Final Scientific Meeting of 4D-MB & AlpArray

Summary of meeting and projects

Bad Hofgastein, Austria
3-6 October 2023

Deutsche Forschungsgemeinschaft
German Research Foundation

Contents

Foreward

This volume contains the proceedings of the final meeting of Research Priority Program (SPP) of the German Science Foundation (DFG) entitled *Mountain-Building in 4-Dimensions (4D-MB)* in Bad Hofgastein (Austria). It includes the meeting program as well as extended abstracts by principal investigators of all 4D-MB projects from both phases of the SPP (2017-2020, 2020-2023). These abstracts formed the basis for posters and oral presentations at the meeting. Also attending were many members of the European *AlpArray* seismological project, of which 4D-MB was an integral part. Their contributions are marked separately (Non-SPP). We note that this report is a summary and NOT the full, final report of 4D-MB which will be submitted to the DFG in 2025.

Bad Hofgastein was a fitting venue for the meeting, as it is situated in the heart of the Eastern Alps where many SPP activities were centered. The program was loosely structured to highlight the main themes and working groups of the SPP as outlined in the proposal of 2020:

Themes

1. Reorganisation of the lithosphere during mountain-building
2. Surface & crustal responses to changes in mountain-building

Working groups

- Neogene orogenic (r)evolution – from bottom to top, and back in time
- Bridging models of Alpine deformation and sedimentary systems
- Active tectonics at the Alps-Dinarides transition

The keynote speakers were recruited from the ranks of current and former early-career scientists in the SPP. Two other keynotes were held by members of the DFG panel who reviewed the SPP proposals in 2017 and 2020 (four members attended). Talks were scheduled in the morning, with the afternoon sessions devoted almost entirely to poster presentations that covered all the SPP projects. These sessions were followed in the late afternoon by plenary discussions that lasted for approximately an hour. Participants then retreated to nearby pubs in Bad Hofgastein before adjourning to a well-earned dinner sponsored by the SPP.

Following the meeting, twenty SPP members took part in a one-day field trip over the Grossglockner Pass (M.R. Handy) which, in clear autumn weather, traversed lower-plate units of the Alpine subduction exposed in the Tauern Window. This is the site of a paleo-subduction channel with spectacular structures and mineral parageneses that were exhumed from high-pressure conditions in Paleogene time.

We all enjoyed a productive time at the meeting, thus bringing memorable years of collaboration to a fitting close.

Mark R. Handy (FU-Berlin), Speaker

Peter J. McPhee (FU-Berlin), Coordinator

Members of the 4D-MB Steering Committee attending (*early career, **emeriti)

Todd Ehlers (Tübingen & Glasgow), Wolfgang Friederich (Bochum), Christoph Gruetzner* (Jena), Mark R. Handy (FU-Berlin), Timm John (FU-Berlin), Emanuel Kaestle* (FU-Berlin), Boris Kaus (Mainz), Heidrun Kopp (Geomar-Kiel), Peter J. McPhee* (FU-Berlin), Klaus Reicherter** (RWTH-Aachen), Leni Scheck-Wenderoth (GFZ-Potsdam.,RWTH-Aachen), Nevena Tomasevic* (KIT Karlsruhe), Michael Weber** (GFZ & U. Potsdam).

DFG panel members in attendance:

Thorsten Becker (Austin, Texas), Matthew Fox (UC London), Liviu Matenco (Utrecht), Stefan M. Schmid (ETH-Zürich)

AlpArray & 4D-MB Scientific Meeting

Bad Hofgastein 2023

Wednesday, 4th of October 2023

08:45	**Registration (Name Badges)**	
09:15	Opening: Mark Handy	
09:30	**Keynote**	**Emanuel Kästle & Marcel Paffrath: Advances in imaging of the Alpine lithosphere**
10:00	Christian Haberland	Local earthquake tomography in the Eastern and eastern Southern Alps using SWATH-D data
10:15	Georg Rümpker	Layered anisotropy and mantle flow beneath AlpArray from shear-wave splitting
10:45	**Coffee Break**	
11:15	**Keynote**	**Nevena Andrić-Tomašević & Eline Le Breton: The Alpine foreland basins – what we have learned from 4D-MB**
11:45	Christoph von Hagke	Foreland dynamics as a measure of mountain building processes
12:00	[Non-SPP] László Fodor	Connections of the Alps-Carpathians-Dinarides-Pannonian basin: from mantle processes to crustal structures
12:15	Leni-Scheck-Wenderoth	INTEGRATE - Integrated 3D structural, thermal, gravity and rheological modeling of the Alps and their forelands
12:30	**Lunch**	
14:00	Poster presentations	
15:00	Poster session	
16:30	Session wrap-up	
Dinner	**18:30 Appetisers and Drinks – 19:00 Dinner**	

AlpArray & 4D-MB Scientific Meeting

Bad Hofgastein 2023

Thursday, 5th of October 2023

09:00	**Keynote**	**Marcel Thielmann: Processes and repercussions of slab detachment**
09:30	[Non-SPP] Thorsten Becker	Subduction, continental collision, and mantle dynamics in the Mediterranean - Tethyan realm: impact on oceanic circulation, climate, and the biosphere
09:45	Ajay Kumar	Role of lithospheric-scale geological heterogeneity in the continental lithosphere dynamics
10:00	Boris Kaus	3D geodynamic modelling of the present day and long term deformation of the Alps and Adria
10:15	Nikolaus Froitzheim	Eclogite dating and subduction zones in the Alps
10:30	**Coffee Break**	
11:00	**Keynote**	**Christoph Grützner: Active Tectonics of the Alps-Dinarides junction – what have we learned?**
11:30	[Non-SPP] Miklos Kazmer	Pustertal-Mölltal-Gailtal-Drautal – Periadriatic Fault activity revealed by ruined buildings
11:45	Valentina Argante	Dating the youngest deformation in the Alps with ESR thermochronometry
12:00	Klaus Reicherter	Paleoseismicity of the foreland: the Upper Rhine Graben
12:15	[Non-SPP] Götz Bokelmann	What AlpArray tells us about stress and water resources under the Alpine Region
12:30	**Lunch**	
14:00	Poster presentations	
15:00	Poster session	
16:30	Session wrap-up	
Dinner	**18:30 Appetisers and Drinks – 19:00 Dinner**	

AlpArray & 4D-MB Scientific Meeting

Bad Hofgastein 2023

Friday, 6th of October 2023

09:00	**Keynote**	**Matthew Fox: Imaging mountain belt geomorphic processes with inverse methods and diverse datasets**
09:30	Christoph Glotzbach	Deriving the exhumation history of the Alps with thermochronological data
09:45	**Keynote**	**Maud Meijers & Sebastian Mutz: Reconstructing Neogene surface uplift of the Alps: Integrating stable isotope paleoaltimetry and paleoclimate modelling**
10:15	Daniel Boateng	Synergistic effects of diachronous surface uplift and global climate change on the isotopic composition of meteoric waters: implications on paleoelevation estimates across the European Alps
10:30	**Coffee Break**	
11:00	Thomas Meier	Slabs in the Alpine region: inferences down to 300 km depth from surface wave tomography and receiver functions
11:15	[Non-SPP] Anna-Katharina Sieberer	Control of inherited structures and mechanical heterogeneities on the internal deformation of the Dolomites Indenter, eastern Southern Alps: a multi-scale analogue modelling study
11:30	Peter McPhee	Investigating the post-collisional reorganisation of the Eastern Alps using a 4D reconstruction
11:45	Mark Handy	How AlpArray & 4D-MB are guiding us to a new model of Alpine orogenesis
12:15	**Lunch**	
13:30	Poster presentations	
14:30	Poster session	
16:15	Session wrap-up	
16:45	**Steering Committee Meeting**	4D-MB, AlpArray, and DFG panel members
17:15	**Quo Vadis? & Thanks!**	Mark Handy
Dinner	**18:30 Appetisers and Drinks – 19:00 Dinner**	

Phase 1 Projects (2017-2020)

Principal Investigator	Project title
Wolfgang Friederich Michael Korn Thomas Meier Georg Rümpker Frederik Tilmann Christine Thomas Joachim Wassermann	Activity Field A - UNIBRA / DSEBRA: the German seismological contribution to AlpArray
Heidrun Kopp Dietrich Lange Ingo Grevemeyer	Activity Field B - LOBSTER: Ligurian Ocean Bottom Seismology and Tectonics Research
Michael Weber Frederik Tilmann Christian Haberland	Activity Field D – SWATH D: Providing seismological data for the SPP 4D-MB, A dense seismological station network in the Central and Eastern Alps
Wolfgang Friederich Thomas Meier Boris Kaus	Imaging structure and geometry of Alpine slabs by full waveform inversion of teleseismic body waves
Nikolaus Froitzheim Ruth Keppler	Slab factory – ocean formation and subduction in the Western Alps
Christoph Glotzbach Jonas Kley	Constraining the near-surface response to lithospheric reorientation - Structural thermochronology along AlpArray geophysical transects
Christoph Gruetzner Klaus Reicherter Friedhelm von Blankenburg	Earth surface response to Quaternary faulting and shallow crustal structure in the eastern Adria-Alpine collision zone and the Friulian plain
Mark Handy Christian Haberland Eline Le Breton	Linking surface kinematics to deep structure of the Adriatic indenter near a potential subduction-polarity switch – the Giudicarie Belt (Southern Alps)
Boris Kaus Wolfgang Friederich Thomas Meier	Constraining the dynamics of the present-day Alps with 3D geodynamic inverse models
Ruth Keppler Michael Stipp Nikolaus Froitzheim	Alpine subduction revisited – new structural and elastic wave velocity models for improved geophysical imaging towards greater depths
Rainer Kind	Seismic imaging of the newly discovered Sub-Lithospheric Discontinuity (SLD) in the larger Alpine region
Jörn Kummerow Simone Cesca Joachim Wassermann	From Top to Bottom- Seismicity, motion patterns & stress distribution in the Alpine Crust

Thomas Plenefisch Dietrich Lange Martin Thorwart Ingo Grevemeyer	Generation, destruction and of lithosphere of the Ligurian Sea
Elco Luijendijk Christoph von Hagke	Quantifying crustal fluid flow and its role in the thermal structure of the Alps
Thomas Meier Wolfgang Friederich Jörg Ebbing	Surface Wavefield Tomography of the Alpine Region to Constrain Slab Geometries, Lithospheric Deformation and Asthenospheric Flow in the Alpine Region
Andreas Mulch Todd Ehlers Katharina Methner Sebastian Mutz	Neogene Paleoelevation and Paleoclimate of the Central Alps – Linking Earth surface processes to lithospheric dynamics
Alexey Petrunin	Inverse and forward multiscale numerical modeling of the Alpine orogeny (IFMMALPO)
Jan Pleuger Timm John Frederik Tilmann Mark Handy Xiaohui Yuan Boris Kaus James Mechie	Understanding subduction by linking surface exposures of subducted and exhumed crust to geophysical images of slabs
Klaus Reicherter Joachim Ritter Jochen Hürtgen	Stress transfer and Quaternary faulting in the northern Alpine foreland
Georg Rümpker Harro Schmeling	Mantle deformation beneath the Alps and the physics of the subduction polarity switch - Constraints from thermomechanical modelling, seismic anisotropy and waveform modelling
Magdalena Scheck-Wenderoth Jörg Ebbing Judith Sippel Hans-Jürgen Götze	Integrated 3D structural, thermal, gravity and rheological modeling of the Alps and their forelands - INTEGRATE
Christoph von Hagke Elco Luijendijk David Hindle Jonas Kley	FB-4D - Foreland basin evolution records the effects of plate reorganization, surface evolution and crustal deformation on mountain building

Phase 2 Projects (2020-2023)

Principal Investigator	**Project Title**
Klaus Bauer Anne Bernhardt Mark Handy	Switching pro- and retro-wedges in the Eastern Alps and their peripheral basins - clues to a change in subduction polarity?
Christian Brandes Christoph von Hagke David Tanner Sumiko Tsukamoto	The Last Pulse – dating the youngest deformation in the Alps with ESR thermochronometry
Christian Brandes Rebecca Kühn Michael Stipp David Tanner	The Brenner base tunnel (BBT) natural laboratory – From cross-section construction over fabric and elastic anisotropy analysis to 4D structural modeling
Eline Le Breton Boris Kaus	From plate tectonic reconstructions to 4D geodynamic models of the Alpine Orogeny
Eline Le Breton Dietrich Lange	Linking the deep structure to surface deformation: Body wave tomography of the Ligurian Sea and South-Western Alps
Simone Cesca Jörn Kummerow	Constraints on Quaternary processes in the Eastern Alps from a new detailed image of seismicity
Todd Ehlers Maud Meijers Andreas Mulch Sebastian Mutz	Reconstructing Eastward Propagation of Surface Uplift in the Alps: Integrating Stable Isotope Palaeoaltimetry and Palaeoclimate Modelling
Todd Alan Ehlers Nevena Tomasevic	Integrated records of tectonic and climate interactions in the Northern Alpine Foreland Basin sedimentary architecture
Todd Alan Ehlers Paul R. Eizenhöfer	Quantifying the Effects of Mantle Processes and Climate Variability on Hinterland Denudation in the Central and Eastern Alps since the Oligocene
Todd Alan Ehlers Christoph Glotzbach Laura Stutenbecker	Constraining the geodynamic evolution of the Alps with sedimentary provenance and detrital thermochronometer data
Wolfgang Friederich Timm John Jan Pleuger Frederik Tilmann	Applying scattered wave tomography and joint inversion of high-density (SWATH D) geophysical and petrophysical datasets to unravel Eastern Alpine crustal structure
Hans-Jürgen Götze Boris Kaus Magdalena Scheck-Wenderoth	Deformation patterns in relation to the deep configuration of the lithosphere of the Alps and their forelands – DEFORM
Christoph Grützner	

Klaus Reicherter Kamil Marek Ustaszewski	Mountain building in the Eastern and Southern Alps - large earthquakes and active faults
Mark Handy	Coordination Funds
Mark Handy Rainer Kind Thomas Meier Georg Rümpker	Identifying Main Lithospheric Structures in the Eastern Alpine Domain by Joint Inversion of Receiver Function and Surface Wave Measurements for Seismic Anisotropy
Christian Haberland Andreas Rietbrock	A comprehensive high resolution 3D P- and S-wave velocity model for the Alpine mountain chain using local earthquake data: Constraining crustal structure, lithologies and mountain-building processes
Christoph von Hagke Florian Wellmann	ThinkALPS - Thermokinematic models including Uncertainty of Geometry in the Alps
Timm John Jan Pleuger	How large are tectonic deviations from lithostatic pressure in a continent-derived, lithologically heterogeneous Alpine UHP nappe (Koralpe-Saualpe-Pohorje Complex, Austria and Slovenia)?
Emanuel David Kästle	Imaging the Alpine crust with ambient-noise tomography: linking surface observations to deep structures
Sabrina Metzger	From Uniform to Distributed Faulting - Present-day Kinematics of the Southern and Eastern Alps
Dirk Scherler Ricarda Winkelmann	Glacial and erosional contributions to Late Quaternary uplift of the European Alps
Antje Schlömer	Load/Unload Mechanisms of the Seismically Active Mt. Hochstaufen, Bad Reichenhall (Germany) - Identified by Seismological, Geodetic and Meteorological Aspects
Marcel Thielmann	Quantifying Detachment Induced Surface Uplift in the Alps
Sumiko Tsukamoto Kamil Marek Ustaszewski	Identifying fossil fault activity along the eastern Periadriatic Fault system by means of combined OSL- and ESR-dating of fault gouges (NE Italy, S Austria and N Slovenia)
Nikolaus Froitzheim Michael Stipp	High- and ultrahigh-pressure rock exhumation and tectonic structure of the southeastern Austroalpine crust

List of extended abstracts/project reports

Integrated records of tectonic and climate interactions in the Northern Alpine Foreland Basin sedimentary architecture

Nevena Andrić-Tomašević [1], Lucas H.J. Eskens[1], Giridas Maiti[1], Todd A. Ehlers[2,3]

1. Karlsruhe Institute of Technology, Institute of Applied Geosciences, Karlsruhe, Germany
2. University Tübingen, Department of Geosciences, Tübingen, Germany
3. University of Glasgow, School of Geographical and Earth Sciences, Glasgow, UK

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Peripheral foreland basins form due to flexural subsidence of the downgoing plate driven by topographic- and slab loading. Their architecture records lithospheric- and crustal-scale processes, and the climate history of the adjacent growing orogen. Previous geological and geophysical observational studies revealed that many foreland basins show along-strike heterogeneous sedimentary architecture, implying that mechanisms controlling basin evolution varied laterally. In the Northern Alpine Foreland Basin (NAFB, also known as Molasse Basin) the along-strike heterogeneity in basin architecture is represented by eastward shallowing of depositional environments during Oligocene-Miocene times. This coincided with the suggested two slab break-off and/or tearing events occurring below the Alps. In this project, we test the hypothesis of whether slab break-off and tearing can control along-strike variable foreland basin architecture. We do this by combining tectonostratigraphic analysis of the NAFB fill and numerical models. Tectonostratigraphic analysis includes interpretation of the 2D/3D seismic data located in the transitional zone of the NAFB (German Molasse) connecting the western and eastern parts of the basin. To investigate the effect of the slab-break off and tearing on the foreland basin evolution we combine 3D thermomechanical- and stratigraphic forward models.

The results of the tectonostratigraphic analysis reveal a northward younging trend of syn-flexural normal fault nucleation which agrees with forebulge migration driven by the advance of the Alpine thrust front during the Oligocene-Miocene. Furthermore, the eastward increase in the magnitude of syn-flexural normal fault offsets suggests an increase in the magnitude of flexural bending of the lower plate. This may have been controlled by lateral variations in the architecture of the lower plate and/or spatiotemporal variations in slab breakoff/tearing. The observed along-strike seismic facies integrated with the published data suggests that the north-south trending intrabasinal coastline migrated from west to east at an average rate of ~ 6 cm/yr. Furthermore, 3D thermomechanical models show that slab tearing will initiate either at the location of a subducted continental terrain (if present along the slab) or where collision starts first in the case of oblique convergence. Subsequently, tearing propagates along the strike at velocities ranging from ~35 cm/yr to 120 cm/yr depending on the margin obliquity, slab age and mantle rheology. The surface expression of slab tearing is the orogen parallel migration of uplift, affecting both the orogen and peripheral foreland basin. In the peripheral foreland basins associated with the collision of oblique margins, this uplift leads to a gradual along-strike decrease of accommodations space followed by shallowing of depositional environments. However, during the collision of irregular margins, the size and rheology of irregular terrains exert a key influence on the along-strike distribution of the surface uplift during tearing. Typically, this yields a more stepwise distribution of the accommodation space along the peripheral foreland, i.e. lower above the previously accreted terrain.

Currently, we are focusing on integrating thermomechanical- and forward stratigraphic models to estimate the effect of environmental factors such as sea-level variations, and precipitation rates on the preservation of the slab break-off and tearing signals in the stratigraphic record of peripheral foreland basins.

Dating the youngest deformation in the Alps with ESR thermochronometry

Valentina Argante[1], Sumiko Tsukamoto[1], David C. Tanner[1], Christoph von Hagke[2], Christian Brandes[3],

1. Leibniz Institute for Applied Geophysics, Germany
2. Department of Geography and Geology, University of Salzburg, Austria
3. Institut für Geologie, Leibniz Universität Hannover, Germany

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Low-temperature thermochronology is a useful tool to reconstruct tectonic deformation and landscape evolution within the first 2 km of the crust. It is a suitable tool to investigate deformation associated with cooling and exhumation of the lower crust in orogenic settings. Low temperature thermochronology is applied here to understand the Neogenic post-collisional extensional event that occurred in the Alps, because a gap in previous age dating exists between a thousand and a million years.

Quartz is the most common mineral in the crust; occurring in magmatic as well as sedimentary and metamorphic rocks. The potential of quartz electron-spin resonance (ESR) as a radiation dosimeter has been well documented, and many studies applied the method to date sediments and heated rocks (e.g. tephra). In this study, we apply quartz ESR dating as an ultralow-temperature thermochronometer, characterized by a closure temperature of 30°-90°, and dating range of 10^3-10^7 years.

We show the results of ESR thermochronometry on quartz applied to rocks from crustal-scale faults in the Central (Simplon Fault) and Eastern Alps (Brenner and Salzachtal Faults). Here, the lower crust has been tectonically exhumed, associated with exhumation of the Lepontine Dome and Tauern Window, respectively. Thermochronological data are available from this area, such as fission tracks or U-Th/He data on zircon and apatite. Results of the ESR measurements of 15 samples crossing the Brenner and Salzachtal faults (northern and western border of the Tauern Window) show that the ESR ages of quartz get younger (<1Ma) inside the western part of the Tauern Window, in accordance with fission track and (U-Th)/He ages. In general, younger ages (between 200 and 500 ka) are also obtain closer to the fault zone, localized near (e.g. Simplon Fault) or at the bottom of the valley (e.g. Brenner Fault), compared with the protolithic rocks (600-900 ka). We interpret the trend of the ESR ages as an exhumation of the isotherms due to both recent uplift of the footwall of the fault and for erosion of the valley, where the later overprints the former. These results promise to establish ESR as an ultra-low thermochronometer using quartz for the Quaternary landscape reconstruction of the Alpine chain.

Miocene (23–13 Ma) continental paleotemperature record from the northern Mediterranean region (Digne-Valensole Basin, SE France) within a global climatic framework

Armelle Ballian[1,2], Maud J.M. Meijers[3], Katharina Methner[4], Isabelle Cojan[5], Damien Huyghe[5], Jens Fiebig[2], Andreas Mulch[1,2]

1. Senckenberg Biodiversity and Climate Research Centre, Frankfurt am Main, Germany
2. Institute of Geosciences, Goethe University Frankfurt, Frankfurt am Main, Germany
3. Institute of Earth Sciences, NAWI Graz Geocenter, University of Graz, Austria
4. Department of Geological and Environmental Sciences, Stanford University, Stanford, United States
5. Centre de Géosciences, MINES-ParisTech, Fontainebleau, France

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During the Middle Miocene, the Earth's climate transitioned from a warm phase, the Miocene Climatic Optimum (MCO, 16.9–14.7 Ma), to a colder phase associated by formation of major ice sheets on Antarctica. This climatic shift, the Middle Miocene Climatic Transition (MMCT, 14.7–13.8 Ma), considerably impacted not only the structure and formation of major ecosystems (e.g. Jimenez-Moreno & Suc, 2005) it also affected global ocean circulation (Holbourn et al., 2014), terrestrial temperatures as well as precipitation patterns (e.g. Methner et al., 2020). While the MCO and the subsequent MMCT are well described in marine records, knowledge about the magnitude and rate of terrestrial paleoclimate changes is often limited by lack of temporal resolution and reliable quantitative proxy records (Steinthorsdottir et al., 2021).

Here, we present a long-term (23–13 Ma) biostratigraphically-controlled terrestrial stable ($\delta^{18}O$, $\delta^{13}C$) and clumped (Δ_{47}) isotope paleosol carbonate record from the northern Mediterranean region (Digne-Valensole basin, SE France).

