratigraphy of the Sarmatian (Upper Middle Miocene) in the western Central Paratethys. Stratigraphy, 1(1), 65–86. https://doi.org/10.29041/strat.01.1.04

Harzhauser, M. & Piller, W.E. (2004b). The Early Sarmatian – hidden seesaw changes. Courier Forschungsinstitut Senckenberg, 246, 89–112.

Harzhauser, M., & Piller, W. E. (2007). Benchmark data of a changing sea — Palaeogeography, Palaeobiogeography and events in the Central Paratethys during the Miocene. Palaeogeography, Palaeoclimatology, Palaeoecology, 253(1–2), 8–31. https://doi.org/10.1016/j.palaeo.2007.03.031

Harzhauser, M., Mandic, O., & Zuschin, M. (2003). Changes in Paratethyan marine molluscs at the Early/Middle Miocene transition: diversity, palaeogeography and palaeoclimate. Acta Geologica Polonica, 53(4), 323–339.

Harzhauser, M., Daxner-Höck, G., Piller, W.E. (2004). An integrated stratigraphy of the Pannonian (Late Miocene) in the Vienna Basin. Austrian Journal of Earth Sciences, 95/96, 6-19.

Harzhauser, M., Neubauer, T.A. & Schimitsberger, O. (2019). The gastropod fauna from the opalite of the late Miocene Lake Tschaterberg (Austria). Jahrbuch der Geologischen Bundesanstalt, 159, 163–173.

Harzhauser, M., Landau, B., Mandic, O., & Neubauer, T. A. (2024). The Central Paratethys Sea – Part of the tropical eastern Atlantic rather than gate into the Indian Ocean. Global and Planetary Change, 243, 104595. https://doi.org/10.1016/j.gloplacha.2024.104595

Hiden, H.R. (1997). Die Mittelmiozanen „Florianer Schichten“ des weststeirischen Tertiarbeckens und ihre Fossilfuhrung. Der Steirische Mineralog, 8/11, 32–35.

Hilber, V. (1878). Die Miocan-Ablagerungen um das Schiefergebirge zwischen den Flussen Kainach und Sulm in Steiermark. Jahrbuch der k. k. Geologischen Reichsanstalt, 28/3, 505–580.

Hohenegger, J., Rögl, F., Ćorić, S., Pervesler, P., Lirer, F., Roetzel, R., et al. (2009). The Styrian Basin: a key to the Middle Miocene (Badenian/Langhian) Central Paratethys transgressions. Austrian Journal of Earth Sciences, 102, 102–132.

Hohenegger, J., Ćorić, S., & Wagreich, M. (2014). Timing of the Middle Miocene Badenian Stage of the Central Paratethys. Geologica Carpathica, 65(1), 55–66. https://doi.org/10.2478/geoca-2014-0004

Ivančič, K., Bartol, M., Marinšek, M., Kralj, P., Gale, E. M., Atanackov, J., et al. (2025c). Stratigraphy and structure of the Slovenian part of the Pannonian Superbasin: a brief overview. Geological Society, London, Special Publications, 554(1), SP554-2023–190. https://doi.org/10.1144/sp554-2023-190

Kern, A. K., Harzhauser, M., Soliman, A., Piller, W. E., & Gross, M. (2012). Precipitation driven decadal scale decline and recovery of wetlands of Lake Pannon during the Tortonian. Palaeogeography, Palaeoclimatology, Palaeoecology, 317–318, 1–12. https://doi.org/10.1016/j.palaeo.2011.11.021

Kollmann, K. (1965): Jungtertiär im Steirischen Becken. Mitteilungen der Geologischen Gesellschaft in Wien, 57/2, 479–632.

Konečný, V., Kováč, M., Lexa, J., Šefara, J., (2002). Neogene evolution of the Carpatho – Pannonian region: an interplay of subduction and back-arc diapiric uprise in the mantle. In: EGS Stephan Mueller Spec. Publ. Ser. vol. 1. pp. 105–123.

Kováč, M., Barath, I., Harzhauser, M., Hlavaty, I. & Hudáčková, N. (2004). Miocene depositional systems and sequence stratigraphy of the Vienna Basin. Courier Forschungsinstitut Senckenberg, 246, 187–212.

Kováč, M., Márton, E., Oszczypko, N., Vojtko, R., Hók, J., Králiková, S., et al. (2017). Neogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. Global and Planetary Change, 155, 133–154. https://doi.org/10.1016/j.gloplacha.2017.07.004

Kovar-Eder, J., Haas, M., Hofmann, C., & Meller, B. (2001). An Early Miocene Plant Assemblage Severely Influenced By A Volcanic Eruption, Styria, Austria. Palaeontology, 44(4), 575–600. https://doi.org/10.1111/1475-4983.00192

Kralj, P. (2011). Eruptive and sedimentary evolution of the Pliocene Grad Volcanic Field, North-east Slovenia. Journal of Volcanology and Geothermal Research, 201(1–4), 272–284. https://doi.org/10.1016/j.jvolgeores.2010.09.004

Krainer, B. (1987). Sedimentation und Shoshonit von Weitendorf, Badenien, Steirisches Becken. Mitteilungen der Österreichischen Geologischen Gesellschaft, 80, 143–156.

Kröll, A. (1988). Steirisches Becken – SüdburgenländischeSchwelle. Reliefkarte des prätertiären Untergrundes.Geologische Bundesanstalt

Kröll, A., Flügel, H.W., Seiberl, W., Weber, F., Walach, G., & Zych, D. (1988). Erläuterungen zu den Karten überden prätertiären Untergrund des Steirischen Beckensund der Südburgenländischen Schwelle.

Kurz, W., Fritz, H., & Wölfler, A. (2024). Tectonic Evolution of the Eastern Alps. In C. L. Rosenberg & N. Bellahsen, Geodynamics of the Alps 1: Present-Structure and Regional Alpine Studies from Extension to Collision (pp. 209–292). Wiley. https://doi.org/10.1002/9781394299508.ch5

Magyar, I., Geary, D. H., & Müller, P. (1999). Paleogeographic evolution of the Late Miocene Lake Pannon in Central Europe. Palaeogeography, Palaeoclimatology, Palaeoecology, 147(3–4), 151–167. https://doi.org/10.1016/s0031-0182(98)00155-2

Malzer, O. & Sperl, H. (1993): Das Steirische Becken (Steiermark und Südburgenland. in: Brix, F. & Schultz, O. (ed.): Erdöl und Erdgas in Österreich, 312 pp., Nat. hist. Mus. Wien und F. Berger, Horn.

Matenco L., & Radivojević D. (2012). On the formation and evolution of the Pannonian Basin: constraints derived from the structure of the junction area between the Carpathians and Dinarides. Tectonics 31:TC6007. https://doi.org/10.1029/2012tc003206

Messner, F. & Bernhard, F. (2016): Zwei aktuelle Fossilfundstellen im Bereich Wetzelsdorfberg, Weststeiermark. Der Steirische Mineralog, 31, 28–34.

Müller, P., Geary, D. H., & Magyar, I. (1999). The endemic molluscs of the Late Miocene Lake Pannon: their origin, evolution, and family-level taxonomy. Lethaia, 32(1), 47–60. https://doi.org/10.1111/j.1502-3931.1999.tb00580.x

Neubauer, F., & Genser, J. (1990). Architektur und Kinematik der östlichen Zentralalpen – eine Übersicht. Mittielungen des Naturwissenschafltihcen Vereins für Steiermark, 120. 203–219.

Neubauer, F., Genser, J. & Handler, R. (2000). The Eastern Alps: Result of a two-stage collision process. – Mitteilungen der Österreichischen Geologischen Gesellschaft, 92, 117–134.

Papp, A. (1956): Fazies und Gliederung des Sarmats im Wiener Becken. Mitteilungen der Geologischen Gesellschaft in Wien, 47, 35–97.

Papp, A. (1963). Die biostratigraphische Gliederung des Neogens im Wiener Becken. – Mitteilungen der Geologischen Gesellschaft in Wien, 56/1, 225–317.

Peresson, H., & Decker, K. (1997). The Tertiary dynamics of the northern Eastern Alps (Austria): changing palaeostresses in a collisional plate boundary. Tectonophysics, 272(2–4), 125–157. https://doi.org/10.1016/s0040-1951(96)00255-7

Piller, W.E. (ed.) (2022). The lithostratigraphic units of Austria: Cenozoic Era(them). Abhandlungen der Geologischen Bundesanstalt, 76, 357 pp.

Piller, W. E., & Harzhauser, M. (2005). The myth of the brackish Sarmatian Sea. Terra Nova, 17(5), 450–455. https://doi.org/10.1111/j.1365-3121.2005.00632.x

Piller, W. E., & Harzhauser, M. (2024). On the status and occurrence of the foraminiferal genera Nubecularia and Sinzowella in the late Middle Miocene of the Paratethys Sea. *Micropaleontology*, *70*(5), 485–494. https://doi.org/10.47894/mpal.70.5.04

Piller, W. E., Harzhauser, M., & Mandic, O. (2007). Miocene Central Paratethys stratigraphy – current status and future directions. Stratigraphy, 4(2/3), 71–88.

Piller, W. E., Harzhauser, M., Kranner, M., Mandic, O., Mohtat, T., & Daneshian, J. (2024). The Tethyan Seaway during the early to middle Miocene – New data and a review. Gondwana Research, 135, 57–74. https://doi.org/10.1016/j.gr.2024.08.004

Popov, S. V., Rögl, F., Rozanov, A. Y., Steininger, F. F., Shcherba, I. G., & Kováč, M. (2004). Lithological-paleogeographic maps of Paratethys. Courier Forschungsinstitut Senckenberg, 250, 1–46.

Reuter, M., Piller, W. E., & Erhart, C. (2012). A Middle Miocene carbonate platform under silici-volcaniclastic sedimentation stress (Leitha Limestone, Styrian Basin, Austria) — Depositional environments, sedimentary evolution and palaeoecology. Palaeogeography, Palaeoclimatology, Palaeoecology, 350, 198–211. https://doi.org/10.1016/j.palaeo.2012.06.032

Rögl, F. (1998). Palaeogeographic considerations for Mediterranean and Paratethys seaways (Oligocene to Miocene). Annalen Des Naturhistorischen Museums in Wien. Serie A Für Mineralogie Und Petrographie, Geologie Und Paläontologie, Anthropologie Und Prähistorie, 99 A, 279–310.

Rolle, F. (1855). Uber einige neue Vorkommen von Foraminiferen, Bryozoen und Ostracoden in den tertiaren Ablagerungen Steiermarks. Jahrbuch der k. k. Geologischen Reichsanstalt, 6, 351–354.

Sant, K., Palcu, D. V., Turco, E., Stefano, A. D., Baldassini, N., Kouwenhoven, T., et al. (2019). The mid-Langhian flooding in the eastern Central Paratethys: integrated stratigraphic data from the Transylvanian Basin and SE Carpathian Foredeep. International Journal of Earth Sciences, 108(7), 2209–2232. https://doi.org/10.1007/s00531-019-01757-z

Sant, K., Kuiper, K. F., Rybár, S., Grunert, P., Harzhauser, M., Mandic, O., et al. (2020). 40Ar/39Ar geochronology using high sensitivity mass spectrometry: examples from middle Miocene horizons of the Central Paratethys. Geologica Carpathica, 71(2). https://doi.org/10.31577/geolcarp.71.2.5

Sauerzopf, F. (1952). Beitrag zur Entwicklungsgeschichte des südburgenländischen Pannons. Burgenländische Heimatblätter, 14/1, 1–16.

Schönlaub, H.P. 1979. Das Paläozoikum in Österreich – Verbreitung, Stratigraphie, Korrelation, Entwicklung und Paläogeographie nicht-metamorpher und metamorpher Abfolgen. Abhandlungen der Geologischen Bundesanstalt, 33.

Schönlaub, H.P. (2000). Das Altpaläozoikum im Südburgenland. In: Schönlaub, H.P. (ed.). Burgenland: Erläuterungen zur Geologischen Karte des Burgenlandes1:200.000. Geologische Bundesanstalt, 31–35.

Schouppe, A. (1952). Hydrologische Studien zur Genesis der Heilquellen von Gleichenberg. – Berg- und Hüttenmännische Monatshefte, 97(10), 185–192.

Schreilechner, M.G. & Sachsenhofer, R.F. (2007). High Resolution Sequence Stratigraphy in the Eastern Styrian Basin (Miocene, Austria). Austrian Journal of Earth Sciences, 100, 164–184.

Schreilechner, M. G., Goldbrunner, J. E., Gold, M., Muhr, D., Dax, F., Sachsenhofer, R. F., & Ferstl, M. (2024). Geoenergy in the Styrian Basin. Geological Society, London, Special Publications, 555(1), SP555-2023–187. https://doi.org/10.1144/sp555-2023-187

Schulz, H. M., Bechtel, A., & Sachsenhofer, R. F. (2005). The birth of the Paratethys during the Early Oligocene: From Tethys to an ancient Black Sea analogue? Global and Planetary Change, 49(3–4), 163–176. https://doi.org/10.1016/j.gloplacha.2005.07.001

Seghedi, I., & Downes, H. (2011). Geochemistry and tectonic development of Cenozoic magmatism in the Carpathian–Pannonian region. Gondwana Research, 20(4), 655–672. https://doi.org/10.1016/j.gr.2011.06.009

Seghedi, I., Downes, H., Vaselli, O., Szakács, A., Balogh, K., & Pécskay, Z. (2004). Post-collisional Tertiary–Quaternary mafic alkalic magmatism in the Carpathian–Pannonian region: a review. Tectonophysics, 393(1–4), 43–62. https://doi.org/10.1016/j.tecto.2004.07.051

Serri, G., Mukasa, S.B., Renzulli, A., Kolmer, H., and Dostal, J. (1998). Geochemistry and Sr, Nd, Pb isotopes of Miocene and Plio-Pleistocene volcanic rocks from two Neogene sub-basins of the Pannonian system (Styria and Carinthia): geodynamic implications. CBGA XVI Congress, Vienna.

Skala, W. (1967). Kurzbericht über die Untersuchung von Fließrichtungen in den Basisschottern des Obersarmats im Steirischen Becken. Mitteilungen des Naturwissenschaftlichen Vereines für Steiermark, 97, 28–31.

Soliman, A., Feist-Burkhardt, S., Harzhauser, M., Kern, A. & Piller, W.E. (2013). Mendicodinium mataschenensis: a new endemic dinoflagellate cyst from the Late Miocene (Tortonian) of Lake Pannon (Austria). Palynology, 37, 35–47.

Steininger, F.F., Daxner-Höck , G., Haas, M., Kovar-Eder, J.,Mauritsch , H., Meller, B. & Scholger, R.M. (1998). Stratigraphy of the "Basin Fill" in the Early Miocene Lignite Opencast Mine Oberdorf (N Voitsberg, Styria, Austria). Jahrbuch der Geologischen Bundesanstalt, 140/4, 491–496.

Stille, H. (1924). Grundfragen vergleichender Tektonik. Borntraeger, Berlin, 443 pp.

Suttner, T., & Lukeneder, A. (2004). Accumulations of Late Silurian serpulid tubes and their palaeoecological implications (Blumau-Formation; Burgenland; Austria). Annalen des Naturhistorischen Museums Wien, A, 105, 175-187, Wien.

Tari, G., Horváth, F., & Rumpler, J. (1992). Styles of extension in the Pannonian Basin. Tectonophysics, 208(1–3), 203–219. https://doi.org/10.1016/0040-1951(92)90345-7

Van Husen, D., Reitner, J. M. (2022). Kaiserwaldterrasse / Kaiserwald Terrace. In Piller, W.E. (ed.) (2022): The lithostratigraphic units of Austria: Cenozoic Era(them). Abhandlungen der Geologischen Bundesanstalt, 76, p. 248.

Winkler, A. (1913). Das Eruptivgebiet von Gleichenberg in Oststeiermark. – Jahrbuch der Geologischen Reichsanstalt, 63. 403–502.

Winkler, A. (1927). Über die sarmatischen und pontischen Ablagerungen im Südostteil des steirischen Beckens. Jahrbuch der Geologischen Bundesanstalt, 77, 393–456.

Winkler von Hermaden, A. (1951). Über neue Ergebnisse aus dem Tertiärbereich des steirischen Beckens und über das Alter der oststeirischen Basaltausbrüche. – Sitzungsberichte der mathematisch-naturwissenschaftlichen Klasse der Akademie der Wissenschaften in Wien, 160, 1–15.

Winkler-Hermaden, A. (1957): Geologisches Kräftespiel und Landformung. Grundsätzliche Erkenntnisse zur Frage junger Gebirgsbildung und Landformung. Springer, 822 pp.

Zotter, G. (2026). Visionäre Energieversorgung im Gemüseanbau. In: Energie aus dem Untergrund. Fink, C. (Ed.). Erneuerbare Energien und Ressourceneffizienz, 02, 9-11.

21.-25. Sept. 2026 PANGEO AUSTRIA Graz

„New Horizons in Geosciences and Geotechnics“

Field Trip 4

Das Grazer Paläozoikum:
Ein Deckenkomplex neu interpretiert
/
The Graz Palaeozoic:
A New Interpretation of a Nappe Complex

Organizers:
Kurt Krenn, Harald Fritz & Bernhard Hubmann

NAWI Graz Natural Sciences

TU Graz

UNI GRAZ

Tectonic architecture of the Graz Paleozoic – insights into new ideas and concepts

Kurt Krenn[1)], Harald Fritz[1)], Bernhard Hubmann[1)], Christoph A. Hauzenberger[1)]

[1)]University of Graz, Departement of Earth Sciences, NAWI Graz Geocenter, Heinrichstraße 26, 8010 Graz

DOI: https://doi.org/10.3217/xxx

1. Introduction

The Graz Paleozoic (GP), part of the highest Austroalpine tectonic units (Drauzug – Gurktal Nappe System), is associated with several positive attributes and therefore appears from a geoscientific point of view to be a particularly attractive research area:

It is confined to a manageable area of about 1250 km², features a consistently revised lithostratigraphic framework, is available on relatively modern geological maps—albeit only partially harmonized with one another—and has a well-established chronostratigraphic architecture in its upper tectonic level.

Less positive, however, is the often moderate density of outcrops due to the continuous vegetation-cover of the low-mountainous area, the lack of a comprehensive tectonic-structural framework, and the geochronological understanding of the metamorphic units in the lower stratigraphic levels.

2. History of research and its impact on recent research findings

Geological investigations of the hilly mountains next to Graz (“Grazer Bergland”) date back to the early 19th century (for a summary of the history of geological research see Hubmann and Krenn (2022) and references cited therein). The first geological - geognostic maps of Styria, including the Graz Paleozoic, were published 1832 („Gebirgskarte von Steyermark“ by Mathias Anker (1771-1843)) and 1865 („Geologische Uebersichtskarte des Herzogthumes Steiermark“ by Dionys Stur (1827-1893)). The first regional map of the Graz Highlands („Geologische Karte der Umgebung von Gratz“ by Conrad Clar (1844-1904)) dates from 1877. Only four years after, Roderick Murchinson (1792-1871) and Adam Sedgwick (1785-1873) defined the Devonian System / Period, Franz Unger (1800-1870) recognized that the limestones at Plabutsch, a mountain range west of Graz, are of Devonian age (Unger, 1843). The first consistent stratigraphy, which is still applicable in many respects, was published 1868 by Eduard Suess (1831-1914). He distinguished six lithological successions, (1) basal green schists with „Brauneisen“ (today possibly the Kehr Formation), (2) lower „greywacke schists“ (today Parmasegg Formation), (3) dolomitic limestone (today Flösserkogel Formation), (4) „limestone at Gaisberg“ (today Plabutsch Formation), (5) massive limestone (today Kollerkogel Formation) and (6) black to reddish “Clymenienkalkstein (today Steinberg Formation). Helmut Flügel (1924-2017) published 1960 the „Geologische Wanderkarte des Grazer Berglandes“, and together with this map an explanatory volume (1961 and 1975 in a revised version). In this publication he defined three facies realms in the GP; (1) the Rannach-Fazies, (2) the Hochlantsch-Fazies containing also the „Folge von Laufnitzdorf“ and the „Kalkschiefer-Folge“, and (3) the Tonschiefer-Fazies. Already 1874 Conrad Clar (1844-1904) introduced the tectonic subdivision of the GP with a lower tectonic group (today Lower Nappe System containing the Tonschiefer-Facies) and a higher one (today Upper Nappe System, Hochlantsch and Rannach Nappes with Hochlantsch and Rannach Facies).

Enormous progress in biostratigraphic subdivision of the GP was achieved through conodont stratigraphy over a period of about 50 years from the 1960s onwards by the students of Helmut Flügel (1924-2017). These studies culminated in a standard reference work “Das Paläozoikum von Graz: Stratigraphie und Bibliographie” by Flügel and Hubmann (2000). Here we comment that the well-established biostratigraphy holds only for the weakly metamorphosed carbonatic successions of the Rannach and Hochlantsch Facies (Nappe respectively) that cover approximately only 35-40% of the entire GP. For the majority of the GP, the Lower Nappe System, lower tectonic group in the sense of Clar (1874), today

Gasen-, Schöckel- and Gschnaidt-Nappes, the stratigraphy is based upon lithological correlation with the fossiliferous sequences of the Rannach Nappe. In short, in recent decades the fundamentally lithologically similar strata of the Schöckel Nappe - although petrographically distinct due to a clear metamorphic difference! - have been correlated with chronostratigraphically fixed anchizonal formations of the Upper Nappe System: for example, the “Schöckel limestone” (i.e. the Schöckel Formation) was seen as a counterpart to the Middle Devonian platform carbonates (e.g., Plabutsch Formation and/or Kollerkogel Formation), the sandy and dolomitic sections below the Schöckel Formation (i.e., Raasberg Formation) were seen as equivalents in parts of the Lower Devonian Flösserkogel Formation or Parmasegg Formation, and the basal volcanoclastic sequences (Taschen Formation) were suspected to be metamorphic representations of the Upper Silurian Kehr Formation of the Upper Nappe System.

Franz Heritsch's maxim that "a sound tectonics is only possible on the basis of a secure stratigraphy" (Heritsch 1943:338) has, of course, lost none of its validity. Due to the currently limited, but clearly divergent, geochronological data of stratigraphic elements of the Lower Nappe System, we harbor skepticism in some cases regarding the long-accepted lithological - and thus lithostratigraphic! - analogousity with the stratigraphic members of the Upper Nappe System. This also necessitates a review of the traditional tectonic concept, which is based on a stratigraphically unsupported "depository series" (see below).

Based on classical correlation, Eberhard Clar (1935) was forced to interpret the “Schöckel limestone” (Schöckel Formation) as an isoclinal fold, since the general idea was that the graphitic schists (Schönberg Formation) at the base form the same stratigraphic unit as the overlying schists (Fig. 1). In his view the Rannach Nappe disconformly overthrusts the folded Schöckel Nappe. This tectonic model of the GP was adopted with minor modifications by several authors (Boigk, 1951; Flügel, 1958; Flügel and Neubauer, 1984; Gasser et al., 2010) and implies an inverted sequence in large parts of the Schöckel Nappe. Here we comment that Erhart-Schippek (1949) and Maurin (1954) ventured the possibility that black schist on top of the “Schöckel limestone”, exposed at Tanneben, are of Carboniferous age, a proposal that was never considered any further.

Geological investigations of the hilly mountains next to Graz (“Grazer Bergland”) date back to the early 19th century (for a summary of the history of geological research see Hubmann and Krenn (2022) and references cited therein). The first *geological - geognostic* maps of Styria, including the Graz Paleozoic, were published 1832 („*Gebirgskarte von Steyermark*“ by Mathias Anker (1771-1843)) and 1865 („*Geologische Uebersichtskarte des Herzogthumes Steiermark*“ by Dionys Stur (1827-1893)). The first regional map of the Graz Highlands („*Geologische Karte der Umgebung von Gratz*“ by Conrad Clar (1844-1904)) dates from 1877. Only four years after Roderick Murchinson (1792-1871) and Adam Sedgwick (1785-1873) defined the Devonian System / Period, Franz Unger

(1800-1870) recognized that the limestones at Plabutsch, a mountain range west of Graz, are of Devonian age (Unger, 1843). The first consistent stratigraphy which is still applicable in many respects, was published 1868 by Eduard Suess (1831-1914). He distinguished six lithological successions, (1) basal green schists with „Brauneisen“ (today possibly the Kehr Formation), (2) lower „greywacke schists“ (today Parmasegg Formation), (3) dolomitic limestone (today Flösserkogel Formation), (4) „limestone at Gaisberg“ (today Plabutsch Formation), (5) massive limestone (today Kollerkogel Formation) and (6) black to reddish “Clymenienkalkstein (today Steinberg Formation). Helmut Flügel (1924-2017) published 1960 the „*Geologische Wanderkarte des Grazer Berglandes*“, and together with this map an explanatory volume (1961 and 1975 in a revised version). In this publication he defined three facies realms in the GP; (1) the *Rannach-Fazies*, (2) the *Hochlantsch-Fazies* containing also the „*Folge von Laufnitzdorf*“ and the „*Kalkschiefer-Folge*“, and (3) the *Tonschiefer-Fazies*. Already 1874 Conrad Clar (1844-1904) introduced the tectonic subdivision of the GP with a lower tectonic group (today Lower Nappe System containing the Tonschiefer-Facies) and a higher one (today Upper Nappe System, Hochlantsch and Rannach Nappes with Hochlantsch and Rannach Facies).

Enormous progress in biostratigraphic subdivision of the GP was achieved through conodont stratigraphy over a period of about 50 years from the 1960s onwards by the students of Helmut Flügel (1924-2017). These studies culminated in a standard reference work “*Das Paläozoikum von Graz: Stratigraphie und Bibliographie*” by Flügel and Hubmann (2000). Here we comment that the well-established biostratigraphy holds only for the weakly metamorphosed carbonatic successions of the Rannach and Hochlantsch Facies (Nappe respectively) that cover approximately only 35-40% of the entire GP. For the majority of the GP, the Lower Nappe System, lower tectonic group in the sense of Clar (1874), today Gasen-, Schöckel- and Gschnaidt-Nappes, the stratigraphy is based upon lithological correlation with the fossiliferous sequences of the Rannach Nappe. In short, in recent decades the fundamentally lithologically similar strata of the Schöckel Nappe - although petrographically distinct due to a clear metamorphic difference! - have been correlated with chronostratigraphically fixed anchizonal formations of the Upper Nappe System: for example, the “Schöckel limestone” (i.e. the Schöckel Formation) was seen as a counterpart to the Middle Devonian platform carbonates (e.g., Plabutsch Formation and/or Kollerkogel Formation), the sandy and dolomitic sections below the Schöckel Formation (i.e., Raasberg Formation) were seen as equivalents in parts of the Lower Devonian Flösserkogel Formation or Parmasegg Formation, and the basal volcanoclastic sequences (Taschen Formation) were suspected to be metamorphic representations of the Upper Silurian Kehr Formation of the Upper Nappe System.

Franz Heritsch's maxim that "a sound tectonics is only possible based on a secure stratigraphy" (Heritsch 1943:338) has, of course, lost none of its validity. Due to the currently limited, but clearly divergent, geochronological data of stratigraphic elements of the Lower Nappe System, we harbor skepticism in some cases regarding the long-accepted lithological - and thus lithostratigraphic! - analogousity with the stratigraphic members of the Upper Nappe System. This also necessitates a review of the traditional tectonic concept, which is based on a stratigraphically unsupported "depositional series" (see below).

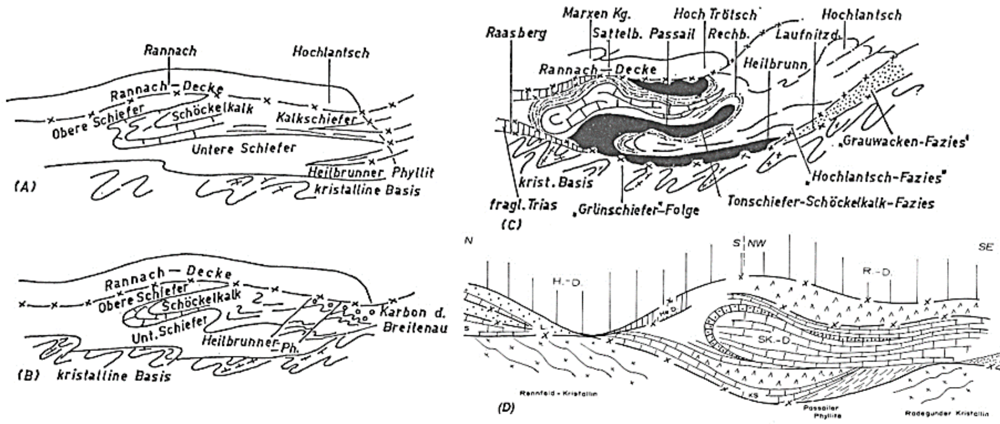

Fig. 1: Models of the Graz Paleozoic Nappe structure after (A) Clar, 1935; (B) Boigk, 1951; (C) Flügel, 1958 and (D) Flügel and Neubauer, 1984. Abbreviation in (D): H.-D.: Hochlantsch Nappe; R.-D.: Rannach Nappe; SK-D: Schöckel Nappe.

Based on classical correlation, Eberhard Clar (1935) was forced to interpret the “Schöckel limestone” (Schöckel Formation) as an isoclinal fold, since the general idea was that the graphitic schists (Schönberg Formation) at the base form the same stratigraphic unit as the overlying schists (Fig. 1). In his view the Rannach Nappe disconformly overthrusts the folded Schöckel Nappe. This tectonic model of the GP was adopted with minor modifications by several authors (Boigk, 1951; Flügel, 1958; Flügel and Neubauer, 1984; Gasser et al., 2010) and implies an inverted sequence in large parts of the Schöckel Nappe. Here we comment that Erhart-Schippek (1949) and Maurin (1954) ventured the possibility that black schist on top of the “Schöckel limestone”, exposed at Tanneben, are of Carboniferous age, a proposal that was never considered any further.