When comparing the northern Mediterranean $\delta^{18}O$, $\delta^{13}C$ and Δ_{47} record with age-equivalent counterparts from central Europe (Northern Alpine Foreland Basin, Switzerland), our Δ_{47} results from the Digne-Valensole basin reveal two important features: 1) Relatively warm and constant carbonate formation temperatures (ca. 30°C) for the Early Miocene (23–18.6 Ma) followed by 2) intensified temperature fluctuations with high values (ca. 37°C) at the onset of the MCO, most probably amplified by changes in seasonality of pedogenic carbonate formation.

The combined Northern Alpine foreland and northern Mediterranean records display a coherent climate pattern for the Middle Miocene circum-Alpine foreland. In both records, high-amplitude, rapid changes in Δ_{47} temperatures (ca. 18°C within 400 ka) characterize the onset of the MCO and MMCT. We furthermore identify warm peaks during the MCO and a distinct fall in apparent Δ_{47}-based temperatures at ca. 14 Ma that is in very good temporal agreement with oceanic isotope records and coincides with the documented global cooling following the MCT. Collectively, these data contribute to understanding of the dynamics and variability in atmospheric circulation controlling Middle to Late Miocene temperature dynamics in the Northern Mediterranean region.

Holbourn, A., Kuhnt, W., Lyle, M., Schneider, L., Romero, O., & Andersen, N. (2014). Middle Miocene climate cooling linked to intensifi cation of eastern equatorial Pacific upwelling. Geology, 42(1), 19–22. https://doi.org/10.1130/G34890.1

Jiménez-Moreno, G., & Suc, J.-P. (2007). Middle Miocene latitudinal climatic gradient in Western Europe: Evidence from pollen records. Palaeogeography, Palaeoclimatology, Palaeoecology, 253(1–2), 208–225. https://doi.org/10.1016/j.palaeo.2007.03.040

Methner, K., Campani, M., Fiebig, J., Löffler, N., Kempf, O., & Mulch, A. (2020). Middle Miocene long-term continental temperature change in and out of pace with marine climate records. Scientific Reports, 10(1), 1–10. https://doi.org/10.1038/s41598-020-64743-5

Steinthorsdottir, M., Coxall, H. K., de Boer, A. M., Huber, M., Barbolini, N., Bradshaw, C. D., Burls, N. J., Feakins, S. J., Gasson, E., Henderiks, J., Holbourn, A. E., Kiel, S., Kohn, M. J., Knorr, G., Kürschner, W. M., Lear, C. H., Liebrand, D., Lunt, D. J., Mörs, T., ...

Strömberg, C. A. E. (2021). The Miocene: The Future of the Past. Paleoceanography and Paleoclimatology, 36(4). https://doi.org/10.1029/2020PA004037

The Alps Paleoelevation and Paleoclimate Experiment: Reconstructing Eastward Propagation of Surface Uplift in the ALps (REAL)

Armelle Ballian[1,2], Daniel Boateng[3], Sebastian G. Mutz[3,4], Maud J.M. Meijers[1,5], Katharina Methner[1,6], Andreas Mulch[1,2], Todd Ehlers[3,4]

1. Senckenberg Biodiversity and Climate Research Centre, Frankfurt am Main, Germany
2. Institute of Geosciences, Goethe University Frankfurt, Germany
3. Department of Geosciences, University of Tübingen, Germany
4. School of Geographical & Earth Sciences, University of Glasgow, UK
5. Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Austria
6. Institute of Geophysics and Geology, University of Leipzig, Germany

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Geological observations, geodynamic models, and seismic studies suggest Neogene eastward propagating surface uplift of the European Alps. Whereas 4DMB Phase I project APE focused on reconstructing surface uplift of the Central Alps, 4DMB Phase II project REAL aims at testing the predicted west-to-east surface uplift of the Alps by combining stable isotope paleoaltimetry and paleoclimate modeling. Stable isotope paleoaltimetry is based on the inverse relationship between elevation and the stable isotopic composition of meteoric water and provides a tool to reconstruct the elevation of mountain belts in the geological past.

First, REAL explores applications of the δ-δ method (see Poster Phase I APE), which requires that various recorders of past rainfall are available in the rock record: soil carbonates from low-elevation (foreland) basins and hydrous minerals from high-elevation fault gouges/shear zones. Paleoelevation estimates are obtained by contrasting time-equivalent low- and high-elevation proxy data sets, provided that the isotopic composition of the fluids during mineral formation is estimated accurately. Whereas formation temperatures of fault gouge minerals (such as illite and syntectonic micas) can be readily estimated, we apply clumped isotope paleothermometry to provide robust estimates of meteoric water $\delta^{18}O$ from the low-elevation foreland basin carbonate record.

Second, meteoric water $\delta^{18}O$ values are not only sensitive to local elevation, but also to the complex climatic changes resulting from different paleoenvironmental boundary conditions and regional topographic configuration. To isolate the contribution of each of these components δ-δ stable isotope paleoaltimetry is applied in combination with ECHAM5-wiso paleoclimate simulations for a number of topographic scenarios of diachronous surface uplift. This unique combination allows for the removal of climate change effects on the stable isotope data, and therefore improves the accuracy of paleoelevation reconstructions.

Results from our ongoing Phase II project (spring 2021 - spring 2024):

1. Reveal that diachronous surface uplift would produce patterns of climate, $\delta^{18}O$ in precipitation values, and isotopic lapse rates that are distinctly different from those of today and those produced by bulk surface uplift scenarios. Importantly, this signal would be detectable in stable isotope paleoaltimetry results (Boateng et al., in revision).
2. Present a Miocene (23–13 Ma) continental paleotemperature record from the northern Mediterranean region (Digne-Valensole basin, SE France), which indicates near-constant temperatures from 23.0-18.8 Ma, followed by a highly variable and warm climate during the Middle Miocene and rapid cooling after 14 Ma (Ballian et al., 2023).
3. Together with new and existing paleotemperature records, preliminary results of the δ-δ method show for the first time that (a) the Central Alps were already high during the Early Miocene and (b) the Eastern Alps were appreciably lower than the Central Alps during the Middle Miocene (Ballian et al., 2022).

Phase 2 publications:

Ballian et al., 2022, EGU General Assembly, doi:10.5194/egusphere-egu22-2346

Ballian et al., 2023, EGU General Assembly, doi:0.5194/egusphere-egu23-14517

Boateng et al., in revision, Earth System Dynamics discussions, doi:10.5194/esd-2022-48

Subduction and continental collision in the Eastern Mediterranean during the closure of the Tethyan gateway

Thorsten W. Becker[1,2], Eivind O. Straume[3], Claudio Faccenna[4,5], Bernhard Steinberger[4], Andrea Sembroni[5], Zohar Gvirtzman[6,7]

1. UTIG & EPS, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX, USA
2. Oden Institute for Computational Engineering & Sciences, The University of Texas at Austin, Austin, TX, USA
3. NORCE Norwegian Research Centre, Bergen, Norway.
4. GFZ German Research Center for Geosciences, Potsdam, Germany
5. University of Roma TRE, Italy
6. Geological Survey of Israel, Yesha'yahu Leibowitz 32, Jerusalem, Israel
7. Institute of Earth Sciences, The Hebrew University of Jerusalem, Jerusalem, Israel

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Plate tectonics and mantle dynamics controlled the continental collision and tectonics of the Eastern Mediterranean – Tethyan realm, including by closing the Tethys Seaway linking the Atlantic and Indo-Pacific oceans. This led to reorganizations in ocean circulation, diversification and migration of marine and terrestrial species, and climatic change. Here, I review some of the work on the geodynamics of the region, including on the evolution of topography, and how paleotopography was influenced by mantle convection and volcanism. Mantle convection appears to have had a significant impact on the paleoenvironment, including by ultimately establishing the Gomphotherium Landbridge in the Miocene, enabling greater faunal exchanges between Africa-Arabia and Eurasia.

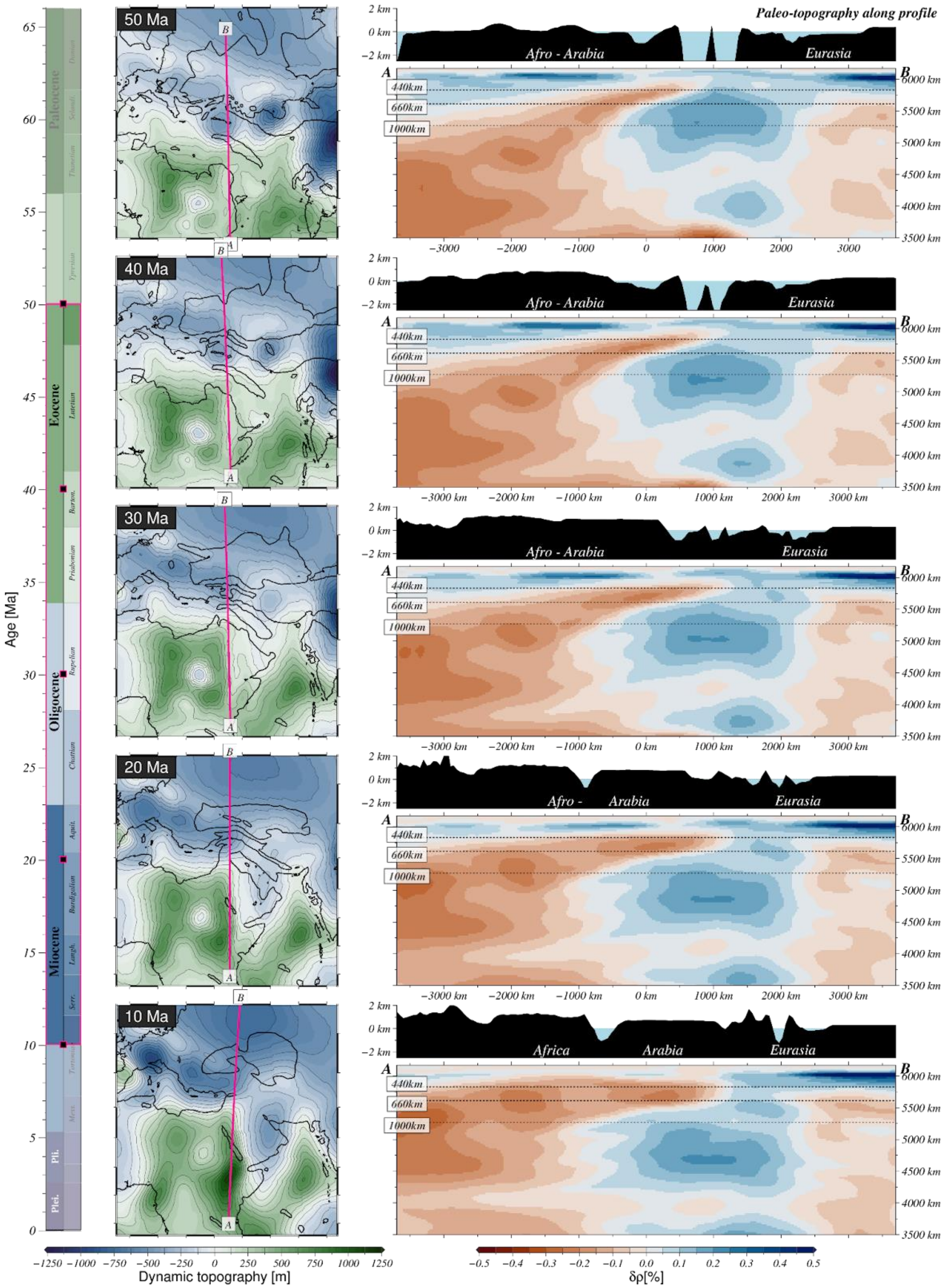

Figure 1: Paleo-dynamic topography, paleotopography, and mantle cross sections. | The maps on the left show paleo-dynamic topography computed by Straume et al. (2023) using TX2019 (Lu et al., 2019) seismic tomography. The right panels show the paleotopography and mantle density structure along the profiles colored pink in the maps on the left. Profiles are moving with the mantle in the paleomagnetic reference frame of Torsvik et al. (2019).

Synergistic effects of diachronous surface uplift and global climate change on the isotopic composition of meteoric waters: implications on paleoelevation estimates across the European Alps

Daniel Boateng[1], Sebastian G. Mutz[1,6], Armelle Ballian[2,3], Maud J. M. Meijers[4], Katharina Methner[5], Andreas Mulch[2,3], Todd A. Ehlers[1,6]

1. Department of Geosciences, University of Tübingen, Germany
2. Senckenberg Biodiversity and Climate Research Centre, Germany
3. Institute of Geosciences, Goethe University Frankfurt, Germany
4. Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Austria
5. Department of Geophysics and Geology, University of Leipzig, Germany
6. School of Geographical and Earth Sciences, University of Glasgow, UK

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Stable isotope paleoaltimetry is widely used to infer past elevations of orogens due to the robust systematic inverse relationships between elevation and oxygen ($\delta^{18}O$) and hydrogen (δD) isotopic composition of meteoric waters recorded in geologic archives, such as paleosol carbonates or hydrous silicates. This $\delta^{18}O$-elevation relationship (or isotopic lapse rate) is commonly attributed to the preferential rainout of heavy water isotopologues from air masses ascending over topography. However, numerous non-linear climatic processes, such as surface recycling, vapor mixing, variability in moisture source, and precipitation dynamics, can also influence the isotopic lapse rate and thus complicate stable isotope paleoaltimetry estimates. This highlights the need for a better quantitative understanding of topographic and regional climatic effects on the isotopic composition of ancient waters. Through topographic sensitivity experiments, Boateng et al. (2023) suggested plausible changes in isotopic lapse rates across the Alps in response to different diachronous surface uplift scenarios and validated that the expected isotopic signal difference due to elevation changes is significant enough to be reflected in geologic archives.

Recent paleoelevation reconstructions across the Alps estimate the mean elevation of >4000 m in the Central Alps during the Middle Miocene (Krsnik et al., 2021). These high elevation estimates have been attributed to the complicated transition from pre- to mid-Miocene Central Alps with a diverse landscape and a complex topography, mainly driven by the rapid exhumation of deep-seated core complexes, followed by a rearrangement of the drainage system. However, the paleoelevation estimate is based on the assumptions that the isotopic lapse rate (1) is similar to the modern lapse rate (~2.0 ‰/km), which is lower than the global average, (2) did not change during the deposition of the paleoaltimetry proxies compared to the present day, and (3) remained constant across the entire Alps.

Here, we use a high-resolution isotope-tracking ECHAM5-wiso General Circulation Model to simulate the Middle Miocene climate and $\delta^{18}O_p$ responses to different surface uplift scenarios of the Alps. More specifically, we performed topographic sensitivity experiments by varying the height of the Western/Central Alps and Eastern Alps under two atmospheric CO_2 concentration scenarios for Middle Miocene paleoenvironmental conditions. The simulated $\delta^{18}O_p$ values are consistent with the proxy reconstructions across the low- and high-elevation sites in the Alps. The topographic scenarios indicated $\delta^{18}O_p$ values differences of up to -10 ‰ between the low- and high-elevation sites, primarily due to changes in orographic precipitation and local near-surface temperature. Even though the differences across the low-elevation sites showed minor changes compared to the present-day climate, the high-elevation sites indicated significant changes mainly due to differences in moisture transport and moisture redistribution. These changes resulted in different isotopic lapse rates across the different transects around the Alps, contradicting the assumption of a regionally similar isotopic lapse rate.

Using the simulated Middle Miocene isotopic lapse rates with the reconstructed $\Delta\delta^{18}O_p$ signal between the low-elevation Northern Alpine Foreland Basin and high-elevation Simplon fault gouge reveals an overestimation of paleoelevation estimates by 2 km when compared to the constant isotopic lapse rate of -2.0 ‰/km across the Alps. These uncertainty estimates are an improvement of the previous paleoelevation reconstruction across the Alps and support the integration of paleoaltimetry and paleoclimate modelling to reconstruct past surface elevations accurately.

What AlpArray tells us about stress and water resources under the Alpine Region

G. Bokelmann[1], Y. Lu[1], Y. Aiman[1], R. Kramer[1]

1. University of Vienna, Austria

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The seismological AlpArray has shed much light on Earth`s structure and earthquakes in the Alpine region. Beside these two classical seismological applications ("events" and "structure"), a dataset of this kind can also be used for other purposes, and the geophysics group at the University of Vienna has been interested in extending the range of applications also into non-classical domains over the last years.

The data have helped us understand non-tectonic phenomena that generate seismic waves in the region, both of natural (such as water, wind, rockfalls, etc.), and of human origin (such as explosions, fires, trains, etc.). This has also extended the use of seismic data across the Earth`s surface, using seismic wave coupling with infrasound.

In this presentation, we focus on new applications of seismic data that extend the "structural" portfolio of seismological techniques, based on nonlinear elasticity (temporal velocity changes). "Pump-probe" approaches use a known test signal to infer subsurface properties. One such test signal is given by tidal stress, which we use as "pump" and ambient noise as "probe", to infer the orientation of mechanical stress acting at crustal depth throughout the Alpine region. This complements the World Stress Map in regions, where we have previously not had stress data - allowing us, for example, to understand why certain major faults in the Eastern Alps (the Periadriatic Line and the Giudicarie Fault) do not rupture seismically, different from less mature, but more favorably-oriented faults.

A particularly promising new application of seismic waves is the study of water in the shallow subsurface, which affects seismic wave velocities. We show that seismic waves can be used to constrain the hydraulic properties of ground water reservoirs from seismic data. Ground water level is often sensitive to air-pressure variations, and we can use the latter as "pump" to explore ground water reservoir characteristics throughout the Alpine region. The large regional variation in observed admissivity throughout Central Europe indicates the effects of thermally-related and air-pressure-related influences.

The study of seismological AlpArray data shows that also changes of soil moisture can be made visible by seismic imaging. Such variations occur periodically, but there are also important long-term trends, which show different characteristics in different regions. Seismic data can fill the observational gap in soil moisture, in a wide range of distances, and importantly, in the depth range that is relevant for plant growth. This shows that seismology can give rather useful constraints for understanding the consequences of climate change.

A comprehensive high resolution 3D P- and S-wave velocity model for the Alpine mountain chain using local earthquake data: Constraining crustal structure, lithologies and mountain-building processes

Benedikt Braszus[1], Andreas Rietbrock[1], Christian Haberland[2], Trond Ryberg[2]

1. Karlsruhe Institute of Technology, Geophysical Institute, Karlsruhe, Germany
2. GFZ German Research Centre for Geosciences, Potsdam, Germany

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Based on the unprecedented amount of densly recorded seismic waveform data and recent advances in machine learning techniques the main objective of this project was the computation of a comprehensive high resolution 3D P- and S-wave velocity model for the Alpine region including station correction terms. Additionally, event locations and associated uncertainties as well as the automatically determined seismic arrival times should be published. The 3D crustal model delivers travel time correction terms for teleseimic tomography studies and thus sharpen the image of subducted slabs in the upper mantle.

We used "SeisBench - A toolbox for machine learning in seismology" to assess the performance of several deep-neural-network based seismic picking algorithms and find PhaseNet to be most suitable. In order to consistently remove outliers from the P- and S- phase pick catalog we developed a purely data-driven pre-inversion pick selection method. We relocated a subset of 384 events while simultaneously inverting for the 1D P- & S-wave velocity structure including station corrections using the established VELEST as well as the recently developed McMC algorithms. This model yields the first consistent travel time based 1D S-wave model of the Greater Alpine region facilitating computation of synthetic travel times and the inclusion of S-phases during the localization process.

Furthermore, it yields the starting model for the final 3D velocity model which is based on records from more than 3000 events on more than 1100 seismic broadband stations. Comparing our hypocentres with event locations from other studies indicates a horizontal and vertical accuracy of ~2km and ~6km, respectively, when using a 1D velocity model and station correction terms for the Greater Alpine region.

Large scale features of the resulting velocity model are in good agreement with previous studies. The Molasse and Po basin in the northern and southern foreland, respectively, are showing up as prominent low velocity zones in the uppermost crust. Generally, the velocity isolines in the lower crust are in rather good agreement with Moho maps from previous studies and ambient noise tomographies.

Combining low-temperature thermochronology with 3-D probabilistic kinematic modeling including uncertainties in the Eastern Alps

Sofia Brisson[1,2], Josefine Ziegler[2], Christoph von Hagke[1], Florian Wellmann[2]

1. Department of Environment and Biodiversity, Paris Lodron University Salzburg, Austria
2. Department of Computational Geoscience, Geothermal, and Reservoir Geophysics, RWTH Aachen University, Germany

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To understand the exhumation history of the Alps and its foreland, it is important to accurately reconstruct its time-temperature evolution. This is often done employing thermokinematic models. However, one problem of many current approaches is that they rely on prescribed geometric structures at depth without considering their uncertainty.

Therefore, the aim of this work is to compare low-temperature thermochronological data with a 3-D probabilistic kinematic model. To this end, we combine 3-D kinematic forward modeling with a systematic random sampling approach to automatically generate an ensemble of kinematic models in the range of assigned uncertainties. These can later be used to obtain a 3-D probabilistic exhumation map, from which exhumation values for the sample positions of thermochronological data can be interpolated, and compared to estimates made solely from thermochronology. In a next step, the uncertainties assigned to the kinematic model can be updated with the thermochronological data, to obtain an even more robust model.

We apply this approach to the Bavarian Subalpine Molasse, which is particularly suited as a test case, as it connects the Alpine orogen with its foreland, and should shed light on the strain distributions during the latest stages of Alpine mountain building.

Preliminary results using previously published data show that the estimated exhumation from the modeling can serve as a constraint to thermochronological interpretations, leading to an uncertainty reduction. In a next step, we will use our own (U-Th)/He measurements to obtain an integrated picture of foreland evolution and associated uncertainties over space and time.

Deformation in the Greiner Shear Zone – Pfitsch Valley, Southwestern Tauern Window

Bryce Carr[1], Gregor Facius[1], Rüdiger Kilian[1], Hannah Pomella[2], Thorsten Nagel[3], Michael Stipp[1]

1. Institute for Geosciences & Geography, Martin-Luther-Universität Halle-Wittenberg, Germany
2. Institute for Geology, Leopold-Franzens-Universität Innsbruck, Austria
3. Institute for Geology, TU Bergakademie Freiberg, Germany

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The Greiner Shear Zone is located within the Subpenninic core of the southwestern Tauern Window, Eastern Alps. It strikes SW-NE and separates the upright folded Zillertaler and Tuxer Zentralgneis Nappes from one another, whilst transecting their parautochthonous cover and allochthonous hanging-wall units. The Greiner Shear Zone is generally regarded as a transpressive shear zone, composed of multiple high strain zone splays, in which dextral, but dominantly sinistral shear sense indicators have been reported (Behrmann & Frisch 1990; Barnes et al. 2004). Deformation in the Greiner Shear Zone is pervasive and characterized by a sub-vertical foliation and west-southwest plunging lineation. However, the tectono-metamorphic history of the Greiner Shear Zone has not yet been fully clarified. To better constrain the structural architecture, kinematics, relative timing and spatial extent of the Greiner Shear Zone, geologic mapping within the Pfitsch Valley was carried out and structural data were collected. Optical and scanning electron microscopy analyses including EBSD were utilized to characterize the microstructure of deformed Furtschagl Schists incorporated within the shear zone. Deformed, inter-tectonic(ally grown) biotite porphyroblasts were characterized to ascertain the finite deformation history, as well as conduct a Schmid Factor analysis for (001)-slip of biotite grains, which is indicative of post-growth kinematics. Crystallographic dispersion axes of quartz grains were used to derive a vorticity axes distribution to better constrain the kinematics of the late Greiner Shear Zone. Furthermore, thermodynamic modelling using Theriak Domino was conducted to constrain the metamorphic evolution for shear zone samples stemming from the Furtschagl Schists, Venediger Nappe and Glockner Nappe.

Geologic mapping resulted in a new geologic map of the study area, and three cross-sections constructed perpendicular to strike of the Greiner Shear Zone of the Pfitsch Valley section. Unoriented biotite grains in the Furtschagl Schist are interpreted to have grown a) over a pre-existing foliation and b) prior to the (late) Greiner Shear Zone activity, the latter resulting in a co-planar fabric with a rather minute overprint of the pre-existing deformation fabric. Schmid Factor analysis on those biotites indicates a sub-horizontal to N-plunging, N-S directed compression direction which resulted in sinistral shearing at the time deformation was ceasing. Results of the crystallographic dispersion axis analyses suggest shallow NE to E plunging axes on a shallow N- to steep NW-dipping flow plane, respectively. Based on the petrological investigations and thermodynamic modelling, a clockwise pT-path from blueschist facies to amphibolite facies conditions of approx. ~570°C and 6.8-7.5 kb could be derived for the Furtschagl Schists of the Venediger Nappe. Peak amphibolite facies conditions occur at the transition from early, syn-kinematic Greiner shearing to an inter-tectonic phase (Tauern Crystallization) as indicated by garnet and biotite growth.

Therefore, post-Tauern Crystallization deformation of the Greiner Shear Zone within the Furtschagl Schists is the result of general shear dominated transpression at amphibolite facies metamorphic conditions, linked to sinistral strike-slip kinematics, which were active during N-S directed compression. The shear zone is further interpreted to exhibit a heterogenous monoclinic deformation symmetry, which is likely the result of an interconnected, anastomosing shear zone network.

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Pseudotachylites along the Pustertal-Gailtal-Line, eastern Periadriatic Fault system, Austria

Muriel Bülhoff[1], Erick Prince[1], Christoph Grützner[1] and Kamil Ustaszewski[1]

1. Institute of Geosciences, Friedrich-Schiller-University Jena, Burgweg 11, 07749, Jena, Germany

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The Pustertal-Gailtal Line (PGL) belongs to the dextrally transpressive Periadriatic Fault system and forms the border between Southern and Eastern Alps. Although part of the ongoing convergence between Adria and Europe appears to be accommodated by this fault system, it reveals little instrumental and historical seismicity. In our study, we attempted to find evidence for past seismic activity along the PGL by investigating pseudotachylite occurrences. We investigated an area of c. 19 km^2 to either sides of the PGL around Maria Luggau (Austria). We identified cataclasites and fault gouges along the fault core zone, from which we investigated only the cohesive rocks. Cataclastic, foliated Oligocene granitoids as well as garnet-mica schists of the Austroalpine basement are crosscut by cm- to dm-scale veins containing black fault rocks, which were sampled for further analyses (Fig. 1).

Polarisation microscopy reveals that the vein-forming black fault rocks are often optically isotropic, testifying to their origin as quenched melts. Sharp margins of mm- to cm-sized injection veins against the surrounding host rock, well-rounded quartz and feldspar clasts, the absence of hydrous minerals in the matrix, as well as spherulites are further hints at a seismogenic origin of the studied fabrics. Some of the optically isotropic veins are internally foliated; their *in-situ* µ-XRF analysis of major element concentrations revealed chemical composition variations in the foliation. Even if this foliation might suggest overprinting by aseismic creep, our observations indicate a seismogenic origin of the studied fabrics as pseudotachylites.

Figure 1: Pseudotachylite veins ('Pt') crosscutting paragneiss of the Austroalpine basement along the Pustertal-Gailtal Line (locality: Maria-Luggau, Lesachtal, Austria).

Investigations of the Oligocene-Miocene opening of the Ligurian Basin using amphibious refraction seismic data

A. Dannowski[1], H. Kopp[1,2], I. Grevemeyer[1], D. Lange[1], M. Thorwart[2], G. Caielli[3], R. de Franco[3], and MSM71 cruise participants

1. GEOMAR, Marine Geodynamics, Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
2. Institute of Geosciences, Kiel University, Kiel, Germany
3. IDPA-CNR, Istituto per la dinamica dei processi ambientali, Sezione di Milano, Italy

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The Ligurian Basin is located north-west of Corsica at the transition from the western Alpine orogen to the Apennine system. The Back-arc basin was generated by the southeast trench retreat of the Apennines-Calabrian-Maghrebides subduction zone. The opening took place from late Oligocene to Miocene. While the extension led to extreme continental thinning and un-roofing of mantle material little is known about the style of back-arc rifting.

To shed light on the present day crustal and lithospheric architecture of the Ligurian Basin, active seismic data have been recorded on short period ocean bottom seismometers in the framework of SPP2017 4D-MB, the German component of AlpArray. Two refraction seismic profiles were shot across and along the centre of the Ligurian Basin. P01 was shot in an E-W direction from the Gulf of Lion to Corsica. The profile extends onshore Corsica to image the necking zone of continental thinning. P02 is a transect along the basin in NE-SW direction extending a previous shot seismic profile reaching to the Italian cost near Genua. The majority of the ocean bottom seismometer data show sedimentary and crustal phases of good quality and weaker in amplitude mantle phases to offsets up to 70 km. The arrivals of seismic phases were picked and inverted in a travel time tomography.

The results for p01 show a crust-mantle boundary in the central basin at ~12 km depth below sea surface. The crust-mantle boundary deepens from ~12 km to ~18 km within 25 - 30 km towards Corsica. The results do not map an axial valley as expected for oceanic spreading. However, an extremely thinned continental crust indicates a long-lasting rifting process that possibly did not initiate oceanic spreading before the opening of the Ligurian Basin stopped. This is in good agreement with recent kinematic modelling performed in the second phase of the SPP2017 4D-MB. The modelling results of p01 indicate that continental crust can be stretched over several million years when the opening rate is low, i.e. <2 mm/year, and syn-rift sedimentation rate is high. Subduction initiation could occur in ultra-thinned continental crust as basin inversion has been observed at the northern Ligurian margin as a result of the African-European convergence. Additionally, the observations from the Ligurian Basin might be transferred to the evolution of the Piemont-Liguro Ocean. So far oceanic crust was assumed as initial conditions for the subduction of the Piemont-Liguro Ocean. An ultra-thin continental crust as initial condition would explain the observed thin subducted Piemont-Liguro plate which seemed to be thinner than 6-7 km oceanic crust. Further, a dry continental crust could explain why no back-arc volcanism was observed. The along-basin profile p02 shows a deepening crust-mantle boundary from 11 to 13 km. Based on the retrieved velocity model, gravity modelling and further results from surrounding studies we conclude that the continental crust is thinning from the northeast to the southwest which is related to the increase of extension away from the rotation pole of the anticlockwise rotation of the Corsica-Sardinia block. It remains unclear if at the southern end of the profile the mantle is overlain directly by sediments or by extremely thinned continental crust of up to 2.5 km thickness. The results however document, that seafloor spreading and the formation of mantle-derived oceanic crust was not initiated during the extension of the Ligurian Basin.

Surface Responses to Subducting Slab Detachment in Small Convergent Mountain Ranges

Paul R. Eizenhöfer[1]

1. School of Geographical & Earth Sciences, University of Glasgow, UK

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Alpine-type mountain ranges emerge from the collision of two continental plates. During the collision the subducting plate descends into the mantle. Given favourable thermo-physical conditions and time, the lower end of the subducting plate detaches from its upper section causing a dynamic surface uplift response over a geologically brief time period. This study investigates how, and if, such a process can be detected solely from the geomorphological record. Furthermore, it aims to identify minimum surface uplift conditions that would favour such observation in nature. The experimental set-up links typical kinematics for the lateral growth of a doubly-vergent orogens over 15 Myr with a surface processes model. This includes isostatic responses to erosion as well as buoyancy effects caused by crustal thickening. Two fundamental slab dynamics scenarios have been tested: the first scenario subjected the evolving orogen to a single surface uplift event representative of a slab break-off (Fig. 1). The orogen responds by immediate increases in mean elevation by ~10%, erosion rates by more than 10%, and river steepness by ~5% assuming a parabolic surface uplift of 1 mm/yr over 1 Myr across-strike the orogen. Notably, the orogen undergoes a prolonged decay period over ~1 Myr to reach conditions prior to the surface uplift event. The second scenario assumes an along-strike propagating surface uplift representing a slab tearing event. Geomorphological responses are similar to the first scenario but restricted to the location of highest surface uplift in space and time causing an asymmetric response along-strike the orogen. Both scenarios induce a two-step inversion of the foreland basins: firstly, as a result of the surface uplift event itself, and secondly, followed by the isostatic response to erosional unloading during the prolonged landscape decay. Hence, the study argues that the identification of geologically short-lived surface uplift events in Alpine-type orogens, caused, for example, by break-off or tearing of the subducting slab, require the observation of a coeval increase in erosion, local relief, river steepness and the inversion of the foreland basins during phases of surface uplift and erosional unloading.

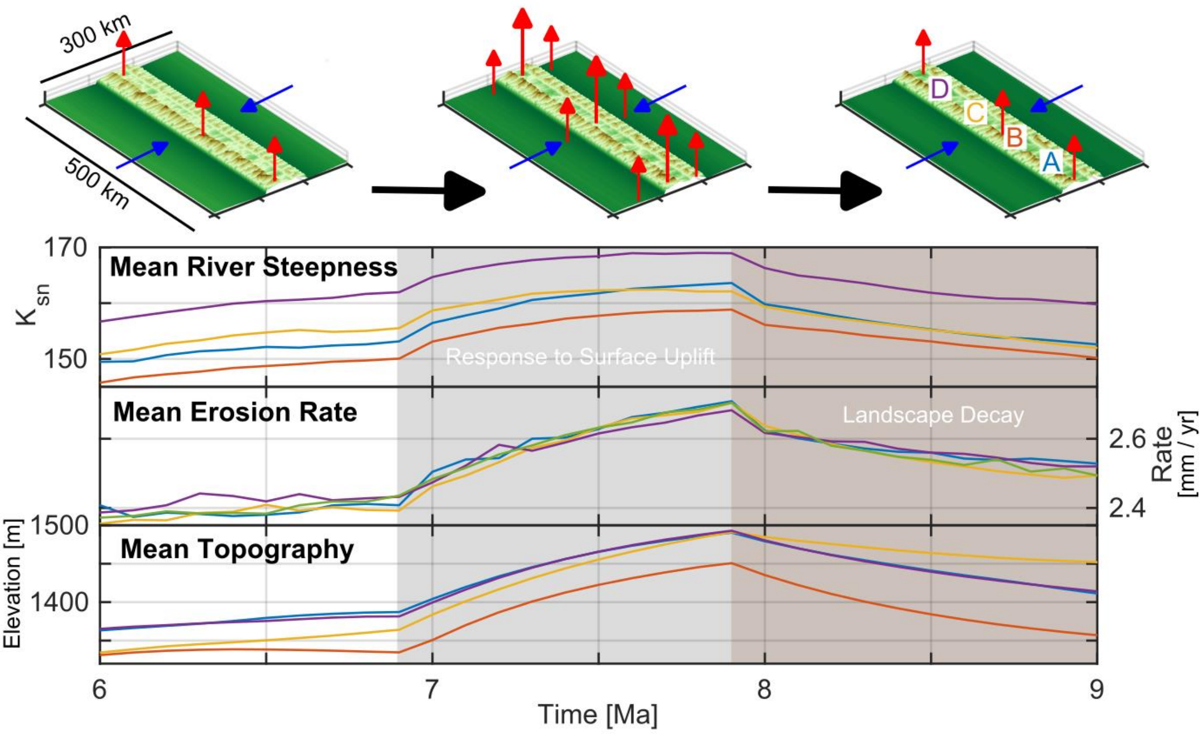

Figure 1: Geomorphological responses in an active Alpine-type doubly-vergent orogen to a symmetric, 1 Myr surface uplift event at 6.9-7.9 Ma at a rate of 1 mm/yr. (Top) Surface processes model output pre-, syn- and post-surface uplift. Blue and red arrows represent imposed tectonic convergence and surface uplift. (Bottom) Temporal evolution of river steepness, erosion rate and topography in colour-coded patches A to D. Note the immediate response to the surface uplift event in contrast to the prolonged landscape decay (~1 Myr) back to levels prior to the event.

Constraining the near-surface response to lithospheric reorientation: Structural thermochronology along AlpArray geophysical transects

Paul R. Eizenhöfer[1,2], Christoph Glotzbach[1], Jonas Kley[3], Todd A. Ehlers[1,2]

1. Department of Geosciences, Universität Tübingen, Germany
2. Now at School of Geographical & Earth Sciences, University of Glasgow, UK
3. Geoscience Centre, Universität Göttingen, Germany

DOI: http://dx.doi.org/10.17169/refubium-40998

The shape of the present-day European Alps results from a complex tectonic and climatic history since the onset of convergence between the African and Eurasian plates. Low-temperature thermochronology data are a unique archive that can trace the cooling history of rocks back in time during exhumation from upper to middle crustal levels to Earth's surface. However, the precise mechanisms that led to cooling and exhumation are still debated. In this study, we investigated the potential for mantle processes, such as potential subducting slab break-off or slab reversal, to leave a fingerprint in the rock cooling record of the present-day surface along three key, north-south oriented geophysical transects: NFP-20E, TRANSALP and EASI. Along all transects, our zircon and apatite (U-Th)/He data reveal reset Neogene (and younger) cooling ages centred around core complexes such as the Lepontine Dome and the Tauern Window indicative of late exhumation during the Cenozoic Alpine orogeny. North and south of these complexes, the cooling ages become older, forming U-shaped age distributions around the reset centres. Thermal history reconstructions along TRANSALP confirm a conspicuous southward shift of cooling towards the Southern Alps approximately at the time of deep-seated exhumation of the Tauern Window driven by motion along the mid-crustal Tauern Ramp in the Mid-Miocene. Thermo-kinematic models along the transect confirm this southward shift of deformation and (i) reproduce the distribution of cooling ages and thermal history reconstructions, (ii) are consistent with the present-day structural geometry along the transect, (iii) and the observed surface heat flux. It is possible that rock cooling is primarily driven by rock displacement along active faults and less by climatic and/or mantle buoyancy forces, which are both not included in the applied modelling approach. Our comprehensive thermochronological analyses allow two interpretations concerning mantle processes: (i) Assuming a strong coupling between the subducting and overriding plate, hence, the applicability of doubly-vergent orogen kinematics, then the thermochronological data are most consistent with an ongoing reversal in continental subduction polarity. (ii) A high degree of decoupling would negate the possibility that mantle processes are archived in the thermochronological record.

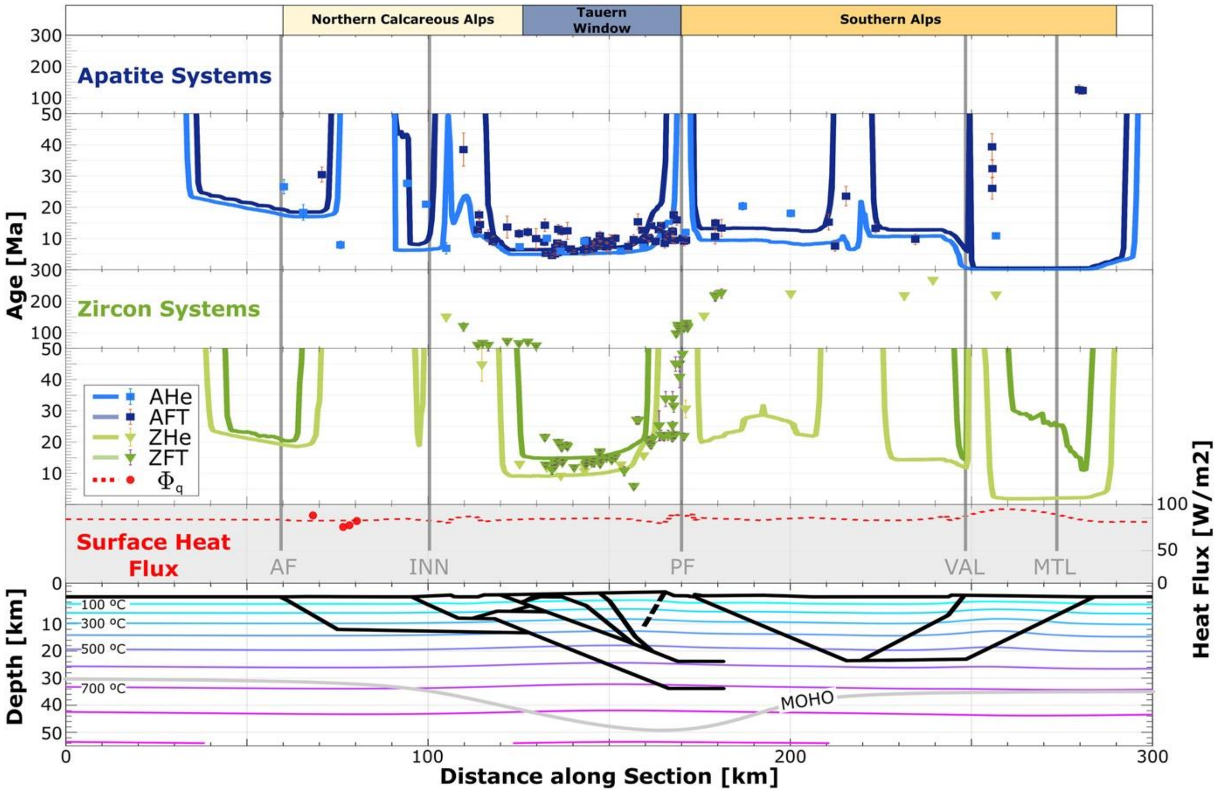

Figure 1: Forward thermo-kinematic model along the TRANSALP transect (Eizenhöfer et al., 2023). Predicted and measured present-day thermochronologic ages (solid lines and data points, respectively) for the apatite (AHe, AFT) and zircon (ZHe, ZFT) systems are shown in the top two panels (see also Eizenhöfer et al., 2021), predicted and observed heat flux in the third (dashed line and data points, respectively), shaded panel, the modeled thermal field based on an updated structural-kinematic reconstruction including modeled MOHO and tapered model topography on the bottom panel (no vertical exaggeration). AHe and ZHe, apatite and zircon (U-Th)/He; AFT and ZFT, apatite and zircon fission-track; Φq, heat flux [W/m2]. AT, Alpine Frontal Thrust; INN, Inntal fault; PF, Periadriatic Fault; VAL, Valsugana/Belluno thrust system; MTL, Montello thrust system.

Eizenhöfer, P. R., Glotzbach, C., Büttner, L., Kley, J., & Ehlers, T. A. (2021). Turning the orogenic switch: Slab-reversal in the Eastern Alps recorded by low-temperature thermochronology. Geophysical Research Letters, 48, e2020GL092121. https://doi.org/10.1029/2020GL092121.

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Identifying Main Lithospheric Structures in the Eastern Alpine Domain by Joint Inversion of Receiver Function and Surface Wave Measurements for Seismic Anisotropy

Amr El-Sharkawy[1], Mate Timko[1], Xiaohui Yuan[2], PIs: Thomas Meier[1], Georg Rümpker[3], Rainer Kind[2,4], Mark Handy[4]

1. CAU Kiel, Germany
2. GeoForschungsZentrum Potsdam, Germany
3. University of Frankfurt, Germany
4. Freie Universität Berlin, Germany

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Rayleigh-wave phase velocity measurements from both earthquakes and ambient noise were combined to image the 3-D shear-wave velocity structure beneath the eastern Alps and in the transitions towards the Pannonian Basin and the Dinarides. This allows us to resolve crust and upper mantle structures down to 300 km including the Moho topography. Continuous waveforms were collected from 1254 stations within a 9° radius for the time period from 2006 to 2018. More than 164,464 inter-station Rayleigh wave phase-velocity curves were automatically extracted after applying a strict quality control. Using the combined dataset, a period and distance dependence correction was applied to account for the bias observed between phase velocities from both datasets that amounts to ~1 % and increases towards longer periods. 2-D anisotropic phase velocity maps were then constructed spanning periods from 5 s to 250 s. 33,981 local dispersion curves were extracted and inverted for a 3-D shear-wave velocity model (PanREA2023) encompassing crust and mantle using a non-linear stochastic particle swarm optimization.

At shallower crustal depths, the horst and graben structure of the Pannonian Basin is imaged, characterized by two NE-SW trending horsts and three graben systems. A pronounced crustal low-velocity anomaly extending to the Moho is found beneath the surrounding Carpathian orogen. A shallow south-dipping Eurasian slab was imaged beneath the eastern Alps down to only 150 km depth. Adriatic lithosphere is near-vertically dipping beneath the northern Apennines and northern Dinarides. The Adriatic slab is short reaching depths of around 150 km.

Seismic discontinuities down to the mantle transition zone are analysed using S-to-P converted phases from teleseismic earthquakes. We stack broadband teleseismic S waveform data to retrieve S-to-P converted signals from below the seismic stations. In order to avoid processing artefacts, no deconvolution or filtering is applied. The Moho signals are always seen very clearly. In addition, a negative velocity gradient below the Moho depth is evident in many regions. A Moho depression is visible along larger parts of the Alpine chain reaching its largest depth of 60 km beneath the Tauern Window. The Moho depression ends abruptly near about 13°E below the eastern Tauern Window. East of 13°E the Moho shallows all the way to the Pannonian Basin. A prominent along-strike change was also detected in the upper mantle structure at about 14°E. There, the lateral disappearance of a zone of negative S-wave velocity gradient in the uppermost mantle is interpreted to indicate that the S-dipping European slab laterally terminates east of the Tauern Window.

Joint inversion of surface wave dispersion curves and Moho travel times inferred from S-to-P converted phases allows to determine shear-wave velocity models consistent with both measurements. The uncertainty of the Moho depth estimates decreases from about 5 to 10 km considerably to 2 to 5 km depending on the depth of the Moho. The joint inversion further enables the determination of the sharpness of the negative discontinuity associated with the lithosphere-asthenosphere boundary. It appears to be rather sharp in the northern Alpine foreland and the Pannonian Basin.