In the 1900s the methodical approach of tectonic analyses changed, motivated by the recognition of shear tectonics by Berthè et al. (1979). Nappe contacts were analysed for successively evolving shear fabrics and displacement directions (e.g., Fritz, 1988; Neubauer, 1989). By the same time geochronological studies started evolving that suggested that the internal nappes of the GP assembled during the Lower Cretaceous at around 130-100 Ma (Flügel et al., 1980; Fritz, 1986, 1988), followed by Upper Cretaceous extensional tectonics associated with deposition of the Kainach Gosau sediments (Fritz et al., 1991; Neubauer et al., 1995, Krenn et al., 2008; for a compilation of geochronological data see Gasser et al., 2010). These studies resulted in a tectonic model of the GP that has undergone hardly any changes since 1992 (Fritz et al. 1992) and remains in broad term valid until today (Fig. 2).

Research received a new boost from re-mapping of the southeastern part of the GP by Ralf Schuster (Matura and Schuster, 2014; Schuster et al., 2015) and associated petrological and geochronological studies (Schantl et al., 2015; Hollinetz et al., 2024). The nappe structure was refined by the introduction of new tectonic units (Gasen Nappe, Gschnaidt Nappe), the existing stratigraphy of the Peggau group (with the distinctive Schöckel Formation and the underlying and overlying stratigraphic units) was modified by the assumption of the existence of Upper Devonian, probably Carboniferous units in the hanging wall of the Schöckel Formation.

Petrological studies and analyses of REE minerals showed that the Schöckel Nappe experienced 450-520 °C and 0.3-0.4 GPa during the Permian (c. 275 Ma) and 400-470 °C and 0.3-0.7 GPa during the early Alpine orogeny. Cooling age data of the Schöckel Nappe are in the range of 119-113 Ma and postdate Alpine nappe stacking.

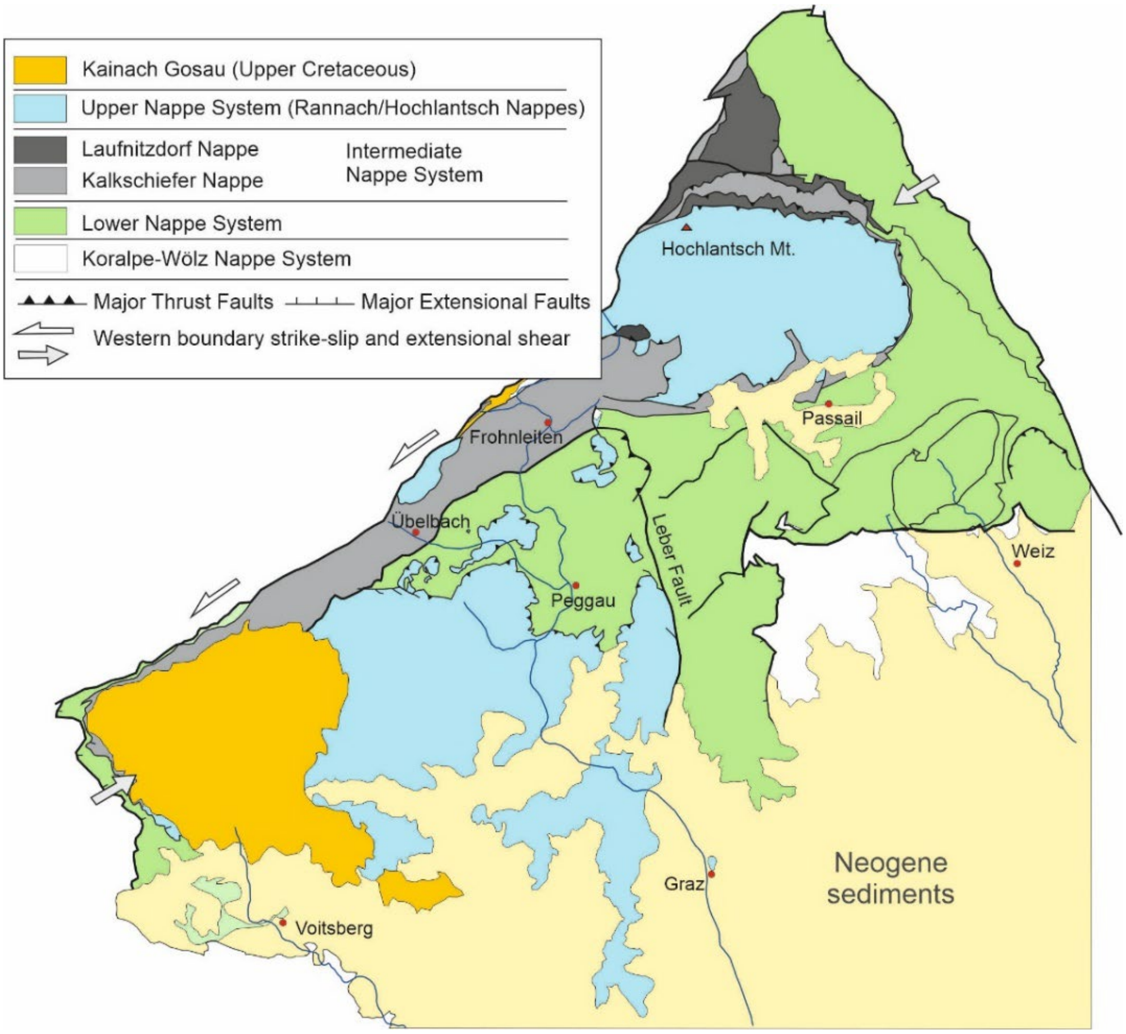

Fig. 2: Classic view on the nappe structure of the Graz Paleozoic, redrawn after Fritz et al. (1992) and Krenn et al. (2008).

3. Stratigraphy

Major controversy arises from uncertainty about the stratigraphy of lithological successions in the Lower Nappe System, the Passail Group and the Peggau Group, and the Hirschkogel Complex. The existence of Lower Devonian graphitic schists (Schönberg Formation: Fig. 3) below and on top of the Middle Devonian Schöckel Formation implies the existence of inverted sections in western parts of the GP - as proposed in the classical tectonic models. The existence of a possibly Upper Devonian/Carboniferous rock suite (Hirschkogel Complex) conformably overlying the Schöckel Formation, as proposed by Matura and Schuster (2014) and Schuster et al. (2015), implies an upright section in the east of the GP. Both scenarios are incompatible because the Schöckel Formation itself can be traced across both domains.

Lacking stratigraphically indicative fossils, we conducted a preliminary study of detrital zircons from sandy or volcanoclastic strata. The underlying, simple assumption is that a sedimentary rock sequence cannot be older than the youngest zircon found in that rock. Although the database has to be expanded, first results suggest that, similar to the situation proposed by Schuster et al. (2015), an upright succession with Upper Devonian rocks exists also in the western part of the GP. The youngest zircons found in greenschists and quartz-sericite phyllites within the Parmasegg Synform, as well as in basic volcanites in the Hochtrötsch area—rocks all mapped as belonging to the Silurian to Lower Devonian Schönberg and Taschen Formations—include Upper Devonian zircons with ages of approximately 389 Ma (Figs. 3 and 4; for sample location, see Fig. 6). This would imply that the classic view of a macroscale fold within the Peggau Group is obsolete. An independent, but weak indication to support this situation arises from differences in lithology. Most of the graphitic schists of the Schönberg Formation contain Pb-Zn-Ag-Ba deposits (Rohrhofer et al., 2024), while those units in which we suspect an Upper Devonian / Carboniferous age do not exhibit such ore deposits.

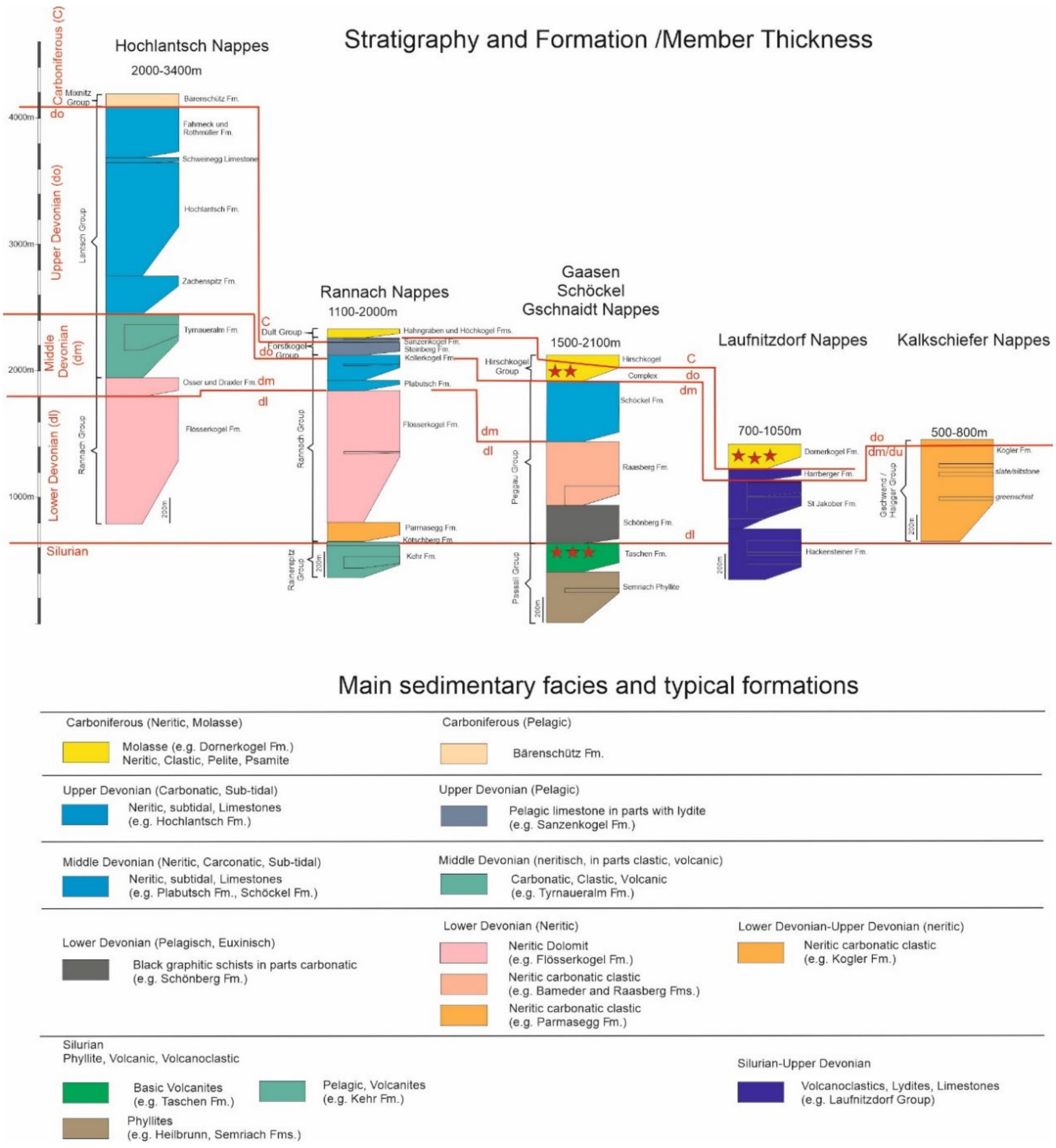

Fig. 3: Stratigraphy, thickness of formations and sedimentary facies of the sediments of the Graz Paleozoic. Stars give position of samples analyzed for zircons.

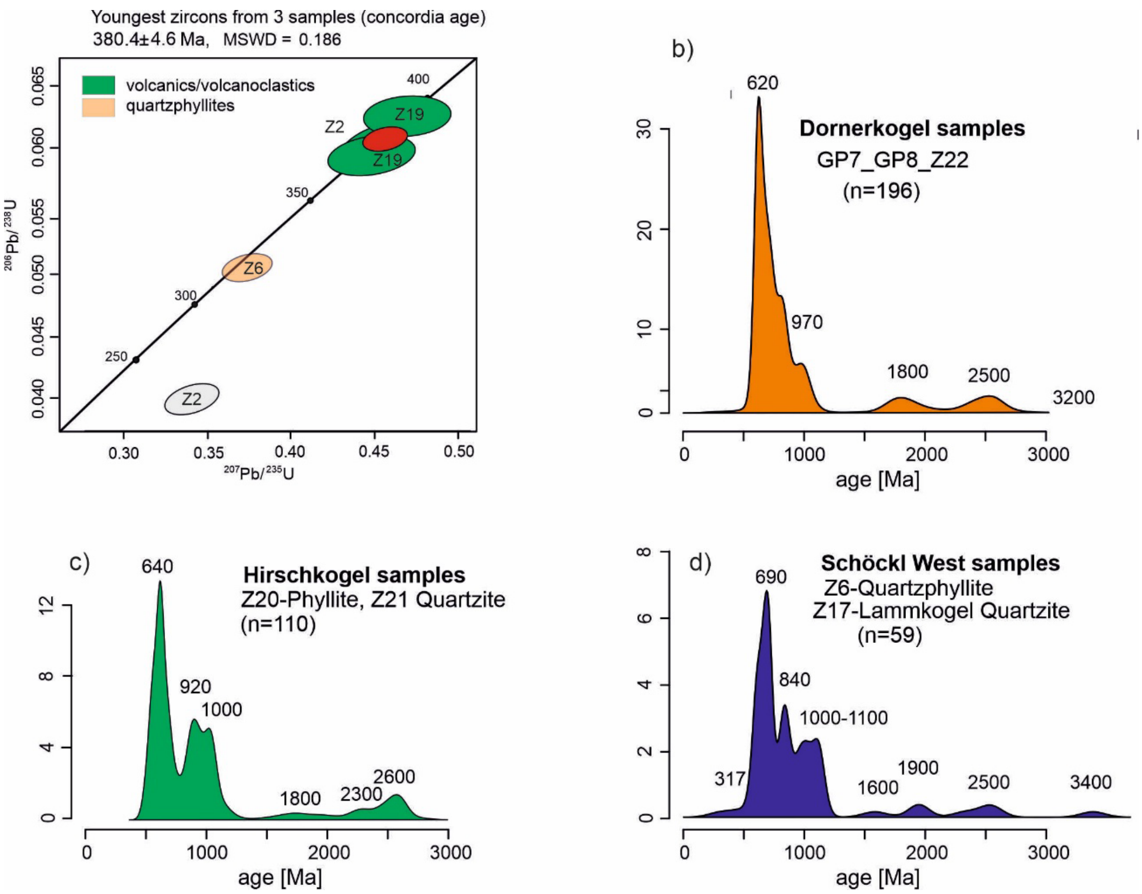

Fig. 4: Summary plots of U/Pb zircon data. a) Three samples from the core of the Parmasegg and Trötsch Synforms. Z2 is a greenschists mapped as Pragian to Emsian carbonatic sericite phyllite. Z19, a greenschist and Z6, a carbonatic sericite phyllite were mapped as Silurian / Lower Devonian "Taschenschiefer" (Taschen Formation). KDE spectra of (b) three samples from the Dornerkogel Formation (Laufnitzdorf Group), (c) two samples from the Hirschkogel Complex (phyllite and quartzite), and (d) two samples from quartphyllite and quartzite of the Peggau Group. Conspicuous is absence of Ordovician zircons as present in most of the Austroalpine / Southalpine Paleozoic sequences (Greywacke Zone / Carnic Alps), a fact not further discussed here.

4. The Nappe Structure

4.1. Mechanic Stratigraphy

Major thrust within the GP is obviously the basal thrust separating the Upper Nappe System (Hochlantsch and Rannach Nappes) from the Lower Nappe System (Gasen, Schöckel and Gschnaidt Nappes). The basal thrust of the Rannach Nappe runs through Silurian greenschists (Kehr Formation) and climbs stratigraphically higher in the Hochlantsch Nappe where it occurs at the base of Lower Devonian dolomites (Flösserkogel Formation). The major rheologically weak lithology within the Rannach Nappe, the lower incompetent group, is the Lower Devonian Parmasegg Formation along which many internal thrusts of the Rannach Nappe developed (Figs. 5 and 6). The rheological equivalent within the Peggau Group is the Lower Devonian Schönberg Formation with its incompetent graphitic schists. Another incompetent lithology ("*middle incompetent group*") is the middle Devonian Plabutsch Formation, especially its basal part, the marly Gaisberg Bed, along which minor thrusts and back-thrusts evolved. Minor thrusts align along the boundary between massif and platy limestones within the Rannach Nappe ("Flaserkalk") ("*upper incompetent group*") or, most likely, along the border between Schöckel limestone (petrographically correct: marble) and the lithostratigraphically unnamed, probably Upper Devonian/Carboniferous quartz-sericite phyllite (in the hanging wall of the Schöckel Formation).

Rocks within the Laufnitzdorf and Kalkschiefer Nappes behave rheologically different. Especially the Kalkschiefer Group with its thin-bedded limestones intercalated with shale and silt layers form a thin-skinned fold-and-thrust belt without distinct decollement levels but with multiple imbricated thrust slices.

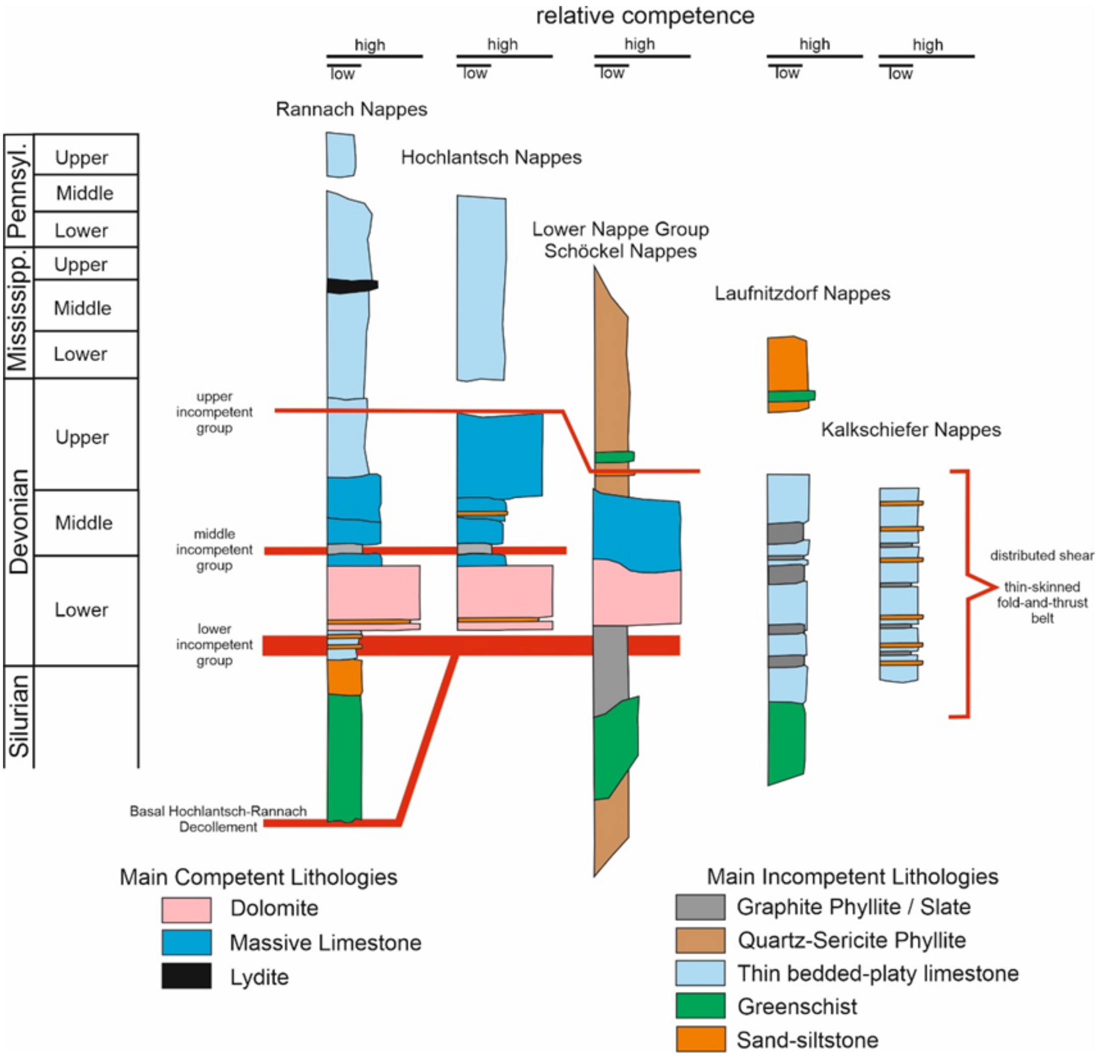

Fig. 5: Mechanic stratigraphy of the Graz Paleozoic rock suite. Major decollement zones form along graphitic phyllite or thin-bedded limestone intercalate with shale.

4.2. Metamorphism

The earliest high temperature / low pressure fabrics within the Schöckel Nappe at Hirschkogel (c. 475 °C) and Raasberg (c. 520 °C) are of Permian age (c. 275-261 Ma) (Hollinetz et al. 2024). The lower Cretaceous overprint occurred at conditions of c. 470 °C and 0.4-0.7 GPa at the base of the nappe, that decreases to c. 400 °C and 0.3-0.6 GPa at higher structural levels, although Hollinetz et al. (2024) claimed that these P-T estimates are subject to greater uncertainty compared to Permian peak conditions. The data correspond roughly to RSCM data (Raman Spectroscopy of Carbonaceous Material) elaborated by Rantitsch et al. (2026). Those data are interpreted to record peak metamorphic conditions and gave c. 520 – 550 °C for the Gasen Nappe, and c. 400-560 °C for the Schöckel Nappe with a trend of north- to north-westward decreasing temperatures in the latter one. RSCM data from the Rannach and Hochlantsch Nappes range between 285 and 328 °C, those from the Laufnitzdorf and Kalkschiefer Nappes to the north of Hochlantsch Mountain show greater range between c. 285 and 500 °C. Our RSCM data are broadly in agreement with those elaborated by Rantitsch et al. (2026), except that we got lower temperatures for rocks of the Laufnitzdorf Nappe (c. 340-380 °C) and temperatures between 350 °C and 370 °C for the rocks of the Kalkschiefer Nappe along the northwestern GP boundary that were not analysed by Rantitsch et al. (2026).

Considering the data elaborated by Hollinetz et al. (2004), most of the nappe internal structures, such as the metamorphic segregation of the Schöckel limestone (light and dark banding), evolved most probably from Permian extensional tectonics. This is in line with dominant coaxial shear found in that unit. This also implies that the nappes were stacked through localized shear, for most of the GP at conditions around 400°C.

4.3. The Nappes

From structural top to bottom we distinguish (1) Hochlantsch and Rannach Nappes, the Intermediate Nappe System with (2) Kalkschiefer and (3) Laufnitzdorf Nappes and a Lower Nappe System with (4) Gschnaidt Nappe, (5) Schöckel Nappe and (6) Gasen Nappe. Most of these major nappes that rest tectonically on surrounding metamorphic units (Koralpe-Wölz System) consist of several minor “sub-nappes” (Fig. 6).

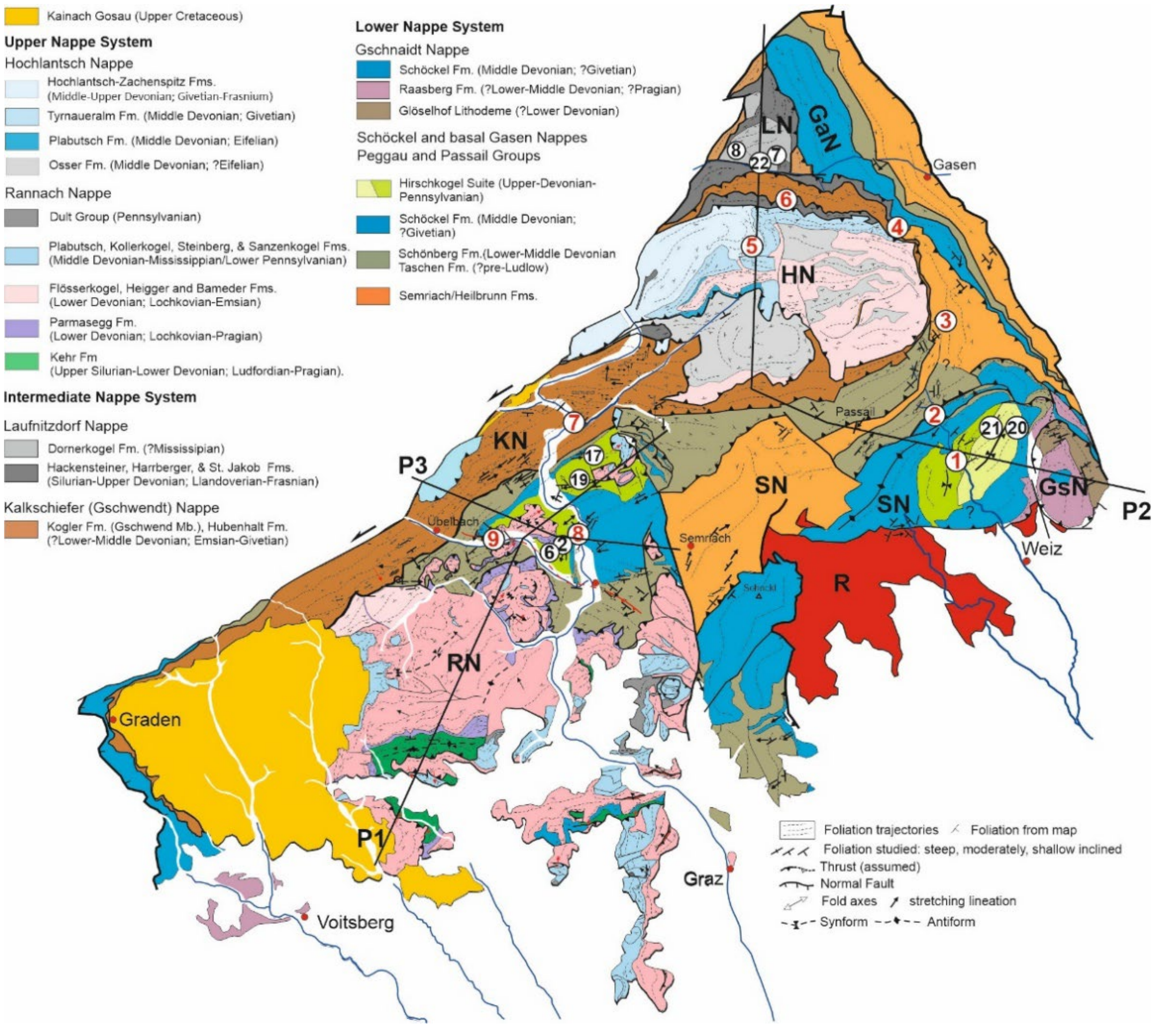

Fig. 6: The Graz Paleozoic Nappes and major formations. HN: Hochlantsch Nappes, RN: Rannach Nappes, KN: Kalkschiefer Nappes, LN: Laufnitzdorf Nappes, GaN: Gasen Nappe, SN: Schöckel Nappes, GsN: Gschnaidt Nappe. R: Radegund metamorphic / magmatic complex. Red numbers are excursion stops, black numbers U/Pb zircon samples (without prefix).

4.4. Restoring Late Cretaceous Shear Zones and Faults

Heterogeneity of structural elements and dispersal of units is best displayed when the youngest structural elements considered here, the syn- to post-Gosauic structures (c.80 Ma), are restored (Fig. 7). Those structures are, in many cases, easily recognized from the incorporation of sediments of the Kainach Gosau into shear zones and faults. Shear zones/faults used for restoration are grouped into boundary shear zones at the margins of the GP to the underlying metamorphic complexes and GP-internal faults. Boundary shear zones are: (1) The Northwestern Boundary Fault with sinistral displacement accompanied by a NW-up component (Neubauer et al., 1995). (2) The southwestern Graden Fault that accompanied subsidence and deposition of Gosau-type sediments (Fritz et al., 1991; Rantitsch et al., 2005; 2006). (3) The Northeastern Boundary Fault defined as part of the Austroalpine Detachment (Hollinetz et al., 2024). (4) The Radegund fault system with a combination of strike-slip, thrusts and normal faults (Krenn et al., 2007). GP internal faults are the (5) sinistral Rabenstein Fault that parallels the Northwestern Boundary Fault and (6) the Leber Fault. The latter has a long and complex history, but early phases of activity are considered of Cretaceous (Gosauic) age. For retro-deformation we kept the western Koralpe-Wölz Nappe System; the amount of displacement along faults is taken from off-set of lithological markers visible on map and from data reported in the literature (Fig. 7a). Restoration results in a simple structure of the Lower Nappe System (Fig. 7b). The synforms to the west of the Leber Fault (Parmasegg and Hochtrötsch Synforms) align with that to the east of it (Hirschkogel Synform) making the superordinate structure of the Schöckel Nappe, although modified by internal thrusts, to a large synform with Upper Devonian lithologies in the core. The Schöckel Nappe is floored by the Gasen Nappe, now exposed at the southwestern and northeastern GP margins and overlain by the Gschnaidt Nappe. We have to admit that the restored position of the northeastern Gasen Nappe is poorly constrained. In our reconstruction, lateral shear is required to move this unit into the position shown. For illustration purposes the position of the Rannach Nappe is not displayed in Figures 7b and 7c. Fig. 7c is an abstracted version of Fig. 7b, now implementing the effect of lateral displacement along the northwestern GP margin. After nappe assembly, during the Late Cretaceous, sinistral shear displaced parts of the Lower Nappe System, but also parts of the Hochlantsch, Laufnitzdorf and Kalkschiefer Nappes south-westwards, thereby forming the western Kalkschiefer Belt.