Signals of slab breakoff- and tearing in the stratigraphic architecture of a foreland basin

Lucas H.J. Eskens[1], Nevena Andrić-Tomašević[1], A. Piccolo[2], M. Thielmann[2], B. Claussmann[3], M. Lejri[4], Todd A. Ehlers[5]

1. Karlsruhe Institute of Technology, Institute of Applied Geosciences, Karlsruhe, Germany
2. Bayreuth Universität, BGI, Bayreuth, Germany
3. SLB UK, SLB Abingdon Technology Centre, Abingdon, UK
4. SLB Norway, SLB Norway Technology Center, Oslo, Norway
5. University of Glasgow, School of Geographical & Earth Sciences, Glasgow, UK

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A significant change in the architecture of peripheral pro-foreland basins observed in all natural examples is the flysch to molasse transition (i.e., shift from underfilled- to overfilled conditions). Forcing mechanisms for pro-foreland basin architecture include changes in sediment supply from the adjacent growing orogen and flexural subsidence in the basin. As these forcing mechanisms themselves are driven by orogenic processes in the adjacent mountain range, the flysch to molasse transition can be regarded as the sedimentary fingerprint of hinterland tectonics.

Slab breakoff of the foreland plate leading to isostatic rebound of both the pro-foreland basin and adjacent orogen (leading to increased sediment supply) has been suggested to be a driver of the flysch to molasse transition[1,2,3]. However, this cause-and-effect relationship between slab breakoff and the flysch to molasse transition is based on qualitative assessments. This raises the question whether other external forcings may have masked the contribution of slab breakoff to the flysch to molasse transition.

In this study we investigate the stratigraphic signal of slab breakoff in a pro-foreland basin. To quantitatively assess the relationship between slab breakoff and the flysch to molasse transition, we coupled 2D geodynamic models (GMs) of slab breakoff using LaMEM[4] with 2D forward stratigraphic modelling (FSM) using the GPM software (SLB). To better understand the influence of slab breakoff on pro-foreland basin architecture, we tested slab breakoff scenarios in our GMs for varying 1) slab bending angles and 2) slab necking durations (depending on slab rheology). To test whether the stratigraphic signal of slab breakoff may be masked by other external forcings, we introduced eustatic sea level changes (50 m amplitude with a 1 My period). From our FSMs we generated sediment thickness maps used to reconstruct sediment supply rates, grain size distribution- and facies maps and synthetic seismic data to compare with observed seismic data.

Our preliminary results indicate that vertical uplift due to isostatic rebound in the pro-foreland basin (1.5 – 7 cm/yr, where fast necking of steep slabs yields higher values) decreases the accommodation space, leading to a stratigraphically upward shallowing. Furthermore, isostatic rebound of the adjacent mountain range (2-5 cm/yr, same relationship with slab dynamics as pro-foreland basin) results in up to 2.5x increased rates of sediment supply with very little lag time, adding to the stratigraphically upward shallowing. The eustatic sea level changes do not mask the stratigraphic signal of slab breakoff. Lastly, the facies of the flysch to molasse transition in our synthetic seismics looks similar to that observed on seismics of the Austrian Molasse which occurred coeval with slab breakoff under the Eastern Alps[5].

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Constraining the geodynamic evolution of the Alps with sedimentary provenance and detrital thermochronometer data, II. Detrital thermochronology

Sarah Falkowski[1], Christoph Glotzbach[1], Laura Stutenbecker[2,3], Daniela Krieg[2], Ann-Kathrin Maier[1], and Todd A. Ehlers[1,4]

1. Department of Geosciences, University of Tübingen, Germany
2. Institute of Applied Geosciences, Technical University of Darmstadt, Germany
3. Institute for Geology and Palaeontology, University of Münster, Germany
4. School of Geographical and Earth Sciences, University of Glasgow, UK

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This project was designed to disentangle sedimentary signals controlled by changes in the lithosphere, the upper crust, and climate change in the European Alps. The hypothesis was that if lithospheric reorganisation in the Alps (such as slab break-off or tearing) occurred, it would lead to spatio-temporal changes in buoyancy, influencing the location of rock uplift and erosion. Specifically, we wanted to test this hypothesis using a multi-proxy provenance approach (sedimentary provenance tools, detrital thermochronology) at key stratigraphic time slices (28, 25, 20, 17, 15, and 12 Ma) from the northern and southern foreland basins. Foreland basin deposits represent a rich archive of erosional processes controlled by tectonics, climate, and lithology. This presentation concerns part II of the study, the detrital thermochronology, which we use as "tracer thermochronology".

Applications of tracer thermochronology exploit a known or assumed surface thermochronometric age map (based on either interpolated observed or modelled bedrock ages) to determine the provenance of detrital grains within fluvial or glacial catchments. The goal is to interpret the erosion pattern and processes within the sampled catchment. Before reconstructing and interpreting past erosion patterns and exhumation from detrital zircon fission-track (ZFT) age distributions and modelled bedrock ZFT ages back in time, we produce a frame of reference for today's situation. We do this by investigating signals from 26 modern river samples (21 previous [1,2] and nine new samples) and the present-day erosion pattern and mineral fertility in the Alps. We discuss observed and predicted (based on possible erosion scenarios) ZFT age distributions and potential pitfalls of the method (such as poor bedrock control in some areas of the Alps and challenges in combining previous and new data). Modern river results are consistent for adjacent, similar-size catchments and with expected erosion patterns. Most samples show a higher proportion of younger ZFT ages than would be predicted for uniform erosion and zircon fertility scenarios. Furthermore, we show preliminary results from stratigraphic sections from north and south of the Alps.

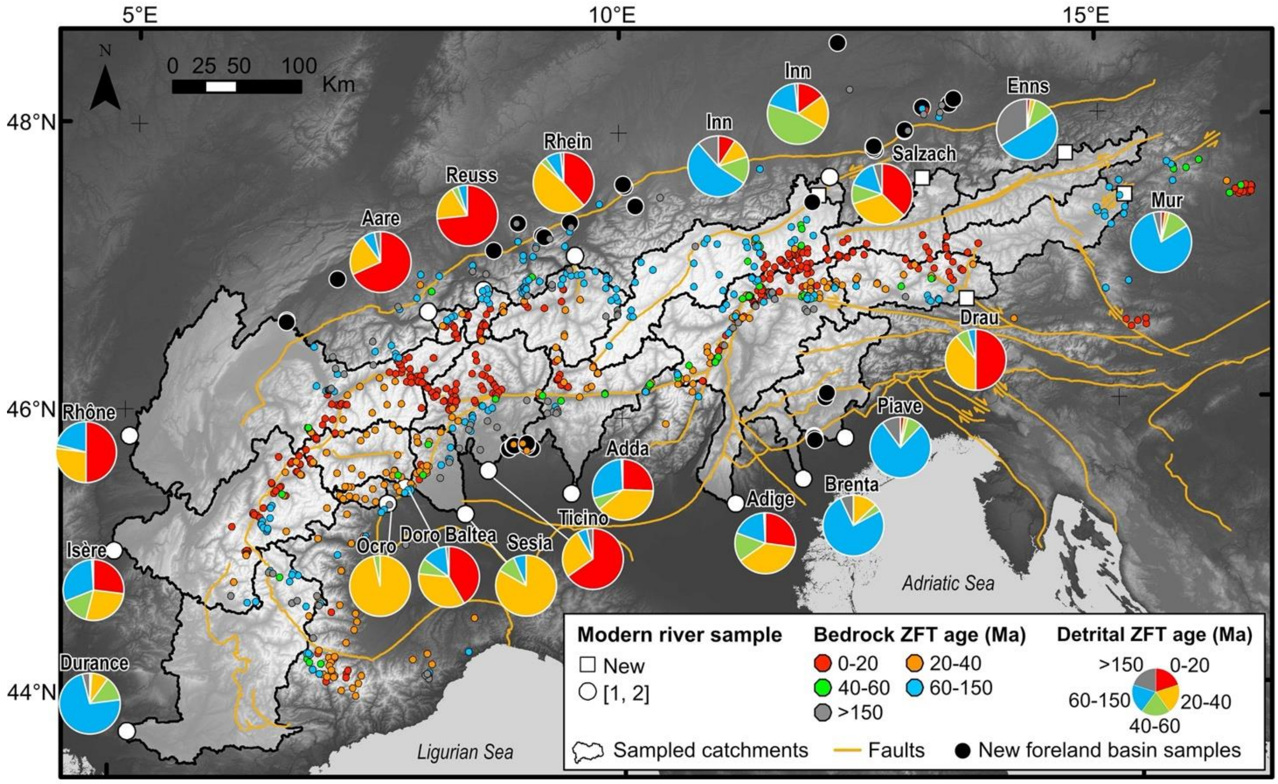

Figure 1: Overview of available bedrock ZFT ages (small circles) and previous and new modern river detrital ZFT data (pie charts, binned single-grain ages for visualisation; four additional samples are still being analysed) from the European Alps. Locations of new foreland basin samples are marked (black circles). Faults from [3].

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Recognizing salt-tectonics and the need for re-assessing strike-slip displacements in the Northern Calcareous Alps: Implications for lateral orogenic extrusion

Oscar Fernandez[1], Bernhard Grasemann[1]

5. Department of Geology, University of Vienna, Austria

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Salt tectonics has only been recently recognized as a significant element in the evolution of the Northern Calcareous Alps (NCA), along their entire length. Specific to the central NCA, a number of sedimentary growth wedges (implying Triassic salt-related syn-sedimentary deformation) and other evidence for Triassic salt tectonics have been recognized along two of the main Neogene strike-slip corridors of the central NCA: along the KLT (Königssee-Lammertal-Traunsee) fault and along the Ennstal segment of the SEMP (Salzach–Ennstal–Mariazell–Puchberg) fault. Similar features indicating Triassic salt tectonics have been documented along the Wolfgangsee corridor. Salt structures are typically characterized by the absence or condensation of stratigraphy above them. This explains why the Neogene strike-slip features are so consistently associated to the outcrop of "deep" (old) units of the NCA stratigraphy.

Recycling and tectonic of overprinting of zones of weakness is a usual feature, and it is therefore unsurprising that strike-slip of the NCA thrust sheets during Neogene lateral extrusion concentrated on previously existing salt structures. More surprising is the fact that, if Neogene strike-slip faults follow the trace of previous salt structures, this implies that the genesis of the rhomboidal map pattern of Neogene strike-slip corridors is actually inherited from a Triassic salt tectonics framework. This in turn implies that far from being a Neogene feature, the offsets of geological elements observed along the strike-slip corridors is, at least partially, Triassic in origin. An immediate conclusion is that estimates provided to date on the magnitudes of displacement for the central NCA Neogene strike-slip system require a revision. Likewise, the nature of the SEMP and its splays as purely Neogene structures (at least in their shallowest portion across the NCA stratigraphy) is questionable.

This contribution does not raise questions about the documented kinematics of the Neogene strike-slip system, which is solidly researched, but merely seeks to provide new insights that can help re-assess the actual role of strike-slip along the key strike-slip elements of the central NCA.

UNIBRA / DSEBRA – the German seismological contribution to AlpArray

Antje Schlömer[1], Wolfgang Friederich[2], Michael Korn[3], Thomas Meier[4], Georg Rümpker[5], Frederik Tilmann[6], Christine Thomas[7], Joachim Wassermann[1]

1. LMU München, Germany
2. Ruhr University Bochum, Germany
3. University of Leipzig, Germany
4. University of Kiel, Germany
5. Goethe University Frankfurt, Germany
6. GFZ Potsdam, Germany
7. Westfälische Wilhelms-Universität Münster, Germany

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UNIBRA was a joint initiative of German universities to install and maintain 74 seismic broadband stations at the beginning of the international AlpArray project in 2015 when the proposal for the 100 station broadband array DSEBRA was not yet approved by DFG. In this way, full participation of German teams in the AlpArray project could be secured. Most of these stations were deployed in southern Germany and a few in Austria. After approval in 2017 and installation of DSEBRA in 2018, the UNIBRA stations were replaced and further DSEBRA stations were deployed east of the SWATH-D array and also in Hungary. At that time, DSEBRA made up about one third of AlpArray's temporary stations. After deinstallation of SWATH-D in autumn 2019 DSEBRA stations were used to reoccupy some of SWATH_D's critical sites. In spring 2020, the Covid19 pandemic started in Europe and it became unfeasible to move the DSEBRA stations to new sites. Instead of deinstallation, DFG allowed us to use remaining investment funds to continue the operation of DSEBRA at the current sites. As collaboration partners from Austria, Czech Republic, Poland, Slovakia and Hungary had already relocated many of their AlpArray stations to new sites towards the north-east and east of the Alps before Covid19 started, DSEBRA became part of the PACASE deployment with 214 temporary stations operated by partners from these countries and University of Lausanne. In summer 2022, new funds from DFG could be acquired by RU Bochum and LMU München to move 42 DSEBRA stations to Greece and Northern Macedonia and further 19 stations to Albania, Kosovo and Montenegro as part of the new AdriaArray project. The remaining DSEBRA stations stayed in Austria and Hungary to form a major part of AdriaArray's backbone circling the Adriatic plate. With little exceptions, the DSEBRA stations have been in the field now without interruption for nearly 6 years. They massively contributed to the collection of a unique, large-scale and long-term seismological dataset which has enabled investigations into the structure of the crust and mantle beneath the greater Alpine area using receiver functions, shear-wave splitting, teleseismic body and surface wave tomography, local earthquake tomography and teleseismic full waveform inversion. Moreover, they allowed new insights into the seismic activity and hazard of active faults. DSEBRA will continue to do so in the framework of AdriaArray as part of an even larger seismic network comprising about 1300 permanent and temporary stations and doubling the size of AlpArray.

Noise at the DSEBRA stations on the vertical component stayed below the Peterson high noise model by 20 dB over the entire seismic frequency band. Noise on the horizontal components was partially higher, in particular at low frequencies below 1 Hz. Thanks to special measures to avoid failures of mobile communication and battery charging and efforts to keep the low-power data logger running as long as possible in case of power failures, data availability of the DSEBRA stations reached extremely high values of 98% to 100%. The data were archived and disseminated on the EIDA node at LMU München during the experiment and transferred to the GEOFON for long-term archiving.

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Eclogite dating and subduction zones in the Alps

Nikolaus Froitzheim[1], Matthias Hauke[1]

1. Institute of Geosciences, University of Bonn

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We applied Lu-Hf geochronology on eclogites from different tectonic units in the Penninic nappe stack of the Western Alps. Overall, older ages were found in structurally higher units of the nappe stack and younger ages in lower units, in accordance with a progression of subduction and accretion from originally more internal (SE) to external (NW) domains. The oldest age, 52,96 ± 0,91 Ma, was determined for Monte Emilius, a unit originally at the transition from the Cervinia Microcontinent (Sesia nappe) to the Zermatt-Saas Basin of the Piemont-Ligurian Ocean (Weber et al., 2021). Eclogites from the Zermatt-Saas Basin yielded ages of 49,79 ± 0,52 Ma (Champorcher), 47,98 ± 0,21 (Punta Nera), and 47,39 ± 0,34 Ma (Colle delle Finestre). A sample from the top of the Monte Rosa Nappe, a continental thrust sheet beneath the Zermatt-Saas Ophiolites, yielded 44,24 ± 0,83 Ma (Passo dei Salati).

A significantly youger age (36,09 ± 0,59 Ma) was determined for an eclogitic meta-andesite from the ultrahigh-pressure Dora-Maira Nappe (locality Parigi), a continental thrust sheet thought to be a lateral equivalent of the Monte Rosa Nappe. This age accords well with a U-Pb zircon age of 35.4 ± 1.0 Ma from the same area (Gebauer et al., 1997) and confirms that this nappe records the youngest subduction-related metamorphism of the Western Alps. The ca. 36 Ma old Parigi UHP rocks come from the structurally lowermost unit of the Dora-Maira Nappe, whereas the ca. 44 Ma old Passo dei Salati eclogite mentioned above comes from the top of the Monte Rosa nappe. Therefore, the age difference may again reflect progradation of subduction and accretion from SE to NW and from higher to deeper units. In the Central and Eastern Alps, the youngest eclogites, ca. 37 and ca. 33 Ma old, occur in the distal parts of the former European margin (Adula Nappe and Eclogite Zone in the Tauern Window, respectively). This supports the derivation of Dora-Maira from the European margin.

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Deformation during exhumation of Cretaceous high pressure units of the Eastern Alps

Niko Froitzheim[1], Ruth Keppler[1]

1. Institute for Geosciences, University of Bonn

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The Saualpe-Koralpe high pressure (HP) complex as well as the UHP units of the Pohorje mountains are part of the Eoalpine HP belt which extends over about 350 km from west to east. It formed in conjunction with the Cretaceous orogenic cycle in the Eastern Alps and comprises eclogite lenses in a matrix of gneisses. The protoliths of the eclogites are gabbros and basalts which were probably emplaced along a continental rift zone. Most recent studies suggest that subduction took place within the Adriatic continent along an intra-continental subduction zone which formed along the pre-existing weakness caused by the Permian rift.

The Saualpe/Koralpe and Pohorje units reached peak pressure conditions of 2.2-2.4 GPa/630-690°C, 1.8-1.9 GPa/670°C and 3.0–3.7 GPa/710–940 °C, respectively at 100-90 Ma. PT-analyses, microstructural investigations and dating allow different mechanisms for the exhumation of these units.

In this study a set of samples containing pristine and retrogressed eclogite, as well as neighboring gneiss was collected in both the Koralpe and Pohorje HP units and analyzed using electron backscatter diffraction at the transmission electron microscope of the Institute of Geosciences at the University of Cologne.

Omphacite in both pristine and retrogressed eclogite forms a weak foliation and shows a moderate to pronounced crystallographic preferred orientation (CPO). The CPO indicates plane strain to slightly prolate strain. Omphacite in the samples displays a shape preferred orientation (SPO) with infrequent subgrain formation and recrystallization. Hornblende deformation is strongly localized. In most areas hornblende forms symplectites with feldspar, however there are frequent amphibolite facies shear zones cross cutting the omphacite foliation. The shear zones mainly contain small, recrystallized hornblende grains with a strong SPO and only few porphyroclasts. Hornblende shows a pronounced CPO in all samples. It is aligned within the omphacite foliation in the symplectitic areas likely mimicking omphacite CPO and aligned in the shear plane within the shear zones. Here, the CPO pattern is variable indicating various strain conditions from constriction over plain strain to flattening.

Where quartz is present in the samples it generally shows a weak but distinct, asymmetric CPO indicating simple shear. In the samples from the Pohorje area, quartz CPO in the eclogites differs from that in the surrounding gneiss pointing to a different sense of shear.

In summary, our study shows distributed deformation at eclogite facies conditions becoming more localized during exhumation to amphibolite facies conditions as indicated by the formation of anastomosing, hornblende-rich shear zones. Latest stages of exhumation are recorded by the quartz CPO of matrix gneisses. The comparison of quartz CPO in the eclogites with that in the gneiss samples in Pohorje indicates a change of shear sense from top- West under amphibolite-facies conditions to a top- East at later stages of exhumation.

The various types of strain, from constriction to flattening, may either be explained by local heterogeneities, e.g. boudins, or by heterogeneous overall flow during exhumation.

Deriving the exhumation history of the Alps with thermochronological data

Christoph Glotzbach[1], Sarah Falkowski[1], Paul Eizenhöfer[1], Todd Ehlers[1,2]

1. Department of Geoscience, University of Tübingen, Germany
2. School of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK

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Thermochronology is a unique tool to derive the exhumation history of rocks over millions of years. Exhumation in orogens is largely controlled by tectonic structures that formed during convergence. Therefore, thermochronological data can be used to reconstruct the geodynamic evolution of mountain ranges and, more precisely, the activity of large fault systems. The Alps are one of the best-studied mountain ranges, with several thousands of low-temperature thermochronological samples dated with a variety of methods (e.g. Herrman et al. 2013; Fox et al. 2015). In this study, we review the most recent thermochronological literature to summarise the exhumation history of the Alps and discuss their driving forces.

The apatite (U-Th)/He system is sensitive to the most recent exhumation (closure temperature of ~60°C) and records in places the (over-)deepening and widening of valleys around the Alps (e.g., Valla et al. 2011; Glotzbach et al. 2011). The higher temperature systems, especially the ZFT system (closure temperature of ~240°C), reveal the location of deeper exhumation (>10 km) caused by large-scale fault activity (Fig. 1). While some parts of the Southern Alps and the northern part of the Western and Eastern Alps were not reset during the Alpine orogeny, most of the internal parts of the Alps reveal reset ZFT ages (Fig. 1). The timing of exhumation of these regions, however, varies significantly with distinct tectonic regions. The most recent ZFT ages are <15 Ma and located in the external crystalline massifs, the Lepontine Dome, and the Tauern Window. The latter two are exhumed by large-scale orogen-parallel extensional faulting and contemporaneous indentation. This event ceased in middle Miocene times when faulting and associated exhumation switched towards the Southern Alps (e.g. Eizenhöfer et al. 2021). Apatite fission-track ages (closure temperature of ~110°C) are the youngest (≤6 Ma) in the external crystalline massifs and record a long-lasting Miocene exhumation, whereas the early Miocene exhumation was caused by vertical tectonics related to rollback of the subducted European slab (e.g. Herwegh et al. 2017; 2019). Ongoing middle to late Miocene exhumation of the external crystalline massifs was instead related to in-sequence thrusting (Herwegh et al. 2019). The young thermochronological ages and related high post-Miocene exhumation in the western external crystalline massifs might be at least partly related to uplift caused by slab detachment (e.g. Fox et al. 2015). In the Eastern Alps, there is no evidence for comparable young (post-Miocene) exhumation 'hotspots', suggesting a rather stable geodynamic state and absence of large-scale changes in mantle processes.

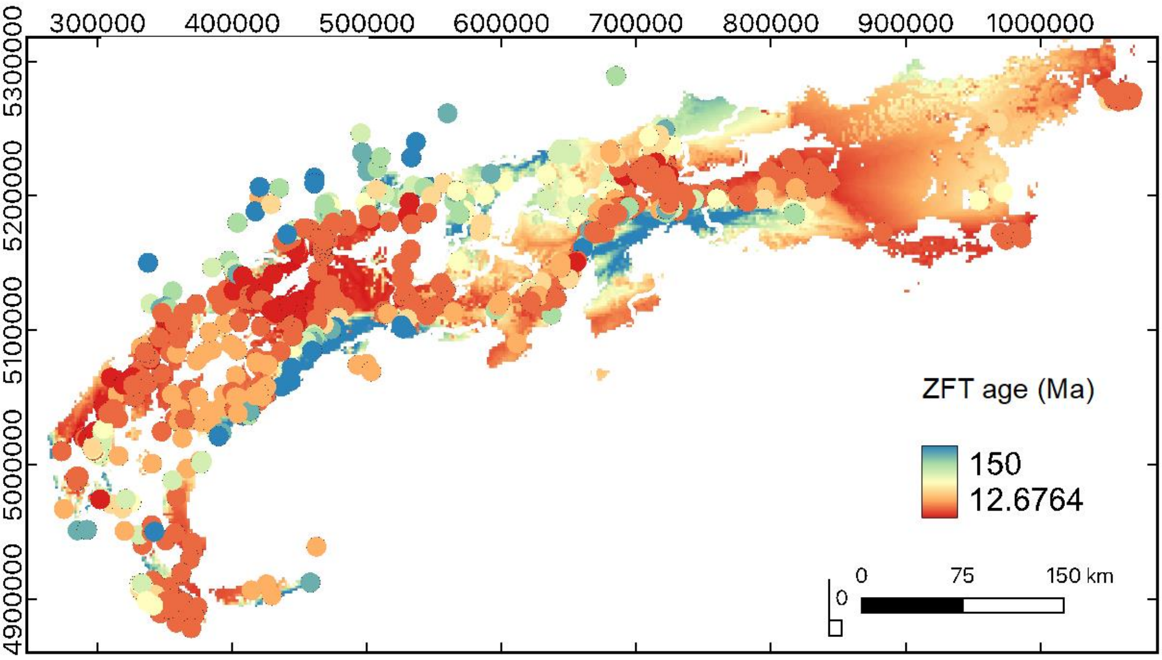

Figure 1: Published ZFT ages and interpolated ZFT age map.