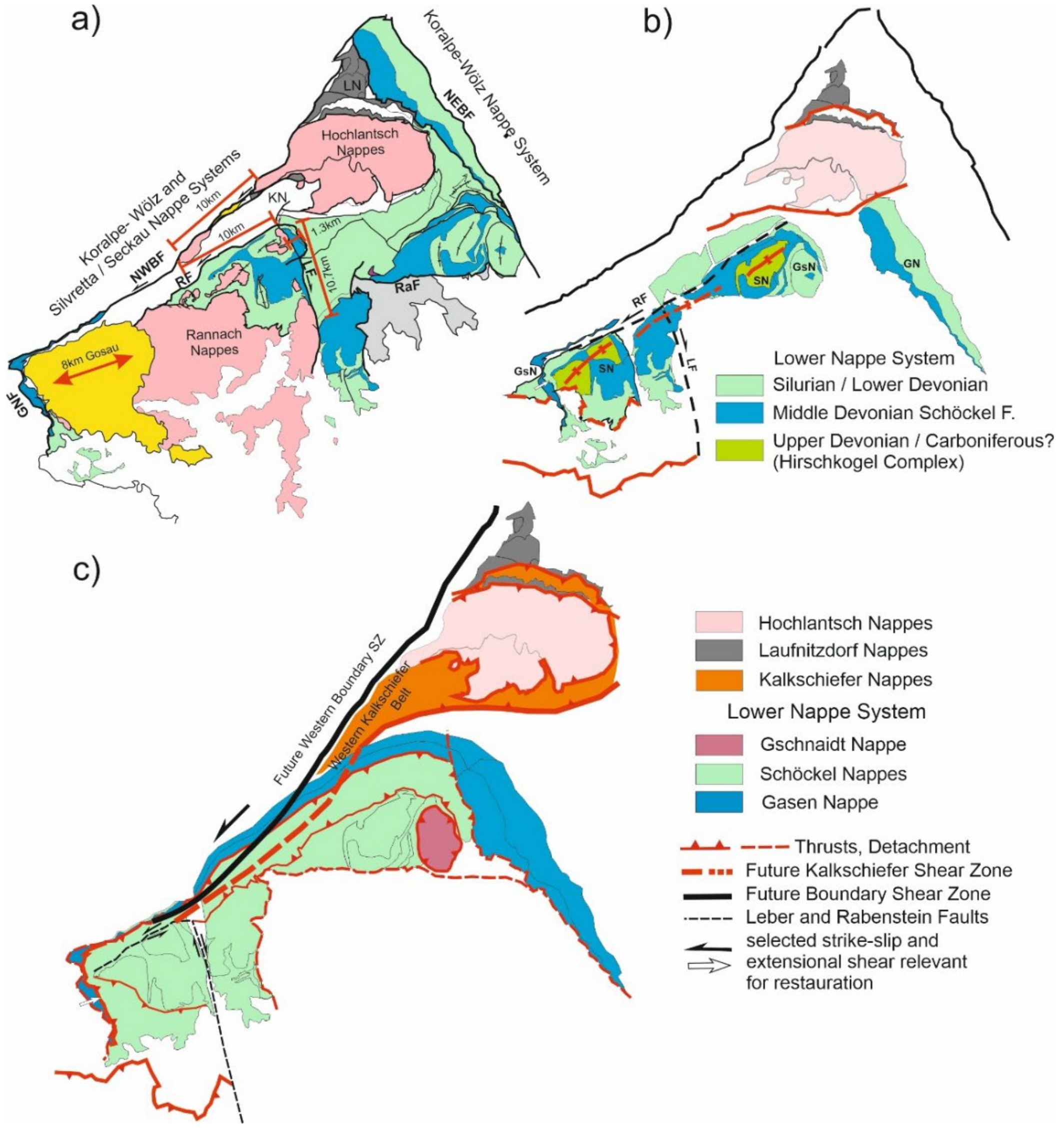

Fig. 7: Retro-deformation of Late Cretaceous shear zones and faults. (a) Direction and amount of displacement used for restoration. (b) Arrangement of Peggau Group Synforms (Schöckel Nappe) after restoration with simplified stratigraphy. Rannach Group rocks are, for better visualization, not shown. c) Conceptual drawing showing the Lower Nappe System (Gasen, Schöckel, Gschnaidt Nappes) and effect of sinistral shear along the western GP margin. Abbreviations: GN: Gasen Nappe, GNF: Graden Normal Fault, GsN: Gschnaidt Nappe, KN, Kalkschiefer Nappes, LF: Leber Fault, LN: Laufnitzdorf Nappes, NEBF: Northeastern Boundary Fault, NWBF: Northwestern Boundary Fault, RaF: Radegund Fault, RF: Rabenstein Fault, SN: Schöckel Nappes.

5. The tectonic architecture with emphasize to excursion stops

5.1. The Central Shear Domain

A key area is the central shear domain between the sinistral Rabenstein and the dextral Leber shear zones (Fig. 8). The western boundary of this domain, the Rabenstein Shear Zone, separates the central domain from the southwestern Kalkschiefer Nappes (Figs. 6 and 7). East of the Leber Fault zone, which marks its eastern boundary, a dominant top-SE thrust developed within the Lower Tectonic Nappe System (Schöckel Nappe). The general shortening direction within this conjugate set of faults is NE-SW, which releases “young” top-NE folds and thrusts (Excursion stop 8) and top-SW back-thrusts. Next to the northeastern tip of both faults, an imbricate zone of Peggau Group units is released (Fig. 8).

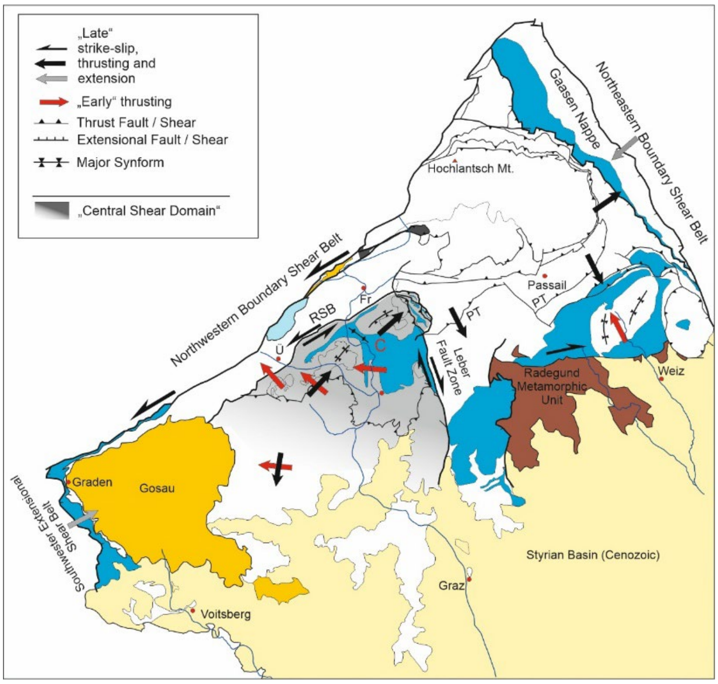

Fig. 8: The central domain (grey shaded) with its conjugate boundary shear zones, the sinistral Rabenstein Shear Belt (RSB) and the dextral Leber Fault Zone. Northeast shortening between the conjugate shear zones/faults released top NE imbrication at the northeastern fault tips and southeast thrusting to the east of the Leber Fault Zone. Black arrows/half arrows show “young”, syn- post Gosauic displacement, red arrows show older displacement directions. Abbreviations: Fr – Frohnleiten Town, Ü – Übelbach Town, PT – Passail Thrust, an internal thrust in the Schöckel Nappe. Selected lithologies: Yellow – sediments of the Kainach Gosau, brown – Radegund metamorphic/magmatic rocks, dark blue – Schöckel marble. Light blue – Hochlantsch limestone and dark grey – Laufnitzdorf Group rocks displaced along the Northwestern Boundary Shear Zone.

All of the Rannach Group rocks appear within the central domain. Early structures include westward to northwestward shear followed by NE-SW convergent structures including both, south-vergent folds (Kehr Antiform: Neubauer, 1991) and top NE-directed folds and thrusts (excursion stop 8). The shift from NW to NE stretching was early recognized from incremental strain analyses using fibre growth around rigid objects (Fritz, 1988). Most Rannach Nappe thrusts developed within the Parmasegg Formation as the main décollement horizon (Figs. 9 and 10).

Fig. 9: Left: Top-NW shear fabrics (red lines) within platy limestone of the Parmasegg Formation. Location is Stübinggraben (WGS 84: 47° 11′ 33″ N 15° 16′ 30). Right: Incremental fibre growth around rigid objects showing a shift from NW- to NE stretching direction. Location: Parmasegg Formation in Stübing Valley. Foto from Fritz (1991).

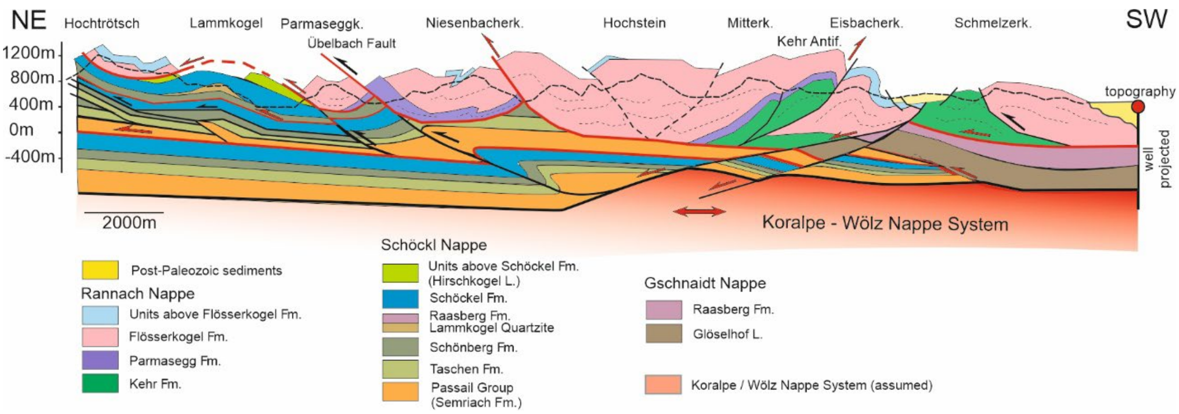

Fig. 10: Profile P1 showing tectonics exposed within the Central Domain (Fig. 8). Rannach thrusts climb from the level of Kehr Formation (SW) to the level of the Flösserkogel Formation (NE). The Kehr Antiform (green) evolved along an important top-south thrust. The northern tip of the central domain at Hochtrötsch contains the imbricate zone with duplication of Schöckel Group elements (Profile section P1 is shown in Fig. 6).

Rocks of the Lower Nappe System within the central domain are exposed along the Mur Valley next to Peggau Village where Schöckel marble forms impressive cliffs to the west (Kugelstein) and east of Peggau (Tanneben). Excellent exposures and the presence of drill holes within the valley allow recognition of internal thrusts sheets within the Lower Nappe System, separated by mylonite zones that developed within the Schönberg Formation. We speculate that the Gasen Nappe (or deeper part of the Schöckel Nappe), forms a duplex, the frontal antiform, which is exposed in the Mur Valley and within the Tanneben mountainous domain. An early top-W shear within graphitic schists is evident from strain shadows around rigid objects (Fritz, 1988), overprinted by east-vergent folds. For further information, see excursion stop 7.

5.2. Kalkschiefer Nappe

Predominantly monotonous calcareous shales of the Kogler and Hubenhalt formations occur in the west of the GP, along the border to the Koralpe- Gleinalpe metamorphic units and to the north of Hochlantsch. Three different tectonic styles can be distinguished. (1) Between Rabenstein Fault and Western Boundary Shear Zone the *“Kalkschiefer Wrench Corridor”* developed. (2) North of Frohnleiten, the structural style is of a classical fold-and-thrust belt with top-N displacement (Fig. 11). (3) North of Hochlantsch, the Kalkschiefer are imbricated together with rocks of the Laufnitzdorf Group, forming the Intermediate Nappe System (see stops 6 and 7). From Gschwendtberg (a hill next to Frohnleiten) southwestwards, the fabric elements (bedding, foliation, fold axes) turn from W-E to NE-SW direction as nicely seen from foliation trajectories (Fig. 11). This rotation is interpreted to result from shearing along the Northwestern Boundary Shear Zone of the GP (see Fig. 7c).

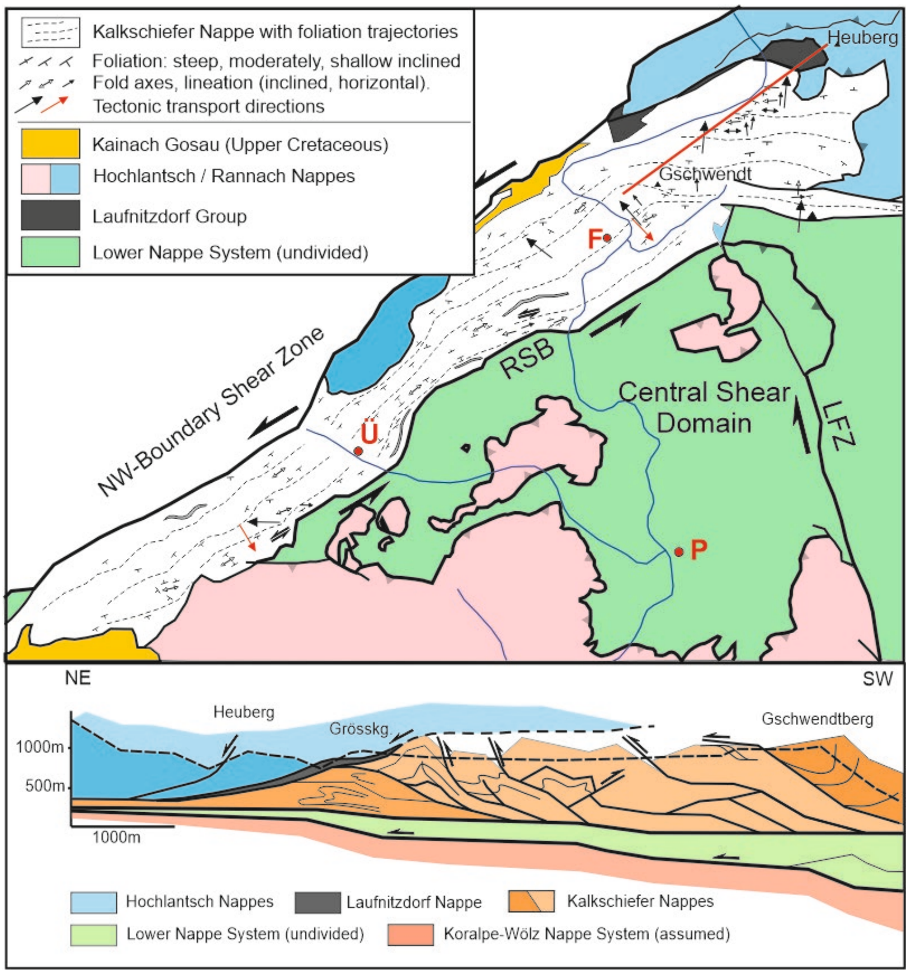

Fig. 11: Map and profile showing the rotation of fabric elements from W-E (north) to SW-NE as a result of shearing along the Northwestern Boundary Shear Zone and associated faults. The profile shows the tectonic style of a fold-and-thrust belt that developed in the northern part of the Kalkschiefer Nappe.