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Does gravity modelling justify a rifted "Ligurian Basin"?

H.-J. Götze[1], R. Strehlau[1], A. Dannowski[3], J. Bott[2], A. Kumar[2], M. Scheck-Wenderoth[2]

1. Christian-Albrechts-Universität zu Kiel, Institut für Geowissenschaften, Kiel
2. GFZ – Helmholtz-Zentrum Potsdam, Basin Modelling Sec. 4.1, Potsdam
3. GEOMAR - Helmholtz-Zentrum für Ozeanforschung Kiel, Dynamik des Ozeanbodens, Kiel

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The geo-historical development of the Ligurian Basin and the structure of the crust and upper mantle in this area are still being discussed. Yet it remains unclear if rifting caused continental break-up and seafloor spreading and one of the key questions is whether rifting can be identified in geophysical measurements. For our investigations we had the following updated data sets at our disposal: the new gravity maps of the AlpArray Gravity Working Group (complete Bouguer - CBA, Free air, and isostatic anomalies) the seismic results of the Lobster campaigns of our GEOMAR partners in the SPP MB4D as well as the dynamic modelling results from our own subproject. The constraining data are supplemented with seismic profile data from French and Italian offshore campaigns, as far as they are usable in publications for us. The GFZ modelling software IGMAS+ was used for an interactive 3D modelling. The resulting model contains density inhomogeneities in the crust as well as in the upper mantle down to a depth of 300 km following the results of dynamic models of our own subproject. Due to the special hybrid modelling of the crust (by polygonal structures) and the upper mantle (by voxels of recent velocity models), the individual contributions to the gravity field are clearly separable. As a further special feature, we point out that the density model used is based on the gravity modelling from the first phase of the SPP MB4D (our former subproject INTEGRATE). Thus, a largely consistent 3D density model for both the Alps and the Ligurian Sea is available for interpretation. The constrained 3D modelling of the gravity field, as well as numerical analyses of the fields (terracing, clustering, filtering, curvature), calculations of the vertical stress and Gravity Potential Energy (GPE) suggest that a rift structure in the area of the Ligurian Sea can be identified and mapped. The interactive modelling is supported by the use of geological maps in the Ligurian Sea area. By overlaying the model gravity maps and the geological maps, the good agreement becomes visible – refer to the attached figure.

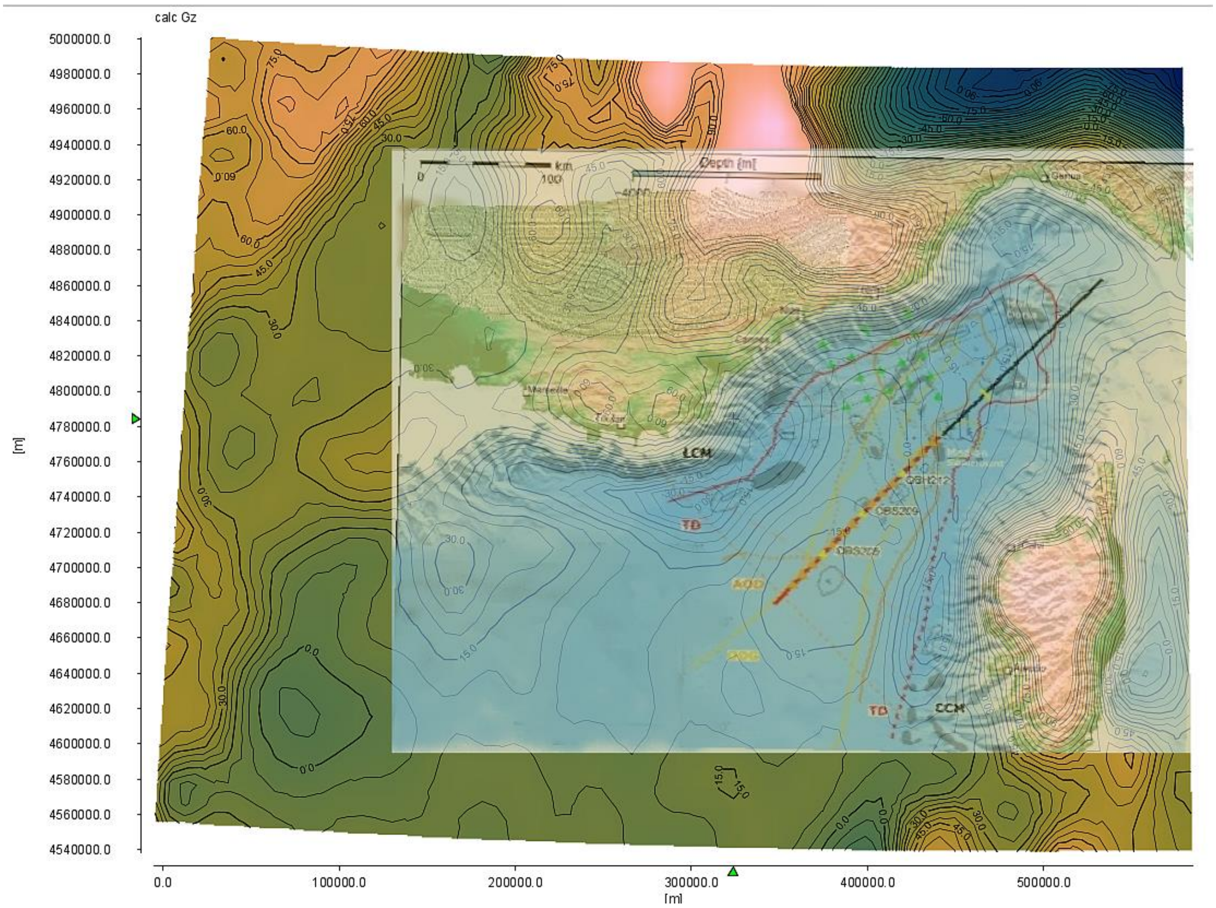

Figure 1: Screen plot of the 3D georeferenced density model (in UTM coordinates) in the area of the Ligurian Basin overlayed by the interpretational map of seismic results (Dannowski et al., 2020). Calculated Free Air anomaly is shown in color (background) and in a gravity contour lines (transparent, isolines spacing: 5 mGals). Greenish and blueish colors indicate lower gravity, reddish tones indicate higher gravity values. The central part with slightly higher gravity values is surrounded by negative anomalies. As a transparent overlay an interpretational map contains the position of the central LOBSTER refraction seismic line in combination with an older profile of Makris et al. (1999). Among other features different crustal domains are marked by thin orange and red lines and are labelled AOD – atypical oceanic domain; CCM – Corsica continental margin; LCM – Ligurian continental margin; and TD – transitional domain. A thin yellow line marks the oceanic domain (ODG). There is a significant correlation between the mentioned domains in the seismic interpretation and the calculated gravity anomalies.

Evolution of a Fossil Subduction Zone: Insights from the Tauern Window, Eastern Alps

Philip Groß[1,2], Jan Pleuger[1], Timm John[1], Mark Handy[1]

1. Institute of Geological Sciences, Freie Universität Berlin, Germany
2. Institute of Geosciences, Heidelberg University, Germany

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Subduction zones play a crucial role in the evolution of Earth's lithosphere. In many orogens, deeply subducted coherent high-pressure (HP) nappes were exhumed from deep to shallow parts of subduction channels. This process significantly affects the deformation pattern and internal structure of the orogen. Exhumation seems to occur preferentially during the transition from subduction to collision, when dense oceanic lithosphere has been consumed entirely and more buoyant continental lithosphere from a passive continental margin enters the subduction zone. Here, we present a detailed study on the structural, kinematic, and metamorphic evolution of a well-preserved paleo-subduction channel within the Tauern Window (Alps).

First, we reevaluated the metamorphic history and regional tectono-stratigraphy of the tectonic units in the central Tauern Window. These units originate from the Alpine Tethys oceanic domain and the adjacent European passive continental margin. They experienced HP conditions during Alpine subduction, which was followed by exhumation to their current position in the Alpine nappe stack. By integrating new structural data and the well-preserved stratigraphy of the ocean-continent transition, we reconstructed the structure and kinematics of the nappes in great detail. Notably, we document a recumbent, tens-of-kilometers-scale sheath fold formed during pervasive top-to-the-foreland shear. This sheath fold comprises an isoclinally folded thrust that transported ophiolite relicts from the former Alpine Tethys onto a distal part of the European continental margin during early stages of subduction. It formed under HP conditions, immediately after the Europe-derived rocks in its core reached their maximum burial depth. The non-cylindrical shape of the sheath fold suggests its nucleation at a promontory of the former margin, inherited from Mesozoic rifting and subsequently amplified to a sheath geometry during top-to-the-foreland shear in the subduction zone.

To gain insight into the temperature (T) structure of the sheath fold, we employed Raman spectroscopy on carbonaceous material (RSCM) thermometry on a large number of samples with high spatial resolution. The systematic spatial temperature trends reveal distinct domains related to the original subduction metamorphism and later T-dominated (Barrovian) metamorphic overprint. Integrating the peak-temperature pattern with the fold geometry unveils a two-stage process of nappe formation and sheath folding during exhumation.

Our results highlight the existence of considerable along-strike heterogeneity within the deep portion of a fossil subduction zone, likely influenced by inherited rift structures and exhumation processes. Understanding such heterogeneities is crucial for interpreting seismic sections and numerical simulations of subduction zones, emphasizing the need to consider three-dimensional complexities beyond the idealized cylindrical models often used. By unraveling the structural and metamorphic evolution of exhumed HP nappes in the Tauern Window, this study contributes to a better understanding of the dynamic processes operating within subduction zones and their implications for mountain building.

Active Tectonics of the Alps-Dinarides junction

Christoph Grützner[1], Petra Jamšek Rupnik[2], Klaus Reicherter[3], Kamil Ustaszewski[1], Blaž Vičič[4], Friedhelm von Blanckenburg[5], Marko Vrabec[6], Hella Wittmann[5]

1. Institute of Geosciences, Friedrich-Schiller University Jena, Germany
2. Geological Survey of Slovenia, Slovenia
3. Neotectonics and Natural Hazards Group, RWTH Aachen University, Germany
4. The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy
5. GFZ German Research Centre for Geosciences, Germany
6. Department of Geology, University of Ljubljana, Slovenia

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The northward motion and rotation of the Adriatic Plate leads to crustal deformation in the Southern Alps and in the Dinarides. Many aspects of the active tectonics in that area have not been properly understood, for example the distribution and localization of strain, the paleoseismic history of the largest faults, the seismic sources for large historical earthquakes, and the landscape record of active faulting. In the framework of SPP2017, we worked in the Southern Alps-Dinarides transition area, encompassing W Slovenia, NE Italy, and S Austria (Fig. 1). We used tectonic geomorphology studies on high-resolution digital elevation models, satellite imagery, field mapping, near-surface geophysics, paleoseismology, and Quaternary dating techniques to understand the pattern of Late Quaternary tectonics. Our results how that in Slovenia, deformation is distributed across a system of major NW-SE striking right-lateral strike slip faults in a more than 60 km-wide zone (Grützner et al., 2021). Many smaller, <15 km long faults show postglacial activity, too. In general, the deformation is widely distributed. In Italy, most of the deformation is accommodated by thrusting at the South Alpine orogenic front. Several thrust faults have stepped out into the Friulian Plain, where they are often blind (Viscolani et al., 2020). Although historical earthquakes with magnitudes larger than M6 occurred in the interior of the mountain chain, instrumental seismicity here is low. There is only very poor geological evidence of fault activity because sedimentation, high erosion rates, and anthropogenic modification dominate the present-day landscape and outpace almost any tectonic signal. In addition, glacial processes have erased most potential evidence for Late Quaternary active tectonics (Diercks et al., 2021, 2022, in press). The situation is similar in Austria, where geological evidence of active faulting is sparse, despite a record of strong historical earthquakes. New dating results from both deformed and undisturbed geomorphic markers allow us to place constraints on the maximum amount of deformation that is accommodated in southern Austria and on fault activity in Slovenia. Our latest results on seismically-triggered mass movements show that the 1348 Earthquake, one of the strongest historical events in the entire Alps, has likely occurred on the Fella-Sava Fault.

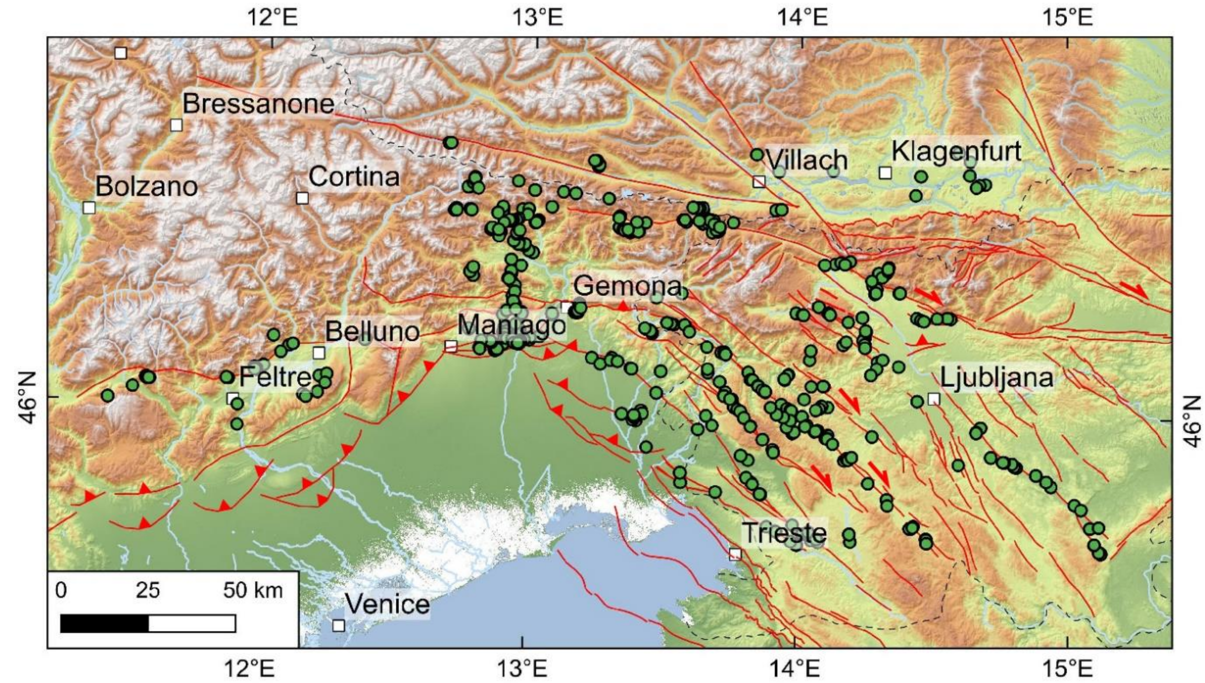

Figure 1: Active faults (red lines) in the Eastern Southern Alps-Dinarides junction compiled from the literature and own mapping, and our field work sites 2017-2023 (green dots).

Diercks, M., Grützner, C., Vrabec, M., Ustaszewski, K. (2021). A model for the formation of the Pradol (Pradolino) dry valley in W Slovenia and NE Italy, Geologija, 64/1, 21-33.

Diercks, M., Grützner, C., Vrabec, M., & Ustaszewski, K. (2022). Addendum to Diercks et al., 2021: A model for the formation of the Pradol (Pradolino) dry valley in W Slovenia and NE Italy. Geologija, 65(1), 93-99.

Diercks, M.-L., Grützner, C., Welte, J. & Ustaszewski, K. (accepted). Challenges and Limits of Remote Sensing of Active Tectonics in the Slowly Deforming Karst Landscape of W Slovenia and NE Italy. Geomorphology.

Grützner, C., Aschenbrenner, S., Jamšek Rupnik, P., Reicherter, K., Saifelislam, N., Vičič, B., Vrabec, M., Welte, J., & Ustaszewski, K. (2021). Holocene surface-rupturing earthquakes on the Dinaric Fault System, western Slovenia. Solid Earth, 12, 2211-2234.

Viscolani, A., Grützner, C., Diercks, M., Reicherter, K., & Ustaszewski, K. (2020). Late Quaternary Tectonic Activity of the Udine-Buttrio Thrust, Friulian Plain, NE Italy. Geosciences 10(2), 84.

Active Tectonics of the Alps-Dinarides junction – what have we learned?

Christoph Grützner[1]

1. Institute of Geosciences, Friedrich-Schiller University Jena, Germany

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The collision of the Adriatic Plate with Europe leads to crustal deformation in the Southern Alps-Dinarides transition. Many aspects of this deformation are still unknown. This concerns for example sources of historical earthquakes in the hinterland of the Southern Alpine orogenic front and the overall distribution and the partitioning of strain. Also, the response of the upper crust to deep-seated processes and the influence of the lithospheric architecture on active tectonics has not been fully understood. In many cases, the reason is the very low overall deformation rate in this region. Several projects in the framework of SPP2017 have shed light on these problems, and many new studies unrelated to the SPP have recently published exciting new results. In this presentation I summarize new findings from the fields of geodesy, seismology, structural geology, geomorphology, and earthquake geology. These studies have used GNSS and InSAR data, seismological data from the AlpArray and SWATH-D experiments, new high-resolution digital elevation models, satellite imagery, field mapping, near-surface geophysics, paleoseismology, and Quaternary dating techniques to understand the pattern of Late Quaternary tectonics. In Italy, most of the deformation is accommodated by thrusting on the Southern Alps mountain front, or thrusting has already stepped southward into the Friulian plain, partly on blind faults. This behavior is known from several contractional regimes around the world. Although strong historical earthquakes (M>6) occurred in the interior of the mountain chain, present-day seismicity is rather low. In this region, geological evidence of fault activity is poor because sedimentation/erosion and anthropogenic overprint outpace most tectonic signals on a Quaternary time scale. This is similar to southern Austria, where there is very poor geological evidence of active faulting, despite a record of strong historical earthquakes. New dating results from both deformed and undisturbed geomorphic markers allow us to place constraints on the maximum amount of deformation that is accommodated here. In Slovenia, a system of NW-SE striking right-lateral strike slip faults in a more than 60 km-wide zone takes up most of the deformation. Additionally, many smaller, <15 km long faults show postglacial activity. In general, the deformation is widely distributed. A similar behavior can be observed in may strike-slip fault systems worldwide. In the study area there is a first order correlation between the distribution of seismicity during the Quaternary and gradients of crustal thickness and crustal density. However, other processes like a still ongoing, though very slow eastward extrusion of Eastern Alps crustal material or vertical motions due to glacial isostatic rebound or erosion are likely to contribute to the overall pattern of active tectonics.

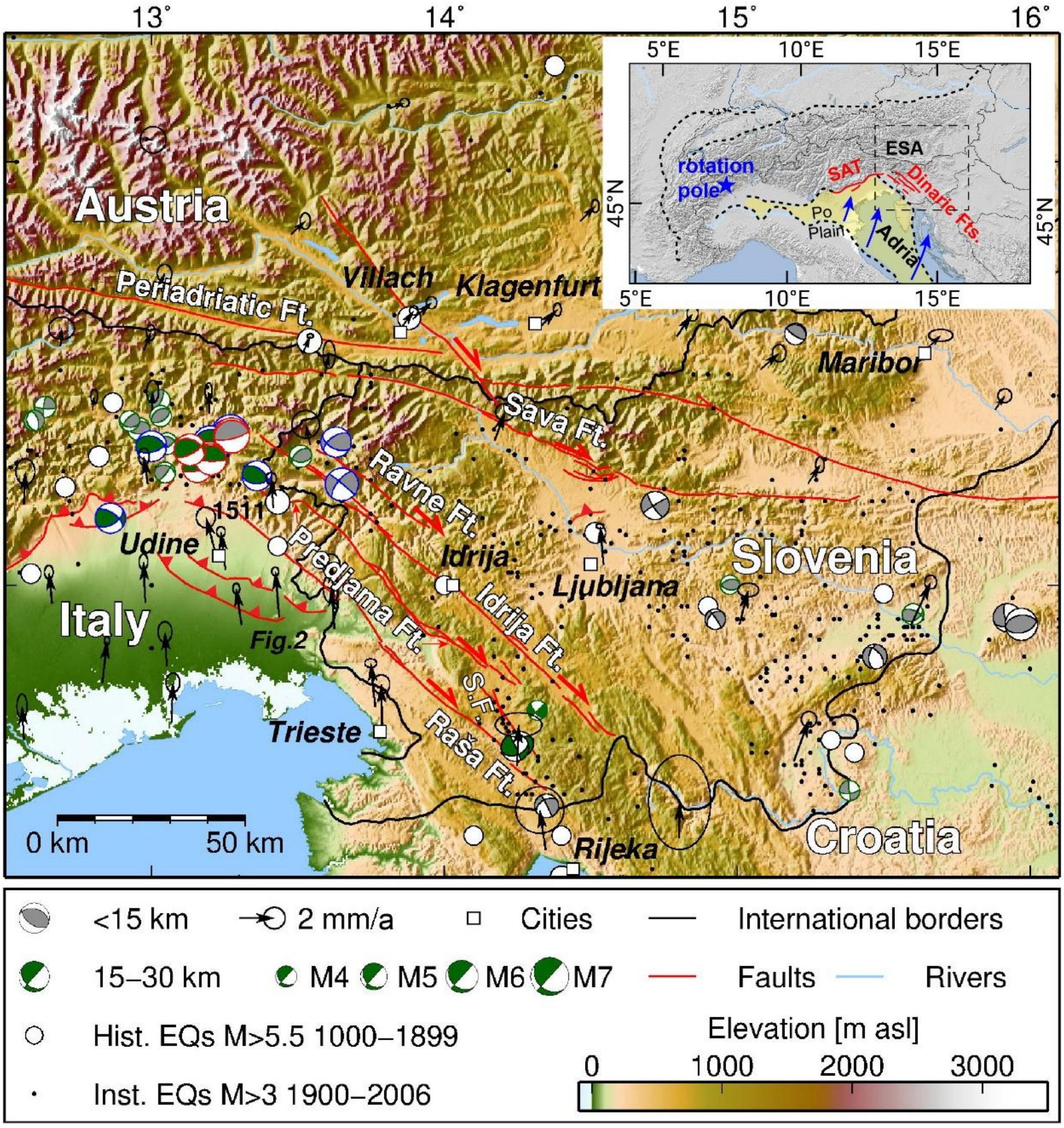

Figure 1: Active tectonics of the Eastern Southern Alps-Dinarides junction.