The northern part of the GP contains the **Intermediate Nappe System** with the imbricate slices of Kalkschiefer and Laufnitzdorf Nappes and the Hochlantsch Nappe on top (Fig. 12). Kalkschiefer and Laufnitzdorf Nappes contain an early W-E stretching lineation but conspicuous top-N-directed folds and thrusts (Fig. 13). The Hochlantsch Nappe contains consistently top-N-directed structures with locally inverted Tyrnaueralm Formation along its northern margin and top-S-directed folds and back-thrusts in its northern margin and in its central portions (Gollner and Zier, 1985).

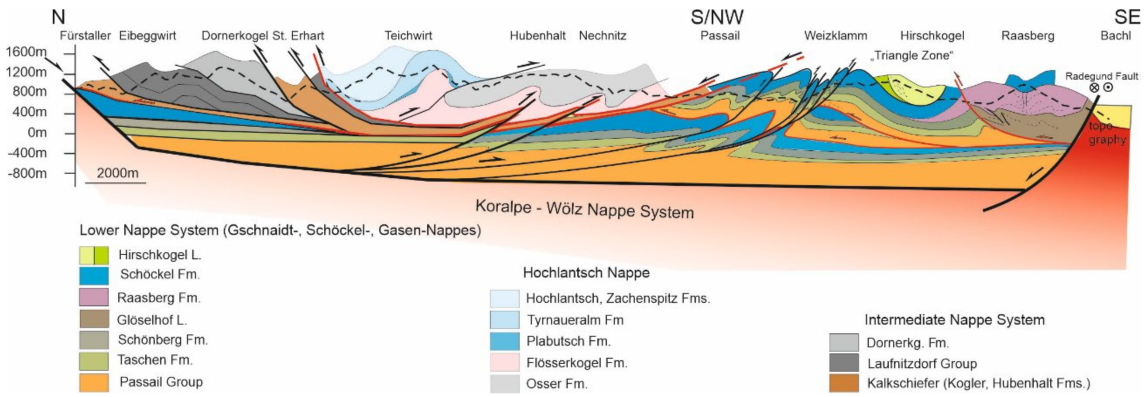

Fig. 12: Profile across Lower-, Intermediate and Upper Nappe Systems. For description see text. (Profile section P2 is shown in Fig. 6).

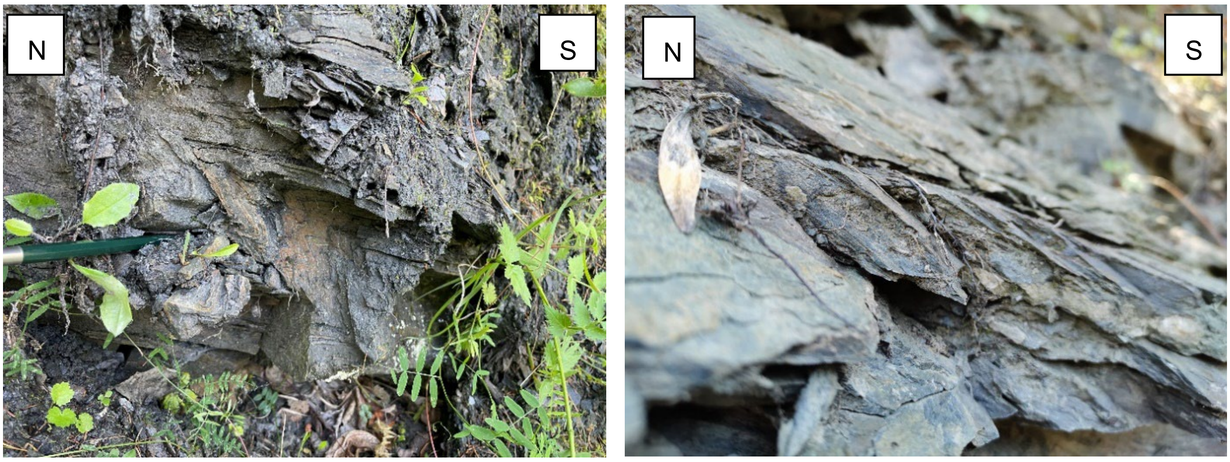

Fig. 13: North vergent fold within platy limestone of the Kalkschiefer Group (left: WGS 84: 47° 22′ 44″ N 15° 29′ 26″ E) and top North shear structures within pelitic schists of the Laufnitzdorf Group (excursion stop 6, Hardberger Formation, right: WGS 84: 47° 22′ 21″ N 15° 28′ 55″ E). Both pictures were taken from roadcuts between Teichalm and Breitenau Valley.

The **Lower Nappe System** to the east of the "Central Domain", i.e., east of Leber Fault, is characterized by dominant top-SE thrusts overprinting earlier formed top-NW to top-N thrusts. In the southeast, next to Weiz Gorge (Weizklamm), the structure with top N-NW-directed thrusts were overprinted by steep top-SE (back)-thrusts (Stops 1 and 2). This is informally called *"Triangle Zone"* (Fig. 12). The steep back-thrust occur all along the northern margin of the Schöckel Formation from Weiz Gorge over Arzberg to the northern slope of the Schöckel Mountain (Fig. 6).

Parts of the **Schöckel Nappe** and **Gasen Nappe**, the deepest tectonic unit of the Lower Nappe System and exposed along the northwestern GP margin, exhibit a different tectonic evolution. Rocks exposed here (i.e., Gasen Nappe with Hochschlag Formation) display relictically preserved top-N to top-NW shear overprinted by dominant top-NE folds and thrusts (Gsellmann, 1987). Later top-SW-oriented extensional structures (Krenn et al., 2007) correlate most probably with normal faulting along the Austroalpine Detachment Zone at the base of the eastern GP (Hollinetz et al., 2024). See excursion stop 3 (Hundsberg Member) and excursion stop 4 (Kogler Formation) for further details.

6. Description of stops

Preliminary remarks: The lithological descriptions and chronostratigraphic information listed below follow Flügel (2000) and Hubmann et al. (2014) and refer to the entire respective lithostratigraphic unit.

First two stops aim to show the Triangle Structure in the eastern GP at Weiz Gorge (Weizklamm). By that, we mean the system of thrusts and back-thrusts which do not necessarily evolve simultaneously (see Fig. 12 and sketch below).

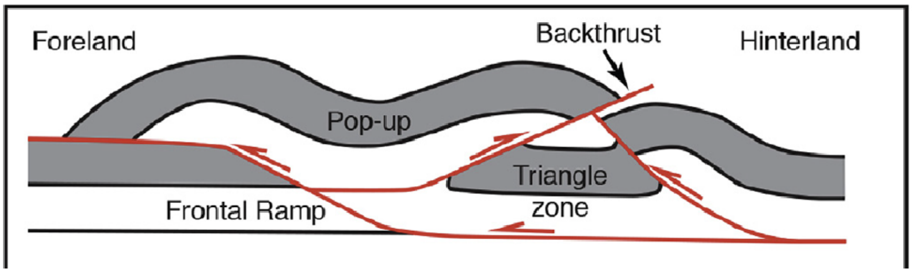

Fig. 14: Sketch explaining the meaning of a “Triangle Structure” after Butler, 1982.

Stop 1 WGS 84: 47° 15′ 15″ N 15° 35′ 27″ E

Nappe: Lower Nappe Complex (Schöckel Nappe)

Unit: Hirschkogel Complex

Lithology: Calcareous phyllites

Structures: Dominant S-C structures indicative of NW-directed shear with locally developed SE-directed backthrusts.

Fig. 15: Top NW-shear structures (left) and back-thrusts (right) that evolve within sheared limbs of kink folds.

Stop 2 WGS 84: 47° 16′ 21″ N 15° 34′ 39″ E

Nappe: Lower Nappe Complex (Schöckel Nappe)

Unit: Peggau Group

Lithology: Schöckel marble alternating in northern parts with graphitic schists of the Schönberg Formation.

Structures: Steep reverse SE-directed backthrusts.

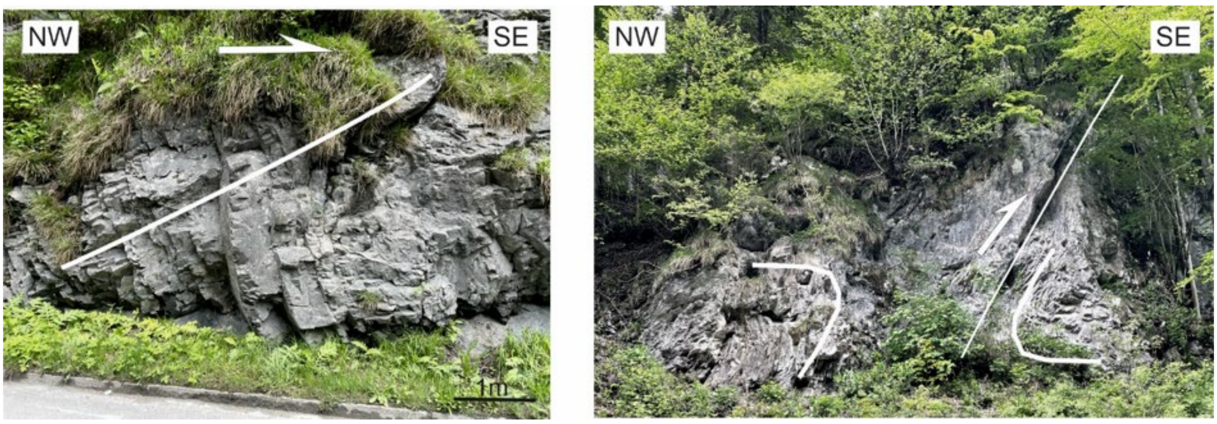

Fig. 16: Outcrop scale steep thrusts associated with drag folds.

Stop 3: Hundsberg Member (WGS 84: 47° 19′ 03″ N 15° 34′ 21″ E)

Nappe: Lower Nappe System, Schöckel Nappe

Unit: Hundsberg Member of the Semriach Formation, equivalent of the Heilbrunn Formation.

Lithology: The Hundsberg Member contains coarse-grained quartzites and quartzitic slates of 10 to 50 m in thickness. The stratigraphic age is unknown; based on its position within lower levels of the Peggau Group, a pre-Devonian age is assumed.

Structures: The eastern GP is characterized by dominant top-east shear overprinting relictically preserved earlier top-N displacement. This deformation is likely related to over-regional Cretaceous eastward flow related to the Austroalpine Detachment Zone (Hollinetz et al., 2026).

Fig. 17: S-C shear fabrics indicating top-east-directed shear within the Hundsberg Member.

Stop 4: Plankogel (WGS 84: 47° 21′ 16″ N 15° 33′ 29″ E)

Scenic stop and lunch break. The summit of Plankogel exposes a tectonic slice containing limestones of the Kogler Formation, supposed age is Upper Silurian to Lower Devonian. Gsellmann (1987) distinguished in this area, from the structural base to the top, Phyllites of the Passail Group and limestones of the Hochschlag Formation. The Hochschlag Formation (Emsian-Eifelian or Givetian) is predominantly composed of platy to slaty limestones with intercalations of black argillaceous shales, calcareous phyllites, whitish dolomites and metavolcanites. It is the dominant calcareous lithology of the Gasen Nappe extending all along the eastern GP margin. Above the Hochschlag Formation follows the Passail Group of the Schöckel Nappe and the Kogler Formation. The latter is considered to be part of the Kalkschiefer Nappe. Immediately south of Plankogel, the siliciclastic carbonatic succession of the Tyrnaueralm Formation is (badly) exposed. Two main deformation events have been recognized: N-S stretching with hints of top-N transport and east-vergent folds and top-NE-directed thrusts superimposing the earlier formed N-S stretching lineation. It is a matter of debate whether lateral displacements exist along lithological or tectonic boundaries that could explain the numerous small tectonic slices mapped by Gsellmann (1987). Outcrops at Plankogel provide a hint for sinistral shear (Fig. 18).

Fig. 18: Top view of limestone from Kogler Formation at Plankogel with hint for sinistral shear to SW.

Stop 5: Plabutsch Formation (WGS 84: 47° 21′ 22″ N 15° 28′ 12″ E)

Nappe: Hochlantsch Nappe

Unit: Plabutsch Formation, Eifelian (?uppermost Emsian-?lowermost Givetian)

Remarks: Due to its rich fossil content, the Plabutsch Formation has become virtually synonymous with the organismal diversity of the Graz Devonian over the course of research history (Hubmann 2003). When using historical literature, it should be noted that before 2003 this sequence was known as “Barrandei Limestone.” The name was derived from the specific epithet (the second element in the Latin binomial name) of the heliolite coral *Heliolites barrandei* (Penecke, 1894). Following international nomenclature proposals for lithostratigraphic terms, the name was changed to Plabutsch Formation (Hubmann 2003).

Lithology: Fossil-rich sequence dominated by dark-coloured, marly bioclastic limestones. In its upper sections, alternating layers of reddish, clayey marl can be characteristic. The diverse fossil record, rich in both species and individuals, is dominated by colonial corals and stromatoporoids. The most common tabulate corals are thamnoporids (*Thamnopora reticulata, T. orthostachys, T. vermicularis, "Striatopora" suessi*), favositids (*Favosites styriacus, F. alpinus*), and heliolitids (*Pachycanalicula barrandei*). The rugose coral fauna is dominated by predominantly fractured dendroid (phaceloid) taxa. A common and characteristic Phillipsatreid taxon is *Thamnophyllum* (*Th. stachei, Th. murchisoni*). Stromatoporoids are largely recrystallized, which complicates precise identification (Hubmann et al. 2014).

Regarding the depositional environment, it is assumed that a differentiated and gently sloping carbonate platform developed in a tropical region during the Late Emsian to Early Givetian stages (Hubmann 1993). Notable features include the rarity of *in situ* organisms (although potentially reef-building organisms are numerous), the periodically high abundance of clayey sediments (marl-limestone alternating layers) and calcareous mud, the periodically high input of continental phytoclasts, and storm impacts (tempestite deposits) (Hubmann 1995).

Structures: Except for North-South opening tension gashes no striking structures are visible.