Local earthquake tomography in the Eastern and eastern Southern Alps using Swath D data

Christian Haberland[1]

1. GFZ Potsdam, Germany

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The AlpArray collaborative project was a multinational, European initiative focused on the Alpine-Apennine-Carpathian-Dinarid orogenic system, established to improve our understanding of the Alpine orogeny and geology (see e.g., Hetényi et al., 2018). The backbone of this project was the large AlpArray seismic network (AASN) with more than 600 stations deployed in the greater Alpine area (Hetényi et al., 2018).

In addition to this regional network, the temporary Swath D network was installed as part of the 4D-MB project (Heit et al., 2021). This network included 163 stations that were operated for two years. It was located along the tip of the eastern Adriatic indenter and covered for example part of the proposed Moho gap in the Eastern Alps and the slab gap between Central and Eastern Alps. With an average station spacing of 15 km it was significantly denser than the AASN (average spacing of 52 km) and thus enabled for high-resolution imaging of key areas within the Alpine region, particularly on the crustal and upper mantle scale as well as the precise location of local earthquakes. The high density of the Swath D network was particularly important for high resolution imaging considering that there is only a moderate rate of seismicity in the study region.

The Swath D data was therefore ideal to be used in local earthquake tomography (LET), which is a mature, powerful inversion method to provide high-resolution images of the subsurface especially on the crustal scale.

In a first step earthquake arrival times of P- and S-waves (observed at Swath D and selected AASN stations) were picked and inverted for velocity models, station corrections, earthquake hypocenters and origin times (Jozi Najafabadi et al., 2021). In this way the seismicity (mainly in the upper 20 km) of the Alpine frontal thrust, e.g., the Friuli-Venetia region, the Giudicarie–Lessini and Schio-Vicenza domains, the Austroalpine nappes, and the Inntal area was revealed.

In a second step the arrival time data were inverted for the 3-D velocity structure (Jozi Najafabadi et al., 2022). Due to the irregular distribution of earthquakes, extensive resolution testing was necessary. The predominantly shallow earthquakes still pose a challenge for the inversion, particularly in terms of resolution of the lower crust and upper mantle. Nevertheless, the derived P-wave velocity model revealed a highly heterogeneous crustal structure in the target area with prominent intracrustal anomalies, Moho topography and a thickened lower crust South of the Periadriatic fault. The models were intensly used for further detailed geological and geophysical investigations (e.g., Verwater et al., 2021).

In a third step the distribution of seismic attenuation of P-waves (1/Qp) was calculated (attenuation tomography). Focussing on the upper crust, several distinct anomalies can be observed. The highest attenuation (lowest QP) anomaly is found in the Friuli-Venetian region which is also characterized by low VP and increased VP/VS. This anomaly may be related to a high fault and fracture density and the presence of fluid-filled sediments of the Venetian-Friuli basin along the eastern part of the Southern Alpine deformation front.

Recently, attempts to obtain vp and vs models from LET have been extended to the greater Alpine region (e.g. Braszus et al., 2023).

Braszus, B. et al. (2023) AI based 1D P & S-wave Velocity Models for the Greater Alpine Region from Local Earthquake Data. Submitted to Geophys. J. Int.

Heit, B., et al. (2021) The SWATH-D Seismological Network in the Eastern Alps. Seismological Research Letters 92 (3), pp.1592–1609. doi: https://doi.org/10.1785/0220200377

Hetényi, G., et al. The AlpArray Seismic Network: A Large-Scale European Experiment to Image the Alpine Orogen. Surv Geophys 39, 1009–1033 (2018). https://doi.org/10.1007/s10712-018-9472-4

Jozi Najafabadi, A., et al. (2021): Relocation of earthquakes in the southern and eastern Alps (Austria, Italy) recorded by the dense, temporary SWATH-D network using a Markov chain Monte Carlo inversion. Solid Earth, 12, 5, 1087-1109. https://doi.org/10.5194/se-12-1087-2021

Jozi Najafabadi, A., et al. (2022): Constraints on crustal structure in the vicinity of the Adriatic Indenter (European Alps) from Vp and Vp/Vs Local Earthquake Tomography.- JGR Solid Earth, 127, 2, e2021JB023160. https://doi.org/10.1029/2021JB023160

Jozi Najafabadi, A., et al. (2023) Seismic wave attenuation (1/Qp) in the crust underneath the Eastern and eastern Southern Alps (Europe): Imaging effects of faults, fractures, and fluids. Submitted to Earth, Planets, Space.

Verwater, V. F., et al. (2021) Neogene kinematics of the Giudicarie Belt and eastern Southern Alpine orogenic front (northern Italy). Solid Earth, 12, 6, 1309-1334. https://doi.org/10.5194/se-12-1309-2021

Role of the Giudicarie Belt and eastern Southern Alps in Adriatic Indentation

Mark R. Handy[1], Eline Le Breton[1], Christian Haberland[2], Peter J. McPhee[1], Azam Jozi Najafabadi[2], Vincent Verwater[1], Vincenzo Picotti[3].

1. Institute of Geological Sciences, Freie Universität Berlin, Germany
2. Deutsche GeoForschungsZentrum, Potsdam, Germany
3. Department Erdwisenschaften, ETH-Zürich, Switzerland

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The Giudicarie Belt (GB) sinistrally offsets the Alpine orogenic edifice by some 70 km, including the front of the Adriatic Indenter as defined at the surface by Periadriatic Fault. The GB is a composite structure, comprising northern and southern segments of the Giudicarie Fault (GF), as well as a ≤50 km wide fold-and-thrust belt that strikes obliquely to ENE-WSW trending thrusts affecting Permo-Mesozoic sediments and basement of the eastern Southern Alps (Fig. 1).

Stratigraphic and thermochronological constraints indicate that sinistral transpression within the GB began at 21-22 Ma and ceased no later than latest Miocene time. Minimum shortening across the GB in the range of 12-35 km was accommodated by thrusts and strike-slip faults that are inferred to reach down to 15-20 km and to link with the GF (Verwater et al. 2021). The GB does not offset the Moho and also does not coincide with observed changes in lithospheric mantle structure imaged by teleseismic V_p tomography. It is therefore not the site of a slab gap or tear, but forms part of an intracrustal fault system that is linked to the north with thrusts and strike-slip faults beneath the Tauern Window.

In the Southern Alps east of the GB, SE-directed folding and thrusting accommodated shortening of 30-50 km. It initiated at 14 Ma (Langhian-Serravalian flysch beneath the Valsugana thrust) and propagated SE-wards to the active Montello thrust along the orogenic front of the Southern Alps (Fig. 1). Thus, thrusting in the eastern Southern Alps began later than within the GB, though deformation within these domains probably overlapped in mid-late Neogene time.

We propose that a 1st phase of Adriatic indentation at 23-14 Ma involving sinistral transpression along the GB was linked to an intracrustal detachment that accommodated rapid exhumation of Penninic units in the Tauern Window and eastward lateral extrusion of orogenic crust in the E. Alps (Fig. 1). A 2nd phase of indentation since 14 Ma involved NNW-SSE-directed shortening that crumpled the leading edge of the Adriatic indenter. Section balancing (McPhee et al., this vol.) indicates that thrusts of this 2nd phase are directly linked to bulging and northward wedging of the Adriatic lower crust, as also indicated by local earthquake tomography obtained from Swath D (Fig. 2, Jozi Najafabadi et al. 2022).

We note that the model above differs from our original interpretation of broadly coeval activity of the GB and the eastern Southern Alps during late Paleogene-Neogene Adria-Europe convergence (Verwater et al., 2021). In our present view, the Trento-Cles strike-slip fault accommodated differential shortening only within the GB and was not linked to the Schio-Vicenza fault system. The latter is marked by only minor (≤ 4 km) sinistral offset and was reactivated as a Mio-Pliocene normal fault in the foreland of the Apennines (Verwater et al. 2021).

Jozi Najafabadi, A., Haberland, C., Le Breton, E., Handy, M. R., Verwater, V. F., Heit, B., et al. (2022). Constraints on crustal structure in the vicinity of the Adriatic Indenter (European Alps) from Vp and Vp/Vs local earthquake tomography. Journal of Geophysical Research: Solid Earth, 127, https://doi.org/10.1029/2021JB023160

McPhee, P., Handy, M.R., Le Breton, E. (2023). Investigating the post-collisional reorganisation of the Eastern Alps using a 4D reconstruction, this volume.

Verwater, V.F., Le Breton, E., Handy, M.R., Picotti, V., Najafabadi, A.J., Haberland, Ch. (2021). Neogene kinematics and strain partitioning within the Giudicarie Belt and eastern Southern Alpine orogenic front (Northern Italy). Solid Earth, 12, 1309–1334, https://doi.org/10.5194/se-12-1309-2021

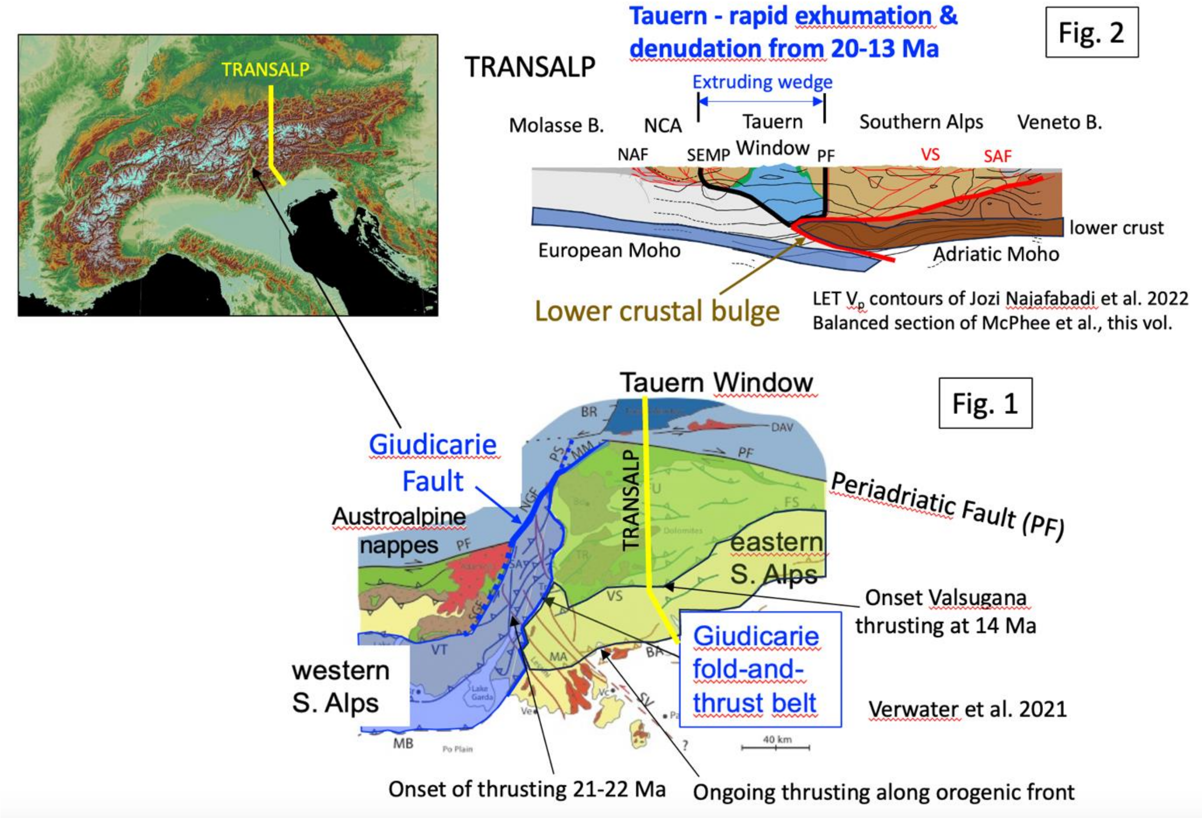

Figure 1: Giudicarie Belt and its relationship to Adriatic indenter tectonics: Domains affected by 1st phase (23-14 Ma, blue-shaded area) and 2nd phase (14-0 Ma, green-shaded area) of Adriatic indentation.

Figure 2: TRANSALP profile showing 1st phase faults bounding wedge of Tauern exhumation and lateral extrusion (black lines) and 2nd phase faults (red lines) linking Adriatic lower crustal wedge to Miocene thrusting in the eastern Southern Alps.

A new 4D model of Alpine orogenesis based on AlpArray

Mark R. Handy[1], Peter J. McPhee[1], Eline Le Breton[1], members of the 4D-MB and AlpArray Groups

1. Department of Earth Sciences, Freie Universität Berlin, Germany

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Wholesale slab breakoff or detachment in the Alps in late Paleogene time has been invoked to explain Periadriatic calc-alkaline magmatism (43-29 Ma), rapid exhumation of HP metamorphics, as well as clastic infill of proximal parts of the Alpine Molasse basin (30-28 Ma). However, the 14 My timespan of these events exceeds the duration of slab detachment estimated from thermomechanical modelling (2-8 My) and from foreland depocenter migration (~5 My) along equivalent lengths of neighboring Alpine orogens with torn slabs (Carpathians, Apennines). Moreover, wholesale slab detachment does not explain major E-W differences in Neogene crustal structure, basin evolution, erosion and indentation in the Alps.

Teleseismic Vp tomography from AlpArray suggests that the slab segment beneath the Central Alps comprises European lithosphere, is attached to its orogenic lithosphere and extends down to ~250 km depth, in parts possibly even to the Mantle Transition Zone (Fig. 1). This marks a first phase of partial slab detachment, probably in late Paleogene time based on comparing slab length with shortening in the C. Alps and of Adria-Europe convergence since 35 Ma. In contrast, the slab segment beneath the Eastern Alps is detached between 80-150 km depth. The age of this second phase of slab detachment is bracketed at 23-19 Ma by criteria below and by comparing vertical detachment distance with global slab sink rates.

We propose a new model of Alpine mountain-building that features the northward motion of subduction singularities above delaminating and detaching Alpine slab segments, respectively in the C. and E. Alps (Fig. 2), to explain the aforementioned E-W differences in Oligo-Miocene structure, magmatism, and foreland sedimentation. Mountain-building began at ~35 Ma with a decrease in Adria-Europe convergence to <1cm/yr collision, causing the European slab to steepen and detach beneath both the Central and Eastern Alps. Periadriatic magmatism may have initiated prior to slab detachment due to fluxing of the cold mantle wedge by fluids from devolatilizing crust along the steepened Alpine slab. Thereafter, the Central and Eastern Alps evolved separately (Fig. 2). Northward motion of the singularity during slab delamination in the Central Alps increased both horizontal shortening and the taper angle of the orogenic wedge, with rapid exhumation and denudation in the retro-wedge. Slab steepening and delamination are inferred to have been more pronounced in the Eastern Alps, possibly due to the greater negative buoyancy of the slab in the absence of Brianconnais continental lithosphere in the eastern part of Alpine Tethys. The delaminating slab in the east drove subsidence and continued marine sedimentation in the E. Molasse basin from 29-19 Ma, while the western part of the basin in the C. Alps filled with terrigeneous sediments. Slab detachment beneath the E. Alps at ~20 Ma coincided broadly with several dramatic events within only 5 Ma (23-17 Ma): (1) a switch from advance of the northern thrust front to indentation of the E. Alps by the eastern S. Alps along the sinistral Giudicarie Fault; (2) rapid exhumation of Penninic nappes in the core of the orogen (Tauern Window) and orogen-parallel escape of orogenic crust toward the Pannonian Basin; (3) rapid filling of the E. Molasse basin. These events are attributed to a northward and upward shift of the singularity to within the orogenic crust during Adriatic indentation (Fig. 2). The eastward propagation of the uplifting depocenter in the E. Molasse basin is interpreted to reflect propagation of a subhorizontal slab tear beneath the E. Alps which is imaged by Vp teleseismic tomography. This slab tearing ultimately accompanied Miocene rollback subduction in the Carpathians, as inferred from the migrating depocenter around the orogenic foredeep.

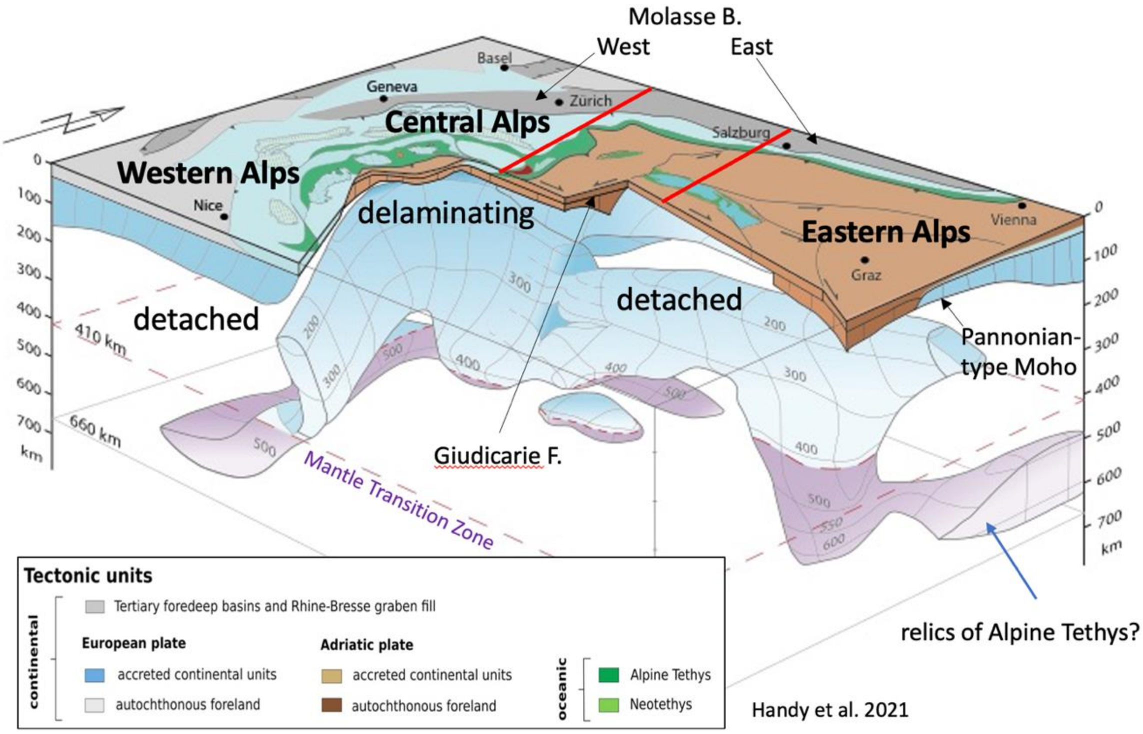

Figure 1: European slab beneath Alps as interpreted from teleseismic V_p tomography (Handy et al. 2021). Red lines show traces of section in Fig. 2

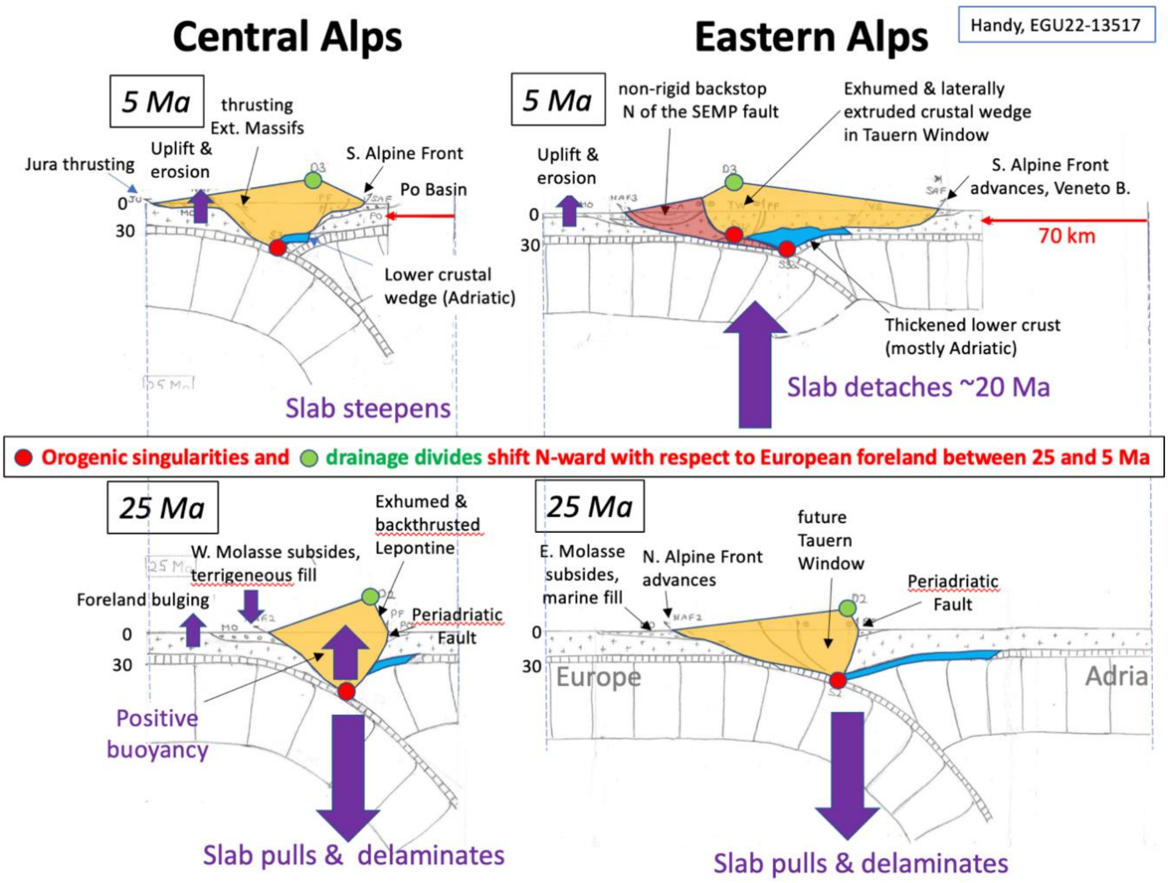

Figure 2: Schematic N-S cross sections for Miocene time showing migrating singularities in relation to the shapes of orogenic wedges, exhumation and deposition in the Central and Eastern Alps. Note that previous slab detachment in Paleogene time is not shown.

The impact of the Bohemian Spur on the cooling and exhumation pattern of the Eastern Alpine wedge

Bianca Heberer[1], Bernhard Salcher[1], Gabor Tari[2], Godfrid Wessely[3], István Dunkl[4], Reinhard Sachsenhofer[5], Michael Wagreich[6], Christoph von Hagke[1]

1. Department of Environment and Biodiversity, University of Salzburg, Austria
2. OMV, Vienna, Austria
3. Siebenbrunnengasse 29, Vienna, Austria
4. Department of Sedimentology and Environmental Geology, University of Goettingen, Germany
5. Department of Petroleum Geology, University of Leoben, Austria
6. Department of Geology, Vienna, Austria

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Fold and thrust belt dynamics and architecture may largely be impacted by the geometry of the overridden basement. The Bohemian Spur, the subcrop extension of the Bohemian massif, guided thrust propagation leading to the arcuate shape of the orogen and a narrowing of the Molasse Basin at the transition to the between the W-E trending Eastern Alps and the SW-NE trending Western Carpathians. Thermochronological studies in the Eastern Alps were mainly focused on the core of the collisional orogen, where deformation has been most prominent. Further to the east, some FT work is concentrated along fault zones but thermochronometers with lower closure temperatures have hardly been applied to higher elements of the nappe pile. Due to the scarcity of the dataset and preferential application of fission track dating uppermost crustal cooling below ca. 80 °C remains undetected.