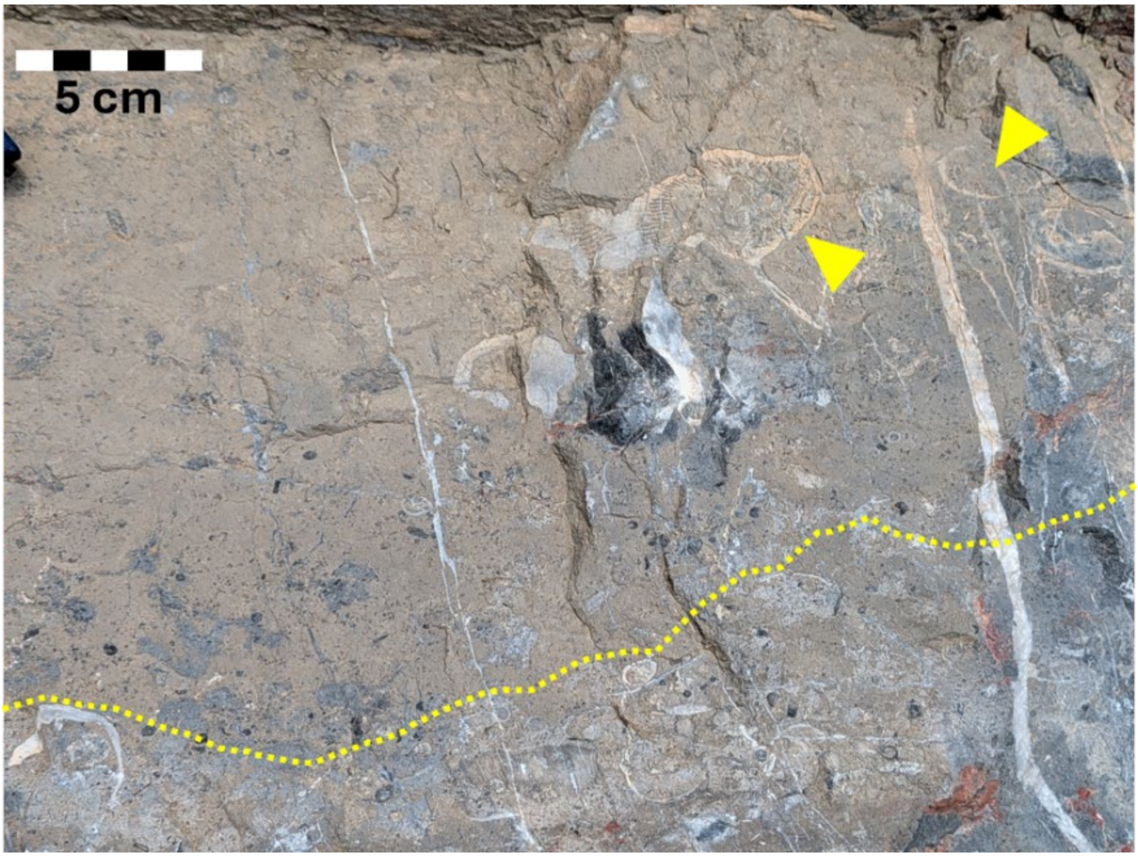

Fig. 19: Limestone bed with a basal graded layer of fossil debris containing *Thamnopora* sp., *Striatopora suessi*, *Thamnophyllum stachei*, and isolated brachiopod shells (up to the dotted line). Yellow triangles indicate the mud sticker *Zelophyllia cornuvaccinum*, a large, funnel-shaped, solitary rugose coral. Note the muddying upward trend typical of storm surge deposits.

Stop 6: Harrberger Formation (WGS 84: 47° 22′ 19″ N 15° 28′ 54″ E)

Nappe: Laufnitzdorf Nappe of the Intermediate Nappe System

Unit: Harrberger Formation: Chronostratigraphic age is Emsian-Frasnian. Lithology: Limestones with tentaculites, argillaceous shales, sandstones, lydites, radiolarites and tuffs.

Structures: The Harrberger Formation is part of the Laufnitzdorf Group that constitutes, together with rocks of the Kalkschiefer Nappe (predominantly Kogler Formation), the slices of the Intermediate Nappe System at the northern slope of the Hochlantsch Mountain with top-N-directed transport. Relics of a W-E stretching lineation are preserved, but dominant structures are top-N-directed shear bodies (Fig. 13).

Stop 7: The Frohnleiten Fold (WGS 84: 47° 16′ 11″ N 15° 20′ 04″ E)

Nappe: Kalkschiefer Nappe.

Unit: Gschwend Member of the Kogler Formation.

Lithology: Alternating limestones, silt- to sandstones and subordinate argillaceous shales and dolomites, locally volcanites. Chronostratigraphic age: Emsian-Givetian.

Structures: Given that the "Frohleiten Fold" is the only large-scale fold with an amplitude of c. 80 meters visible in the GP, it attracted many scientists. Heritsch (1905) described the structure as „überlegte Falte" that evolved from „Rückstauung" against the metamorphic units in the north / northwest. Jesenko (1949, 1952) denied the existence of a fold and considered the structure as "Scheinfaltengebilde" formed through interference of two joint systems, "Bruchsysteme", with bedding planes. Tschelaut (1984) analysed the system of bedding /axial plane foliation and recognized a NW-vergent fold with a flat, upright limb and a steep inverted limb (Figs. 20 a/b). A kinematic study providing details on strain and vorticity during the folding process was performed by Fuchs and Neumann (2000). This study, namely the analyses of incremental fibre growth around rigid objects, allowed reconstruction of the folding phase and post-folding shearing. The evolution of the fold can be divided into an initial phase of top-NW shearing (D1, increment 1 in Figs. 20 c/d/e). Tilting to form the inverted limb passively rotated early formed fibres (spin) and created a new generation of fibres (D1, increment 2). An axial plane foliation developed that occupies an ideal position to be activated as thrust planes during the successive top-NW thrusting event (D2) (Figs. 20 f/g/h/i).

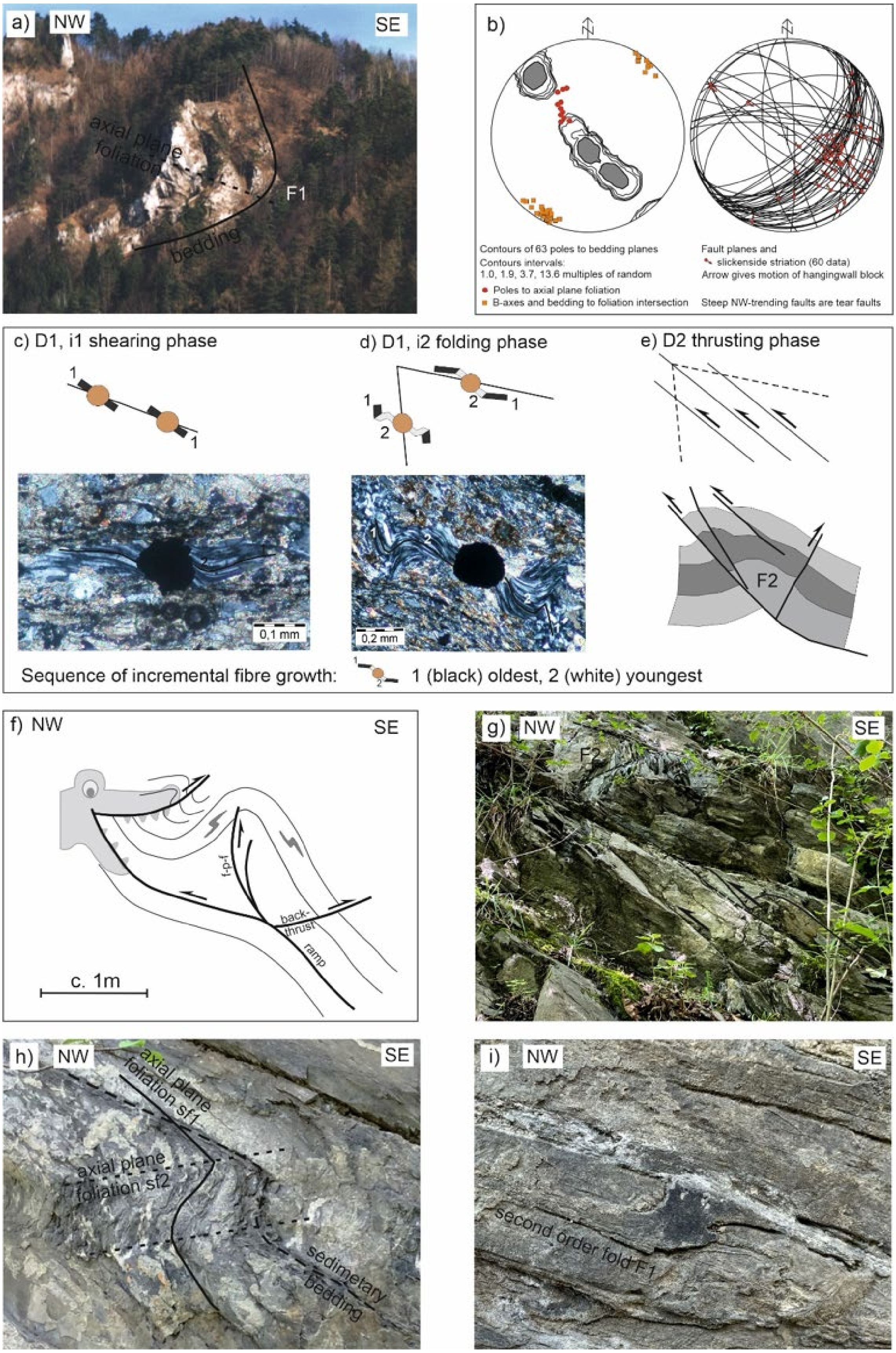
a) NW
SE
axial plane foliation
F1
bedding
b)
N
N
Contours of 63 poles to bedding planes
Contours intervals:
1.0, 1.9, 3.7, 13.6 multiples of random
Poles to axial plane foliation
B-axes and bedding to foliation intersection
Fault planes and
slickenside striation (60 data)
Arrow gives motion of hangingwall block
Steep NW-trending faults are tear faults
c) D1, i1 shearing phase
d) D1, i2 folding phase
e) D2 thrusting phase
0,1 mm
0,2 mm
F2
Sequence of incremental fibre growth:
1 (black) oldest, 2 (white) youngest
f) NW
SE
f-p-f
back-thrust
ramp
c. 1m
g) NW
SE
F2
h) NW
SE
axial plane foliation sf1
axial plane foliation sf2
sedimetary bedding
i) NW
SE
second order fold F1

Fig. 20: (previous page): Succession of deformation increments, all of them associated with top-NW folding and thrusting. a) The Frohnleiten Fold viewed from Frohnleiten Town. F1 is fold axis. b) Orientation data of the fold (left) and fault planes and slickenside striations related to post-folding thrusting (right). c) Early shearing phase and evolution of asymmetric strain shadows around pyrite. d) Rotation to form the steep inverted limb. Within upright limb "regular" fibres formed continuously whereas the fibres in the inverted limb show spin (rotation with respect to an external reference frame) and continued shear (rotation with respect to the internal reference frame). e) The axial plane foliation is further reactivated as thrust and thrust related folding (F2). f) Fold and thrust geometries with flat-ramp structures, fault propagation folds, back-thrusts and "crocodiles". g) Bedding / foliation geometry in upright fold limb. h) Upright limb with axial plane foliation, steeper than bedding, is refolded during back-thrusting event D2. i) Intrafolial second order folds are refolded during D2 folding (f, and i).

Stop 8: Kugelstein: Rauchenberg Member, Lower Nappe System internal thrust.

WGS 84: 47° 13′ 21″ N 15° 20′ 12″ E

Nappe: Lower Nappe System, Schöckel and ?Gasen Nappes.

Unit: Rauchenberg Member of the Schönberg Formation

Lithology: Predominantly black shales and dark gray to black limestones with a high clay content. The unit hosts Pb-Zn-Ag-Ba deposits exposed along strike of black shales between Kugelstein and the "Kirchberg" of Deutschfeistritz.

Structures: The shear zone within the Rauchenberg Member separates the Schöckel Nappe from an underlying tectonic unit, most probably the Gasen Nappe. The upper tectonic unit (Schöckel Nappe) contains an upright succession of Rauchenberg Formation, Schöckel marble and Upper Devonian volcanoclastic and siliciclastic rocks on top. The lower tectonic unit (Gasen Nappe) is exposed in drill core samples at Peggau-Deutschfeistritz, indicating an upright rock sequence of both, the Passail and Peggau Groups (Seelmeier 1941, 1944) (Fig. 21).

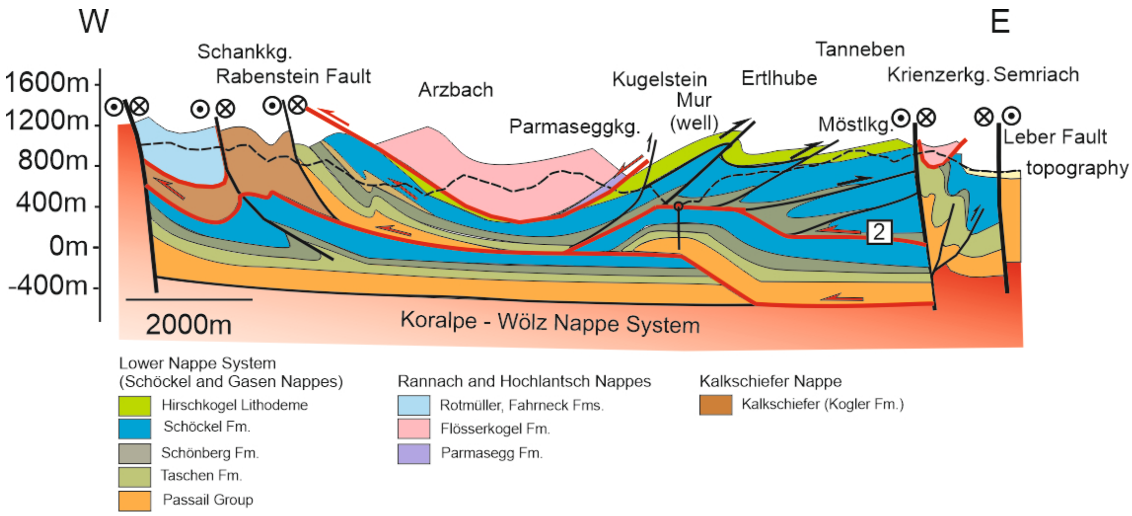

Fig. 21: Profile showing the nappe structure between Leber Fault and Northwestern Boundary Fault. Profile section P3 is shown in Fig. 6. Position of outcrop at Kugelstein is given by the black square. Approximate borehole location within the Mur Valley is indicated. For explanation, see text.

Microstructures of the shear zone show consistent top-W shear and the highest ductile shear strain, as indicated by strain shadows around rigid objects, near the contact between the Schönberg Formation and Schöckel marble (Fig. 22). White mica within that shear zone yielded K/Ar ages of 116 Ma and 128 Ma (Fritz, 1991).