In this study we present new apatite (U-Th)/He and apatite fission track data from clastic units of the Rhenodanubian Flysch zone and the Northern Calcareous Alps. We find reset ages, that monitor a so far un(der)appreciated phase of prominent Late Oligocene to Miocene cooling. Thermal modeling of age data from the flysch samples reveals rapid Early Miocene cooling at rates of up to 40 °C/Ma between ca. 20 and 15 Ma. We propose a buttressing effect of the underlying tectonically structured eastern rim of the Bohemian Spur to be the driving mechanism for this phase of intensified exhumation. Our tectonic model (Fig. 1a) invokes contractional reactivation of pre-existing normal faults inherited from Penninic continental rifting. This positive inversion led to the shortening of the Jurassic half-graben infill and its extrusion as a major fold.

Thermochronological data and thermal modeling of data from samples in the Lunz nappe of the Northern Calcareous Alps nappe pile indicate less punctuated cooling and exhumation. Modeling defines an increase of cooling rates at the latest at ca. 27 to 25 Ma, i.e., earlier than in the Flysch samples. Cooling occurred at a much lower rate of 3 to 6 °C/Ma and was synchronous with northward movement of the deformation front. In our tectonic model (Fig. 1b), we propose a staircase pattern that influences wedge dynamics: The topographically segmented downgoing plate leads to less localized and more distributed deformation invoking a broader area of uplift than the spatially focused uplift of the Flysch samples. Wedge propagation is initially inhibited or retarded by the relief of the basement. The ongoing northward movement of the propagating wedge is compensated through deep duplexing of the autochthonous foreland sequence.

When calling upon deep-seated processes to explain the exhumation pattern the buttressing effect needs to be taken into account. Early Miocene drainage pattern reorganization in the Molasse Basin is proposed to be a consequence of uplift induced by the subcrop promontory.

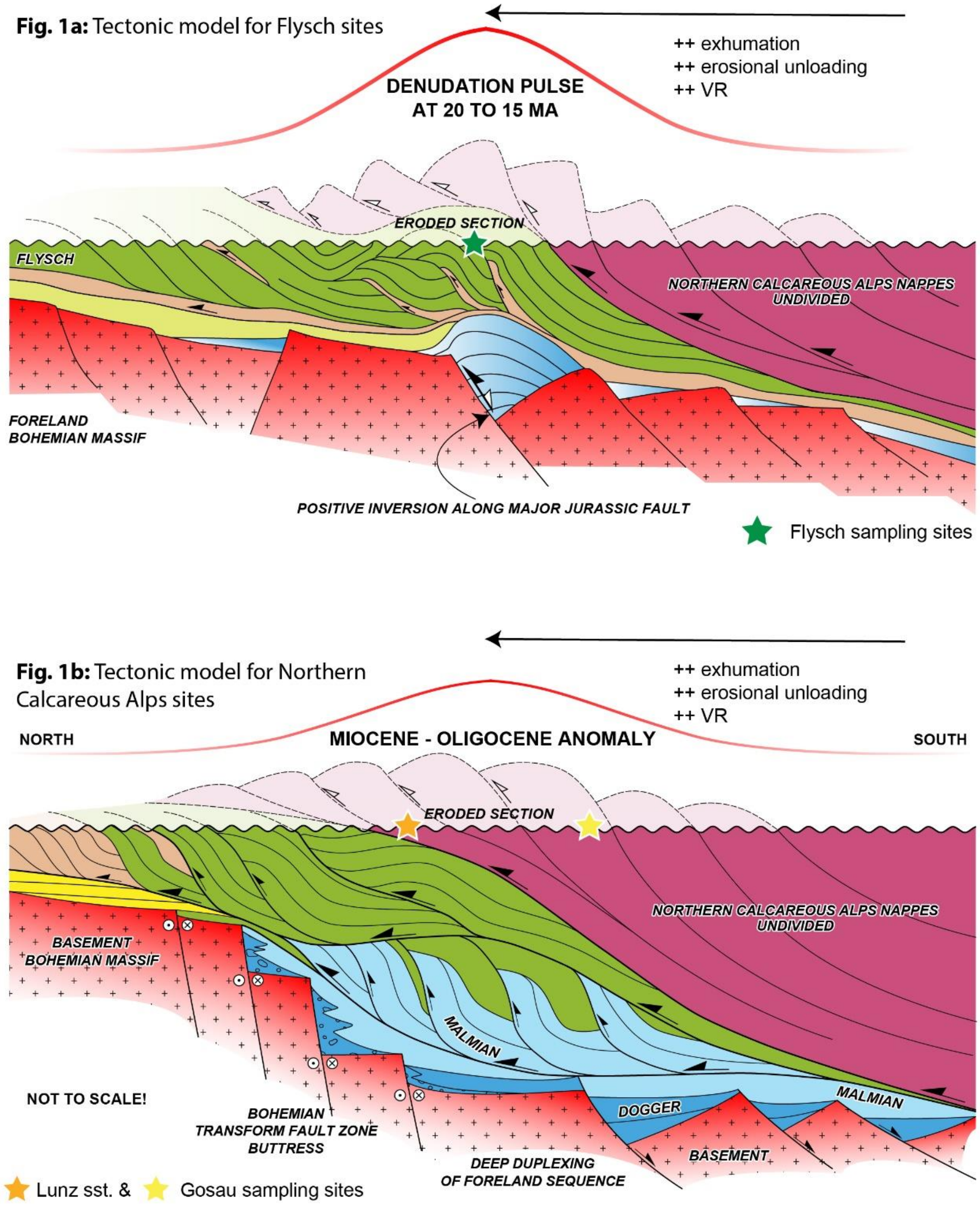

Figure 1: Cartoons depicting the tectonic evolution of **a)** Flysch samples and **b)** samples from the Northern Calcareous Alps above major basement steps of the Bohemian Spur.

The SWATH-D seismological network in the Eastern Alps

Benjamin Heit[1], Luigia Cristiano[1], Christian Haberland[1], Frederik Tilmann[1,2], Damiano Pesaresi[3], Yan Jia[4], Susanne Hemmleb[1], Martin Haxter[1], Thomas Zieke[1], Karl-Heinz Jaeckl[1], Antje Schloemer[5], Michael Weber[1,6]

1. GFZ German Research Centre for Geosciences, Potsdam, Germany
2. Freie Universität Berlin, Berlin, Germany
3. Istituto Nazionale di Oceanografia e di Geofisica Sperimentale–OGS, Sgonico (TS), Italy
4. ZAMG Zentralanstalt für Meteorologie und Geodynamik, Vienna, Austria
5. LMU Universität München, Geophysikalisches Observatorium, Fürstenfeldbruck, Germany
6. Universität Potsdam, Institut für Geowissenschaften Campus Golm, Potsdam, Germany

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The SWATH-D experiment involved the deployment of a dense temporary broadband seismic network in the Eastern Alps. Its primary purpose was enhanced seismic imaging of the crust and crust-mantle transition as well as improved constraints on local event locations and focal mechanisms in a complex part of the Alpine orogen. The study region is a key area of the Alps, where European crust in the north is juxtaposed and partially interwoven with Adriatic crust in the south, and a significant jump in the Moho depth was observed by the 2001 TRANSALP N-S profile. Here, a flip in subduction polarity has been suggested to occur. This dense network encompasses 163 stations and complements the larger-scale sparser AlpArray seismic network. The nominal station spacing in SWATH-D is 15 km in a high alpine, yet densely populated and industrialized region. We present here the challenges resulting from operating a large broadband network under these conditions and summarize how we addressed them, including the way we planned, deployed, maintained and operated the stations in the field. Finally, we present some recommendations based on our experiences.

A geological 3D-model of Austria

Benjamin Huet[1], Clemens Porpaczy[1], Esther Hintersberger[1], Martin Reiser[1], Thomas Fuhrmann[1]

1. GeoSphere Austria – Bundesanstalt für Geologie, Geophysik, Klimatologie und Meteorologie, Vienna, Austria

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GeoSphere Austria (formerly Geologische Bundesanstalt - Geological Survey of Austria) has produced a supra-regional 3D framework model called "3D AUSTRIA" providing a large-scale geological overview for professional geologists, students and the public. This model is intended to act as support for subsequent regional modelling projects as well as for educational and communicational purpose.

The modelled domain of covers a rectangular area of 175 000 km² including the national borders of Austria, down to a depth to 60 km below sea level. Model units are defined following the nomenclature of Schmid et al. (2004) and Froitzheim et al. (2008), each unit having a specific paleo-geographic origin and tectono-metamorphic history. Seven modelling units are considered: two continental plates (1) the Adriatic Plate, (2) the Eurasian Plate, four units from the Alpine orogenic wedge (3) the South-Alpine Superunit, (4) the Austroalpine Superunit, (5) the Penninic Superunit, (6) the Sub-Penninic Superunit and (7) Neogene sedimentary basins in the foreland and within the Alps. Due to the large-scale character of the model, relatively small constituents of the Alpine Orogen are merged together (Meliata Superunit and Inner Western Carpathian Superunit with the Austroalpine Superunit, Helvetic Superunit and Allochtone Molasse with the Sup-Penninic Superunit, intrusive rocks along the Periadriatic Fault with their host unit, minor Neogene basins with the Austroalpine Superunit). The model geometry is constrained by the geological map of Austria 1:1.5M (Schuster et al., 2019), (2) 24 published cross sections and (3) published contour maps for the Moho discontinuity (Ziegler & Dèzes, 2006) and the large Neogene basins. It has been generated with the SKUA-GOCAD software suite following the workflow of Pfleiderer et al. (2016).

The framework model 3D AUSTRIA can be visualized with the web 3D Viewer of Geosphere Austria (https://gis.geosphere.at/portal/home/webscene/viewer.html?webscene=c11cd25795294ba8b6f276ab2d072afb) or downloaded from the Tethys Research Data Repository (https://doi.tethys.at/10.24341/tethys.184) allowing the generation of a physical multi-part model using 3D printing technology. It provides a unique way to comprehend the fundamentally 3D nature of sedimentary and tectonic features, like the unconformity at the base of Neogene sedimentary basins, the Alpine frontal thrust or the Tauern Window. The data acquired in the framework of the AlpArray project can be used in future for refining the geometry of 3D AUSTRIA.

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Kinematics and rifting processes of the Liguro-Provençal Basin, Western Mediterranean

Alex Jensen[1], Eline Le Breton[1], Sascha Brune[2], Anke Dannowski[3], Dietrich Lange[3], Louisa Murray-Bergquist[3], Heidrun Kopp[3]

1. Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany
2. GFZ German Research Centre for Geosciences, Potsdam, Germany
3. GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany

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The Liguro-Provençal Basin, situated at the junction of the Northern Apennines and the Western Alps, formed due to the rollback subduction of the Adriatic-African plate underneath Europe and the subsequent upper plate extension in the Oligocene to early Miocene times. The opening of the basin was accompanied by the counter-clockwise rotation of the Corsica-Sardinia block relative to Europe until 16 Ma, with the basin widening towards the southwest. It remains controversial if the extension ever reached seafloor spreading with the production of oceanic crust, or whether it led to anomalously thin continental crust and/or to mantle exhumation. Although considered as tectonically inactive today, the Liguro-Provençal Basin shows active seismicity, indicating compression and possible basin inversion (Thorwart et al. 2021). Thus it is crucial to better understand the opening of the basin and the tectonic inheritance due to rifting in order to interpret the present-day seismicity.

To this end, we compiled existing geological and geophysical data, including recent data from the 4DMB project ("Mountain Building Processes in Four Dimensions"), to constrain the crustal and sedimentary thicknesses throughout the basin. We focus specifically on two profiles in the NE (Corsica-Provence) and SW (Sardinia-Gulf of Lion) parts of the basin, along the opening direction of the basin. For each selected profile we calculated the average velocity using the kinematic reconstructions of Le Breton et al. (2021) and the amount of extension using an aerial balancing approach. We then compared these profiles and amounts of extension with results of coupled thermo-mechanical of asymmetric rifting and surface processes modelling using Aspect and Fastscape codes from Neuharth et al. (2022).

The results of the thermo-mechanical modelling fit very well the present-day geometry of the rifted continental crust, with a wider hyper-extended rifted margin on the European and a narrower rifted margin on the Corsica-Sardinia side. Rifting migrated southeastward through time and seems to not have reached oceanic spreading nor mantle exhumation in the northeast part of the basin, as observed in the most recent seismic profile A401A-SMPL obtained within the 4DMB SPP project. Towards the southwest, the model confirms the presence of exhumed mantle, as proposed in previous study (Jolivet et al. 2015). The synthesis of geophysical data and thermomechanical modelling also fits very well in the existing kinematic reconstructions from 35 to 0 Ma of the Western Mediterranean, allowing us to infer the lateral extent of oceanic crust and exhumed mantle domains within the basin. Finally, present-day compressional seismicity seems to reactivate rift-related structures.

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Petrophysical properties across scales and compositions

Timm John[1], Sascha Zertani[1,2], Jan Pleuger[1], Frederik Tilmann[1,3], Johannes C. Vrijmoed[1], Torgeir B. Andersen[4], Loic Labrousse[5]

1. Institute of Geological Sciences, Freie Universität Berlin, Berlin, Germany
2. Njord Centre, Department of Geosciences, University of Oslo, Oslo, Norway
3. Deutsches GeoForschungsZentrum Potsdam, Potsdam, Germany
4. The Centre of Earth Evolution and Dynamics (CEED), Department of Geosciences, University of Oslo, Oslo, Norway
5. CNRS-INSU, Institut des Sciences de la Terre Paris, Sorbonne Université, Paris, France

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The scales at which observations from geophysical imaging are made are orders of magnitude larger than those made in field-based studies of fossil subduction and collision zones. Even more so, the determination of petrophysical properties of rocks is typically based on millimeter to centimeter-scale samples, and the so-obtained information is then used to inform large-scale geophysical imaging studies. Information on how such properties can be up-scaled to geophysically relevant scales is rare, underlining the need to combine petrophysical properties with structural data, obtained from relevant field analogues.

We provide results from three field analogues; (1) Tenda massif, Corsica, (2) Monte Mucrone, Sesia Zone, western Alps, and (3) Holsnøy, Lindås nappe, Scandinavian Caledonides. The bulk rock compositions cover a gradient from felsic (1-2) to mafic (3), as would be expected in the upper and lower continental crust, respectively. Petrophysical properties (P and S wave velocities and their ratios and anisotropies) were determined by direct measurement (ultrasonic pulse transmission technique) and calculated (based on texture data from neutron diffraction measurements). The data set is then used for numerical modeling (finite element method) of meter to kilometer-scale structural associations as mapped in the field (3).

The obtained results show that high-pressure metamorphism of mafic rocks results in significant increase in both P and S wave velocities, that in principle would generate a sufficient impedance contrast to be imaged by seismic methods. While structures observed in the field are typically below the scale of geophysical imaging techniques, our considerations of bulk petrophysical properties indicate that significant anisotropy may still be detectable on the kilometer scale. On the other hand, the increase of P and S wave velocities of felsic rocks during high pressure metamorphism is much smaller, however, as such compositions have a higher potential to form rocks with high mica contents, they display a large variability in seismic anisotropy, hinting at the potential to link relatively low seismic velocities, combined with high anisotropy to fluid intake during metamorphism.

Constraints on Crustal Structure in the Eastern and eastern Southern Alps

Azam Jozi Najafabadi[1], Christian Haberland[1], Mark Handy[2], Eline Le Breton[2], Michael Weber[1]

1. GFZ German Research Centre for Geosciences, Potsdam, Germany
2. Institute of Geological Sciences, Freie Universität Berlin, Germany

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In the course of this study, an extensive seismological dataset from both the temporary SWATH-D network (Heit et al., 2021) and selected stations of the AlpArray Seismic Network (Hetényi et al., 2018) was analyzed. The primary aim of this endeavor was to gain comprehensive insights into the crustal structure of the southern and eastern Alps. The small inter-station spacing (average of ~15 km within the SWATH-D network) allowed for depicting crustal structure at unprecedented resolution across a key part of the Alps. The methodological approach employed in this study entailed a sequential series of analyses to unveil the underlying features. The preliminary step encompassed the determination of the arrival times of both P and S seismic waves. Subsequently, a Markov chain Monte Carlo inversion technique was deployed to simultaneously calculate robust hypocenters, a 1-D velocity model, and station corrections (Jozi Najafabadi et al., 2021). This data was then utilized for calculation of 3-D V_P and V_P/V_S models (Jozi Najafabadi et al., 2022). In addition, the path-averaged attenuation values were obtained by a spectral inversion of the waveform data of selected earthquakes. The attenuation structure ($1/Q_P$ model) is then calculated using damped least square inversion of the path-averaged attenuation values (Jozi Najafabadi et al., 2023). These analyses resulted in a multidimensional depiction of the subsurface. The derived models for Q_P, V_P and V_P/V_S indicate subsurface anomalies that can be attributed to rock's physical parameters, presence of fluids within rocks and their motion in pores and fractures, temperature, and partial melting.

The findings reflect head-on convergence of the Adriatic indenter (the part of the Adriatic Plate that has modified the Alpine orogenic edifice) with the Alpine orogenic crust. Furthermore, a highly heterogeneous crustal structure within the study area was unveiled. The velocity model illuminated decoupling of the lower crust from both its mantle substratum and upper crust. The Moho, taken to be the iso-velocity contour of Vp = 7.25 km/s, provided insights into the southward subduction of the European lithosphere, a phenomenon previously investigated in the Eastern and eastern Southern Alps (e.g., Kummerow et al., 2004 and Diehl et al., 2009). The most pronounced high-attenuation (low Q_P) anomaly is found to be closely correlated with the high density of faults and fractures in the Friuli-Venetian region, as well as the presence of fluid-filled sediments within the Venetian-Friuli Basin. Furthermore, the northwestern edge of the Dolomites Sub-Indenter (NWDI) corresponds to a low attenuation (high Q_P) anomaly which is interpreted as a reflection of the NWDI's stronger rocks compared to the surrounding areas.

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Imaging the Alpine crust with ambient-noise tomography: Linking surface observations to deep structures

Emanuel D. Kästle[1]

1. Institut für geologische Wissenschaften, Freie Universität Berlin, Germany

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By making use of the data coverage from the AlpArray and Swath D networks, a dense set of ambient-noise measurements of Rayleigh and Love waves is extracted. This data is used to investigate the Alpine crustal and uppermost mantle structure using different approaches:

(1) Azimuthal anisotropy from Eikonal tomography for the AlpArray network. We show how Eikonal tomography can be used to extract azimuthal anisotropy from surface-wave data. The methodological advantages and difficulties are discussed in detail. It is found that strong velocity heterogeneities can be the source of a major bias by causing strongly deformed wavefronts. By averaging contributions from many azimuthal directions and careful data correction, most of this bias can be removed. The results indicate a mostly orogen parallel upper and orogen perpendicular lower layer of anisotropies. In the forelands, we find good agreement with SKS studies from which we infer that lithospheric and asthenospheric anisotropies are mostly parallel.

(2) Azimuthally anisotropic 3D shear velocity structure of the eastern Alps from rjMcMC tomography. With this innovative approach, we go beyond what is is shown in (1) and are able resolve the depth structure of the azimuthal anisotropy and estimate the model uncertainties. It is shown that under the orogen, a two layer anisotropic structure exists that separates the upper crust which is dominated by arc-parallel anisotropy from the lower crust and uppermost mantle which mostly show arc-perpendicular fast axis. We find that the anisotropy in the upper crust is largely controlled by major fault structures. The isotropic velocity distribution indicates a fast anomaly in the Giudicarie zone that may be related to Permian magmatism and causes a small offset in the Moho proxy. The estimated Moho structure closely resembles the positions of the underlying subudction slabs with a lateral offset between Central and Eastern Alps.

(3) 3D joint inversion of surface and body wave data. To better image the crust-mantle transition zone under the Alps, we apply a 3D rjMcMC imaging approach that combines different datasets and resolves the Vp and Vs structure from the surface to 600 km depth. With this approach there is no need for crustal corrections applied to the body wave travel times since the crustal structure is constrained by ambient noise data. Preliminary results of this model indicate that the slabs are more vertical and vertically more continuous as compared to a pure P-traveltime inversion.

The Python scripts used to obtain the results are already or will be published on the author's github page (github.com/ekaestle).

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Advances in imaging the Alpine crust and mantle

Emanuel D. Kästle[1], Marcel Paffrath[2]

1. Institut für geologische Wissenschaften, Freie Universität Berlin, Germany
2. Institut für Geologie, Mineralogie, Geophysik, Ruhr-Universität Bochum, Germany

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The dense coverage of the AlpArray Seismic Network and related targeted arrays (LOBSTER, Swath D, EASI) has led to numerous new models of the Alpine orogenic lithosphere, slabs and mantle above the Mantle Transition Zone. We highlight some novel features of these models, how they may help to answer old questions, as well as pose new questions:

(1) P-wave images from teleseismic travel-time tomography (Paffrath et al., 2021a,b; Handy et al., 2021) use an innovative approach to include the highly heterogeneous Alpine orogenic crust in their model. In addition to confirming previous models for partial slab detachment beneath the Western Alps, they find evidence for a long (≥300 km), subvertical slab anomaly underneath the Eastern Alps that is detached from the orogenic lithosphere at 70-150 km depth. The latter corroborates images from surface-wave tomographic studies (Kaestle et al., 2018), but contrasts with other past- and present images indicating deeper slab detachment (Handy et al., 2015) and/or a through-going connection of the slab with Adriatic lithosphere (e.g., Plomerová et al., 2022). Cooperation of the Bochum and Prague groups to explain these disparate features reveal that crucial features, e.g., the connection of slabs with the orogenic lithosphere, depends strongly the geometry of the model area and the chosen crustal model.

(2) New receiver function (RF) studies extracted signals in the Eastern Alps where previous work only imaged a 'Moho gap' (Hetényi et al., 2018; Kind et al., 2021; Mroczek et al., 2023, Michailos et al., 2023). These studies confirm the notion of marked, along-strike variations in structure: in the west (TRANSALP, 11.9°E), the European Moho is clearly down-going (e.g., Kummerow et al., 2004), whereas in the east (14°E), competing interpretations range between an underlying Adriatic Moho (Hetényi et al., 2018) and a downgoing European interface to more than 100 km depth (Mroczek et al., 2023). All methods indicate that the upper-plate Moho shallows from the E. Alps to the Pannonian Basin.