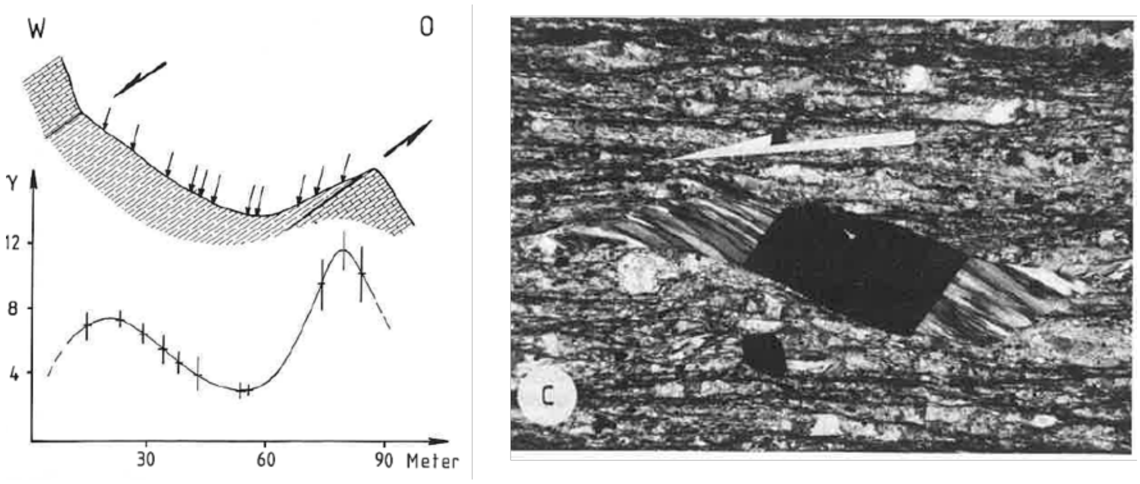

Fig. 22: Sketch of the shear zone at Kugelstein (left) with the Rauchenberg Member of the Schönberg Formation (diagonally hatched) and two tectonic levels of Schöckel marble (limestone ornament). Sites of strain analyses and profile showing shear strains across the profile age shown. Right is an example of fibre growth around pyrite giving top-west shear. Figures from Fritz (1991).

Top-W structural elements are overprinted by east-vergent folds with shallow westward dipping axial plane cleavage that evolve coeval to thrusts with younger top-E displacement (Fig. 23).

Fig. 23: East-vergent folds and top-east shear at Kugelstein overprinting earlier top-west structures.

Stop 9 WGS 84: 47° 13′ 06″ N 15° 17′ 14″ E

Forest road near a bridge over A2 Highway. The section across the boundary between Rannach and Schöckel Nappes was perfectly exposed during road construction, but still nice outcrops are present.

Nappe: Boundary between Rannach and Schöckel Nappes with top NE-directed shear (Übelbach Fault, Fig. 10). The fault /shear zone is one of the major top-NE structures that evolved within the “Central Shear Domain” of the GP (see Fig. 8).

Unit: Greitnerkogel Member of the Parmasegg Formation (Rannach Nappe) and Taschen Formation (Schöckel Nappe)

Lithology: Fe-dolomite, slates with silt layers (Greitnerkogel Member); calcareous phyllites and greenschists (Taschen Formation).

Structures: Dolo- and limestones of the Greitnerkogel Member are heavily fluid-infiltrated and contain numerous tension gashes consistent with NE-directed shear. Phyllites and greenschists of the Taschen Formation show S-C fabrics and folds indicating NE-directed shear.

Fig. 24: Northeast-vergent folds and shear fabrics of the Taschen Formation.

7. References

Berthè, D., Choukroune, P., & Jagouzo, P. (1979). Orthogneiss, mylonite and non-coaxial deformation of granites: the example of the South Amorican Shear Zone. – Journal of Structural Geology, 1, S. 31-42.

Boigk, H. (1951). Zum Bau der Grazer Decken. – Zeitschrift der Deutschen Geologischen Gesellschaft 102 (1951), S. 247-271.

Butler, R. W. H. (1982). The terminology of structures in thrust belts. Journal of Structural Geology, 4, S. 239-245.

Clar, C. (1874). Kurze Übersicht der geotektonischen Verhältnisse der Grazer Devonformation. – Verhandlungen Geologischer Reichsanstalt 3 (1874), S. 62-65.

Clar, E. (1935). Vom Bau des Grazer Paläocoikums östlich der Mur. – Neues Jahrbuchfür Mineralogie, Geologie und Paläontologie, 73 Beil. Bd. Abt. B, S.1-39.

Erhart-Schippek, F. (1949). Das Paläozoikum zwischen Übelbach und Gamsgraben. Ein Beitrag zur Stratigraphie und Tektonik des Paläozoikums westlich der Mur. – PhD Thesis, Universität Graz.

Flügel, H. (1958). 140 Jahre geologische Forschung im Grazer Paläozoikum. – Mitteilungen des Naturwissenschaftlichen Vereines für Steiermark 88 (1958), S. 51–78.

Flügel, H. (1960). Die Geologie des Grazer Berglandes. Erläuterungen zur Geologischen Wanderkarte des Grazer Berglandes 1:100.000. – Geologische Bundesanstalt, Wien 1960. – Second edition 1975. Mitteilungen der Abteilung für Geologie, Paläontologie und Bergbau am Landesmuseum Joanneum 1.

Flügel, H. (1960). Geologische Wanderkarte des Grazer Berglandes 1:100.000. Geologische Bundesanstalt, Wien.

Flügel, H.W. & Hubmann, B. (2000). Das Paläozoikum von Graz: Stratigraphie und Bibliographie. – Verlag der Österreichischen Akademie der Wissenschaften, Schriftenreihe der Erdwissenschaftlichen Kommissionen.

Flügel, H.W. & Neubauer, F. (1984). Erläuterungen zur geologischen Karte der Steiermark. Geologische Bundesanstalt Wien.

Flügel, H.W., Mauritsch, H., Heinz, H. & Frank, W. (1980). Paläomagnetische und adiometrische Daten aus dem Grazer Paläozoikum. – Mitteilungen der Österreichischen Geologischen Gesellschaft 71/72, S. 201–211.

Fritz, H. (1986). Zur Geologie des nordwestlichen Grazer Paläozoikums (im Bereich Schartnerkogel-Parmaseggkogel). – PhD Thesis, Universität Graz.

Fritz, H. (1988). Kinematics and geochronology of Early Cretaceous thrusting in the northwestern paleozoic of Graz (Eastern Alps). – Geodinamica Acta, 2, S. 53-62.

Fritz, H. (1991). Stratigraphie, Fazies und Tektonik im nordwestlichen Grazer Paläozoikum (Ostalpen). Jahrbuch der Geologischen Bundesanstalt, 134, S. 227-255.

Fritz, H., Ebner, F., & Neubauer, F. (1992). The Graz thrust complex (Paleozoic of Graz). – Alpaca field guide, Karl-Franzens-Universität Graz (1992).

Fritz, H., Neubauer, F., & Ratschbacher, L. (1991). Compression versus Extension in the Paleozoic of Graz. – Zentralblatt für Geologie und Paläontologie, S. 55–68.

Fuchs, A., & Neumann, D. (2000). Verformungsgeometries und Strain-Analyse im zentralen Grazer Paläozoikum. – Master Thesis, Universität Graz.

Gasser, D, Stüwe, K., & Fritz, H. (2010). Internal structural geometry of the Paleozoic of Graz. – International Journal of Earth Sciences, 99, S.1067-1081.

Gollner, J. & Zier, C. (1985). Zur Geologie des Hochlantsch (Grazer Paläozoikum, Steiermark). – Jahrbuch der Geologischen Bundesanstalt, 128, S. 43-73.

Gsellmann, H. (1987). Zur Geologie am Nordostrand des Grazer Paläozoikums (im Bereich Hochschlag – Plankogel – Heilbrunn). PhD Thesis, Karl-Franzens-Universität Graz.

Heritsch, F. (1905). Studien über die Tektonik der paläozoischen Ablagerungen des Grazer Beckens. - Mitteilung naturwiss. Verein Steiermark, 42, S. 170-224.

Heritsch, F. (1943). Die Stratigraphie der geologischen Formationen der Ostalpen. Das Paläozoikum. Bornträger Berlin.

Hollinetz, M.S., Huet, B., McFarlane, C.R.M., Schneider, D.A. & Grasemann, B. (2026). P-T-t-d Evolution of Low-Grade Metamorphic Xenotime, Eastern Alps (Austria). – Terra Nova, 38, S. 65-76.

Hollinetz, M.S., Huet, B., Schneider, D.A., McFarlane, C.R., Schuster, R., Rantitsch, G., Schantl, P., Iglseder, Ch., Reiser, M., & Grasemann, B. (2024). Pressure-temperature-time and REE mineral evolution in low-to medium-grade polymetamorphic units (Austroalpine Unit, Eastern Alps). – European Journal of Mineralogy, 36, S. 943-983.

Hubmann, B. & Krenn, K. (2022). Zweihundert Jahre erdwissenschaftliche Forschungs- und Ideengeschichte des Grazer Paläozoikums im Überblick. – Res montanarum, 62, S. 61-76, Leoben.

Hubmann, B. (2003). Plabutsch-Formation: nomen novum pro Barrandeikalk (Mitteldevon, Grazer Paläozoikum). – In: Piller, W.E. (ed.): Stratigraphia Austriaca. Österreichische Akademie der Wissenschaften, Schriftenreihe der Erdwissenschaftlichen Kommissionen, 16, S. 269-292.

Hubmann, B. (1993). Ablagerungsraum, Mikrofazies und Paläoökologie der Barrandeikalk-Formation (Eifelium) des Grazer Paläozoikums. Jahrbuch der Geologischen Bundesanstalt, 136/2, S. 393-461.

Hubmann, B. (1995). Middle Devonian shallow marine deposits of the Graz Paleozoic: fact and fiction for deposition under ecological stress. Beiträge zur Paläontologie, 20, S. 107-112.

Hubmann, B., Ebner, F., Ferretti, A., Kido, E., Krainer, K., Neubauer, F., Schönlaub, H.-P. & Suttner, T.J. (2014). The Paleozoic Era(them), 2nd edition. – In: Piller, W.E. (ed.): The lithostratigraphic units of the Austrian Stratigraphic Chart 2004 (sedimentary successions), Vol. I. Abhandlungen der Geologischen Bundesanstalt, 66, S. 9-133.

Jesenko, P. (1949). Das Paläozoikum zwischen Frohnleiten und Mixnitz. Unpublished PhD Thesis, University Graz.

Jesenko, P. (1952). Die Frohnleitner "Falte" im Grazer Paläozoikum. Verhandlungen Geol. Bundesanstalt, S. 142-146.

Krenn, K., Fritz, H., Mogessie, A., & Schaflechner, J. (2007). Late Cretaceous exhumation history of an extensional extruding wedge (Graz Paleozoic Nappe Complex, Austria). – International Journal of Earth Sciences, 97, S. 1331-1352.

Matura, A. & Schuster R. (2014). Geologische Karte der Republik Österreich, Blatt 135, Birkfeld, 1:50.000. Geologische Bundesanstalt Wien.

Maurin, V. (1954). Das Paläozoikum im Raum zwischen Deutschfeistritz und Semriach. Mitteilungen des Naturwissenschaftlichen Vereines für Steiermark, 84, S. 81-102.

Neubauer, F. (1989). Lithostratigraphie und Strukturen an der Basis der Rannachdecke im zentralen Grazer Paläozoikum. Jahrbuch der Geologischen Bundesanstalt, S. 459-474.

Neubauer, F. (1991). Stratigraphie und Struktur der Rannachdecke bei Kehr. Jahrbuch der Geologischen Bundesanstalt, 134, S. 101-116.

Neubauer, F., Dallmeyer, R.D, Dunkl, I., & Schirnik, D. (1995). Late Cretaceous exhumation of the metamorphic Gleinalm dome, Eastern Alps: kinematics, cooling history and sedimentary response in a sinistral wrench corridor. Tectonophysics, 242, S. 79-89.

Rantitsch, G. & Mali, H. (2006). The geological structure of the Late Cretaceous Graden normal fault (Eastern Alps). Mitteilungen des Naturwissenschaftlichen Vereins Steiermark, 135, S. 25-31.

Rantitsch, G., Sachsenhofer, R.F., Hasenhüttl, C., Russegger, B. & Rainer, T. (2005). Thermal evolution of an extensional detachment as constrained by organic metamorphic data and thermal modeling: Graz Paleozoic Nappe Complex (Eastern Alps). Tectonophysics, 411, S. 57-72.

Rantitsch, G., Schuster, R., Reiser, M., Huet, B., Hollinetz, M.S., & Iglseder, C. (2026). Raman spectroscopy of carbonaceous material thermometry in the uppermost Austroalpine units, Eastern Alps - paleogeographic and tectonic implications. – Austrian Journal of Earth Sciences, 119, S. 69-88. doi: 10.17738/ajes.2026.0005.

Rohrhofer, S., Geringer, A., Melcher, F., & Schuster, R. (2024). Alteration Zones as Exploration Parameters for Stratiform Pb-Zn-Ag-Ba Deposits in the Graz Paleozoic (Eastern Alps, Austria). Berg Hüttenmännische Monatshefte, 169, S. 567-573. doi:https://doi.org/10.1007/s00501-024-01509-w.

Schantl, P., Schuster, R., Krenn, K., & Hoinkes, G. (2015). Polyphase metamorphism at the southeastern margin of the Graz Paläozoic and the underlying Austroalpine basement units. Austrian Journal of Earth Sciences, 108, 219-238.

Schuster, R., Schantl, P., Ilckovic, T., Mooshammer, B., Krenn, K., Puhr, B., Brandner, K., Proyer, A., Richoz, S. & Hoinkes, G. (2015). Tektonik, Metamorphose und Abkühlgeschichte des Grazer Paläozoikums auf Kartenblatt GK50 Blatt 135 Birkfeld. Arbeitstagung 2015 der Geologischen Bundesanstalt, S. 70-86.

Seelmeier, H. (1941). Das Alter des Schöckel Kalkes. Berichte der Reichsanstalt für Bodenforschung, 1941, S. 74-79.

Seelmeier, H. (1944). Beitrag zur Geologie des erzführenden Paläozoikums der Umgebung von Peggau-Deutschfeistritz bei Graz. Berichte der Reichsanstalt für Bodenforschung, 1944, S. 1-25.

Suess, E. (1868). Die Äquivalente des Rotliegenden in den Alpen. – Sitzungsberichte der Akademischen Wissenschaften Wien, math.-naturwiss. Kl. (I) 57 (1868), S. 239–276.

Tschelaut, W. (1984). Die "Frohnleitner Falte" (Grazer Paläozoikum, Steiermark). Jahrbuch der Geologischen Bundesanstalt, 127, S. 507-511.

Unger, F. (1843). Geognostische Skizze der Umgebung von Grätz. In: Schreiner, G.: Grätz, ein naturhistorisch-statistisch-topographisches Gemälde dieser Stadt und ihrer Umgebungen. S. 69-82.