(3) The internal structure of the Eastern Alpine crust is imaged with local earthquake (Jozi Najafabadi et al., 2021) and ambient noise tomography (Molinari et al., 2020; Qorbani et al., 2020; Sadeghi-Bagherabadi et al., 2021; Kästle et al., this vol.). The LET models show a bulge-shaped fast anomaly just to the south of the western Tauern window, possibly indicating stacking of lower crustal nappes, probably of both European and Adriatic affinity (McPhee et al., this vol.), and a fast anomaly east of the Giudicarie Fault that may be related to a Permian magmatic body, as also indicated by gravity studies (Spooner et al., 2021).

(4) AlpArray has opened the door to study crustal and mantle anisotropy in unprecedented detail (Kästle et al., 2022; Soergl et al., 2022; Kästle et al., this vol.). SKS studies (e.g., Hein et al., 2021) suggest that mantle flows around slabs and potentially through slab tears, in the Western and Eastern Alps. Newest results indicate that crustal anisotropy in the Eastern Alps is layered, with an upper layer with fast directions oriented mainly orogen-parallel, approximately following major Neogene oblique-slip faults exposed at the surface. The studies also show a clear distinction between the fast-axis orientations within the Alps and in its foreland. The latter results are in excellent agreement with findings from SKS studies, indicating similar dynamics affecting the entire lithosphere. The detailed analysis of Swath-D data conducted by Link et al. (2021) has further been able to show a sharp transition in SKS splitting orientations at around 13° longitude, that is indicative of the separate evolution of central and eastern Alps.

(5) Preliminary results from the joint inversion of surface- and body-wave data provide a better understanding of the different sensitivities of P- and S-waves to the upper mantle structures under the Alps. Initial results of a P-wave velocity model from teleseismic full-waveform inversion (FWI, Friederich et al., this vol.) provide surprisingly high resolution in the crust and uppermost mantle with clear images of the Alpine orogenic roots and anomalies within the crust (e.g., Ivrea Body, E. Alps lower crustal bulge). The resulting FWI model is independent of any crustal correction and may provide a vital contribution to ongoing discussions on slab origin and detachment.

Taken together, the diversity of seismological images in the same area with often contrasting tectonic implications underscores the need for serious benchmarking of seismological models. Large arrays like AlpArray provide an excellent opportunity to conduct such comparative studies.

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3D geodynamic modelling of the present-day and long-term deformation of the Alps and Adria

Boris Kaus[1], Christian Schuler[1], Georg Reuber[1], Eline Le Breton[1,2]

1. Johannes-Gutenberg University, Mainz, Germany
2. Free University Berlin, Germany

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Linking geophysical data with geological constraints to understand the dynamics of Alpine Mountain building was one of the main goals of the 4D-MB SPP project. Whereas seismic tomography inversions give a snapshot of how the seismic velocity structure may look like today, geological constraints give (incomplete) pieces of information of how it may have evolved over time. Linking such information with the physics of the lithosphere requires geodynamic numerical models and due to the geometric complexity of the region, 3D is a must. A problem with geodynamic models is that the driving forces are usually the density differences of subducting plates with the surrounding mantle (or far-field forces), whereas the (uncertain) rheology of mantle and crustal rocks plays a crucial role as well. As such, there are quite a few uncertainties in the input parameters, even if the geometry is well-constrained.

During the first phase of the 4D-MB project, we focused on present-day models of the Alpine system. Whereas it is possible to invert for the rheology of the lithosphere in mountain belts using probabilistic Bayesian methods (Baumann and Kaus, 2015), this method requires a large number of forward simulations and thus remains infeasible in 3D. An alternative approach is to employ gradient-based inversion methods, in which the adjoint method is employed as a particularly efficient method to compute the gradient of the misfit of the model and data (usually GPS data) versus model parameters (Reuber et al., 2020; Reuber, 2021). Since the adjoint gradient method is computationally cheap (compared to a forward simulation), it can also be used to quickly determine the key model parameters of a particular simulation (Reuber et al., 2018b) or can be combined with gravity and seismic inversions (Reuber and Simons, 2020). We had initially applied this to a case where the starting forward model setup was already giving a reasonably good fit to the uplift data, in which case the method rapidly converged (Reuber et al., 2018a). It thus seemed straightforward to do the same for the Alps. Yet, several issues were encountered in the process: a) we need to consider a much wider region than just the Alps to avoid issues with the lateral boundaries; b) even with high-resolution P-wave tomographic models at hand, one still needs to interpret the seismic velocity anomalies to create an initial model setup, which is a highly non-unique step and results in various possible interpretations; c) coming up with an initial forward model that gives a reasonably good fit to the GPS data turned out to be a significant challenge. Despite running well over 350 forward simulations, we failed to obtain forward simulations that provided a well-enough fit of the velocity in Adria, and without a good starting model, gradient based geodynamic inversions do not converge to a meaningful solution (Reuber, 2020). More recently, we made another attempt in which seismic velocity was directly translated to density and viscosity anomalies using a simple, linear, scaling law, while also prescribing the far-field velocities at the model boundaries (such as that of the N. Anatolian plate). Results give a better fit in Adria (Fig. 1A), but also show that the details of the slab geometry underneath the Alps do not have much impact on the model results, while the model fit within the Alps remains unsatisfying (perhaps because of the small velocities there).

Instead of just focusing at the present day structure of the Alps, it is also interesting to see how the system evolved over the last 20-30 million years, which was the focus of our project during the 2nd phase of 4D-MB. The idea was to start with a plate tectonic reconstruction (Le Breton et al., 2021) and let the model evolve forward in time. As for the present-day models, there are many uncertainties in the plate tectonic reconstructions, such as: What was the slab dip? What were the lengths of the slabs? Were they laterally broken or not? What was the thermal and rheological structure of the plates? Given the difficulties with the present-day models, and the increased computational demands of time-dependent simulations, it is unreasonable to expect model results that magically fit all available constraints. Yet, after performing many hundreds of forward simulations, we do get some consistent results and in some of the simulations Adria moves northward and rotates anticlockwise relative to Europe by about the correct amount. The Gibraltar slab arrives at the correct place (Fig.

1B), and the models clearly show that the northward motion of Africa has little impact on the dynamics of Adria, which is instead mostly driven by the interaction of the Hellenic and Calabrian slabs while being pulled northwards by the retreating Western Alpine slab. The size and thermal structure of the Ionian oceanic lithosphere is important as well.

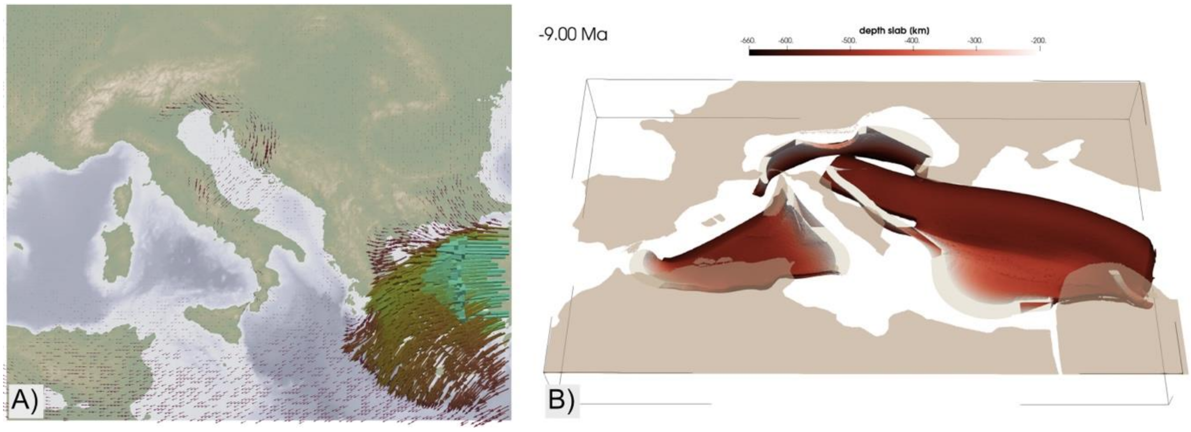

Figure 1: A) Example of present-day geodynamic models, B) Snapshot of a forward geodynamic simulation that started at 30 Ma.

We also made various technical advances, which includes the Julia package GeophysicalModelGenerator.jl to create complicated 3D geodynamic model setups from geophysical/geological data, DataPicker.jl which provides a GUI for GMG, and LaMEM.jl which is the Julia interface to LaMEM and allows installing and running LaMEM in parallel (either directly from Julia or via Jupyter or Pluto notebooks). We also extended LaMEM to include a continuous integration, adjoint inversion (Reuber et al., 2020; Reuber, 2021) and sensitivity testing (Reuber et al., 2018b).

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Pustertal-Mölltal-Gailtal-Drautal – Periadriatic Fault activity revealed by ruined buildings

Miklos Kazmer[1], Krzysztof Gaidzik[2]

1. Eötvös University, Budapest, Hungary
2. University of Silesia in Katowice, Sosnowiec, Poland

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The Periadriatic Fault system was active during the Oligocene and Miocene, producing various, large-scale strike-slip displacements. The Eastern Alpine sector is clearly visible on any relief map of the Alps, raising the interest of geologists whether it is still active today. A recent study by Prince et al. (2023, https://doi.org/10.21203/rs.3.rs-3221175/v1) measured the time of displacements by ultra-low temperature thermometers. Evidence of Late Pleistocene (>200 ky) seismotectonic activity was found. Later, historical records of seismicity along the Periadriatic Fault are exceedingly rare. Instrumental data indicate that seismotectonic deformation is mainly concentrated in the adjacent Southern Alps and Dinarides. We conducted a systematic archaeoseismological study on buildings constructed in the last two millennia along the Pustertal, Mölltal, Gailtal, Drautal, Karavanka, Savinja, and Croatian Periadriatic faults.

Roman settlements (Teurnia, Magdalensberg, Celeia, Siscia) and late Medieval churches (Romanesque in Tyrol, Innichen/San Candido, Millstatt am See, and Gothic in Lienz, Villach) carry evidence for destructive earthquakes.

Besides confirming the 9 AD event at Magdalensberg, the 1348 and 1690 earthquakes, and those in the late 19th and 20th centuries near Zagreb, we discovered several, previously unknown events. Those relevant to regional seismicity are listed below. Our own studies are marked **bold**.

1. An early 13th century earthquake severely damaged the castle of **Tyrol**.
2. The monastery church in **Innichen/San Candido** carries evidence of destruction between 1200 and 1284.
3. Churches and houses of **Lienz** display tilted walls supported by heavy buttresses, probably due to seismic event between 1531 and 1667.
4. Church of **Sachsenburg** was damaged before 1510.
5. Roman **Teurnia** was catastrophically destroyed in the early 3rd century, never to be rebuilt.
6. The Dominican monastery in **Millstatt** am See carries evidence for repeated destruction and restoration in 1201, before 1290, in 1348, and in 1690. Turbidite in the Millstätter See was formed due to the 1201 earthquake.
7. Hillside of Dobratsch suffered a catastrophic, earthquake-generated landslide in 1348.
8. Arnoldstein’s hilltop monastery was severely damaged in 1348, illustrated in a contemporary wall painting.
9. Church and town of **Villach** carry abundant evidence of seismic destruction in 1201, 1348, and 1690.
10. Turbidite in Wörther See was formed due to the 1348 earthquake.
11. **Magdalensberg** town and temple suffered damage right before 9 AD. After restoration, one more event hit the town, contributing to abandonment.
12. Homogenites in Lake Bled are witnesses to the 1348, 1511, and 1690 events.
13. Houses of downtown **Ljubljana** (Slovenia) carry buttresses built after the 1895 earthquake.
14. Roman settlement of Celeia (**Celje**, Slovenia) suffered major liquefaction event.
15. Zagreb has been repeatedly exposed to seismicity: 1880, 1906, and 2020.
16. City walls of Roman Siscia (modern **Sisak**, Croatia) were thrown into the moat sometime between 200 and 350 AD.
17. Petrinja earthquake in 2020, causing >100 sinkholes to open up.

Altogether >400 km long faults, >15 seismic sites along 9 segments, >8 destructive earthquakes indicate that the Periadriatic fault has been seismically active during the past two millennia. Intensities up to IX were observed, and magnitudes up to M 7 were estimated, calling for further detailed studies in archaeoseismology.

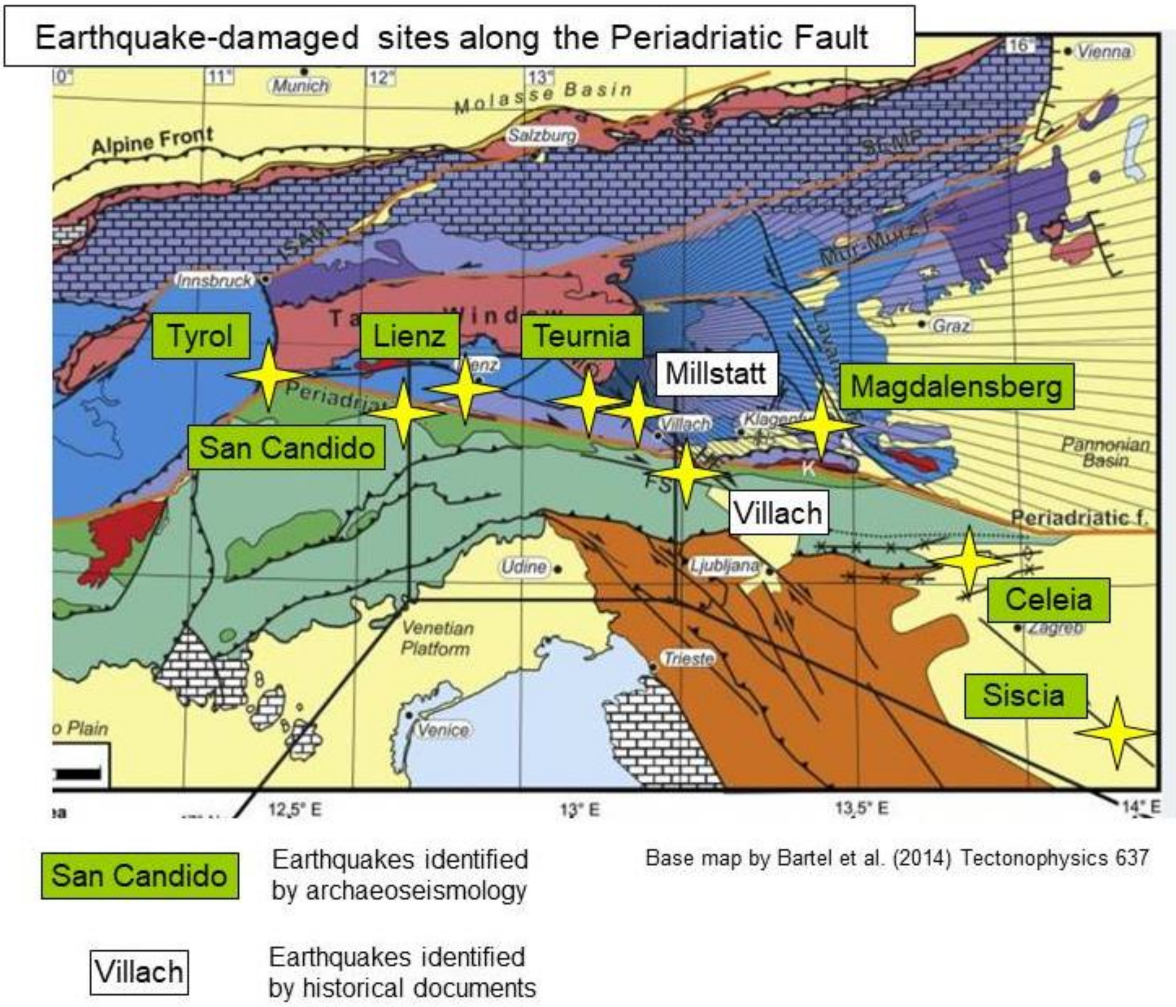

Figure 1: Major earthquake-damaged sites from the past two millennia along the Periadriatic Fault system.

Elastic anisotropies of deformed crustal rocks in the Alps

Ruth Keppler[1], Michael Schmidtke[1], Michael Stipp[2], Nikolaus Froitzheim[1]

1. Institute for Geosciences, University of Bonn, Germany
2. Institute of Geosciences and Geography, University of Halle, Germany

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The crust within collisional orogens is very heterogeneous, in composition as well as in type and intensity of deformation, leading to highly variable physical properties at small scales. This causes difficulties for seismic investigations of tectonic structures at depth since the diverse and partially strong upper crustal anisotropy might overprint the signal of deeper anisotropic structures in the mantle. We characterized the range of elastic anisotropies of deformed crustal rocks in the Alps according to the crystallographic preferred orientation (CPO) of their constituent mineral phases.

In the Lago di Cignana area of the Italian Western Alps, we sampled eclogites, blueschists and greenschists of oceanic origin (Zermatt-Saas-Zone). From the lower crustal and mantle rocks of the Ivrea Zone near Finero metagabbros and marbles were collected. The Adula Nappe in the central Alps, which was intensely deformed during the Alpine orogeny, was sampled for rocks from a typical deformed upper continental crust within the Alps. The two major rock types, orthogneisses and paragneisses and small lenses of eclogites, amphibolites and marbles were sampled.

CPOs of minerals in the samples were measured using time-of-flight neutron diffraction. Combined with single crystal elastic anisotropies these were used to model seismic properties of the rocks.

Similarities can be found within the mafic samples. The eclogite and amphibolite lenses within the continental crust, the eclogites and blueschists of oceanic origin, as well as the metagabbros of the lower crust exhibit highest P-wave velocity (VP) in lineation direction. An exception within the mafic samples is the greenschist, which shows a distribution of high VP within the foliation plane. P-wave anisotropy (AVP) of the metagabbros and eclogites is generally low with about 1.5%. The greenschist, blueschist and amphibolite samples show higher AVP of 2-4.5%. Marble also yields highest VP in lineation direction and high AVP of 8%. It can be distinguished from all other samples in the set by its high VP/VS ratio of 1.8. The felsic rocks of the continental crust show high variability. Those with high mica contents also show VP maxima in the foliation plane. They can be distinguished from greenschists, which show an average VP of 7.30 km/s, by their generally lower average VP of 6.18 - 6.81 km/s.

To approximate an average for upper crustal rocks units, we picked common CPO types of rock forming minerals within gneiss samples of the Adula Nappe representing the most common lithology. These data were used to determine an average elastic anisotropy of a typical crustal rock within the Alps yielding 4 %. This value is an approximation, which can be used for seismic models at a lithospheric scale. At a crustal or smaller scale, however, local variations in lithology and deformation as displayed by the range of elastic anisotropies within the sample set need to be considered. In addition, larger-scale structural anisotropies such as layering, intrusions and brittle faults have to be included in any crustal or smaller scale seismic model.

Sp converted waves reveal the structure of the lithosphere below the Alps and their northern foreland

Rainer Kind[1,2], Stefan M. Schmid[3], Felix Schneider[2], Thomas Meier[4], Xiaohui Yuan[2], Ben Heit[2], Christian Schiffer[5] and the AlpArray and SWATH-D Working Groups

1. GFZ Potsdam, Germany
2. Fachbereich Geowissenschaften, Freie Universität Berlin, Germany
3. Institut für Geophysik, ETH Zürich, Switzerland
4. Institut für Geowissenschaften, Christian-Albrechts-Universität Kiel, Germany
5. Department of Earth Sciences, Uppsala University, Sweden

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The structure of the lithosphere is reflecting its evolution. The Moho of the European lithosphere has already been studied intensively. This is, however, not yet the case for the lower boundary of the lithosphere, i.e., the lithosphere-asthenosphere boundary (LAB). We are using S-to-P converted seismic waves to study the structures of the Moho and the LAB beneath Europe including the greater Alpine Area with data from the AlpArray project and the European networks of permanent seismic stations. We use plain waveform stacking of converted waves without deconvolution and compare the results with stacking of deconvolved traces. We also compare Moho depths determinations using S-to-P converted waves with those obtained by other seismic methods. We present more detailed information about negative velocity gradients (NVG) below the Moho. Its lower bound may be interpreted as representing the LAB. We found that the thickness of the European mantle lithosphere is increasing from about 50°N towards the Alps along the entire east-west extension of the Alps. The NVG has also an east dipping component towards the Pannonian Basin and the Bohemian Massif. The Alps and their northern foreland north of about 50°N are surrounded in the east, west and north by a north dipping mantle lithosphere. Along 50°N, where the NVG is reversing its dip direction towards the north, is also the area along which the volcanoes of the European Cenozoic Rift System are located. Our results possibly indicate that the Alpine collision has deformed the entire lithosphere of the Alpine foreland as far north as about 50°N.

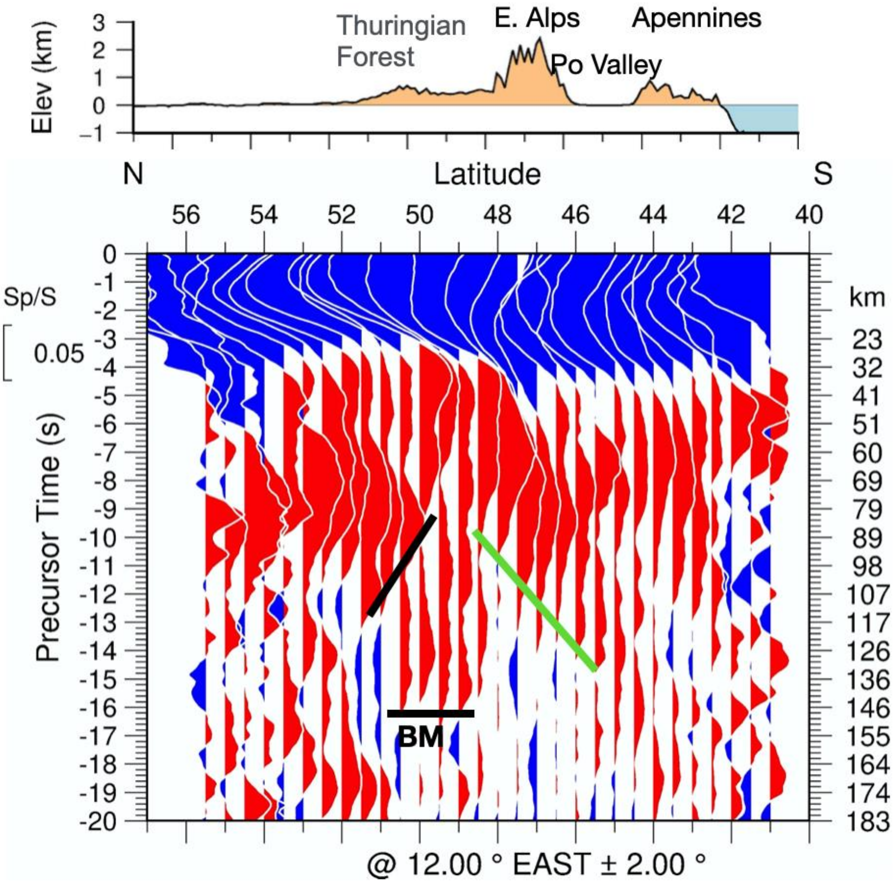

Figure 1a: Dip directions of possible lithosphere-asthenosphere boundary (LAB) in central Europe.

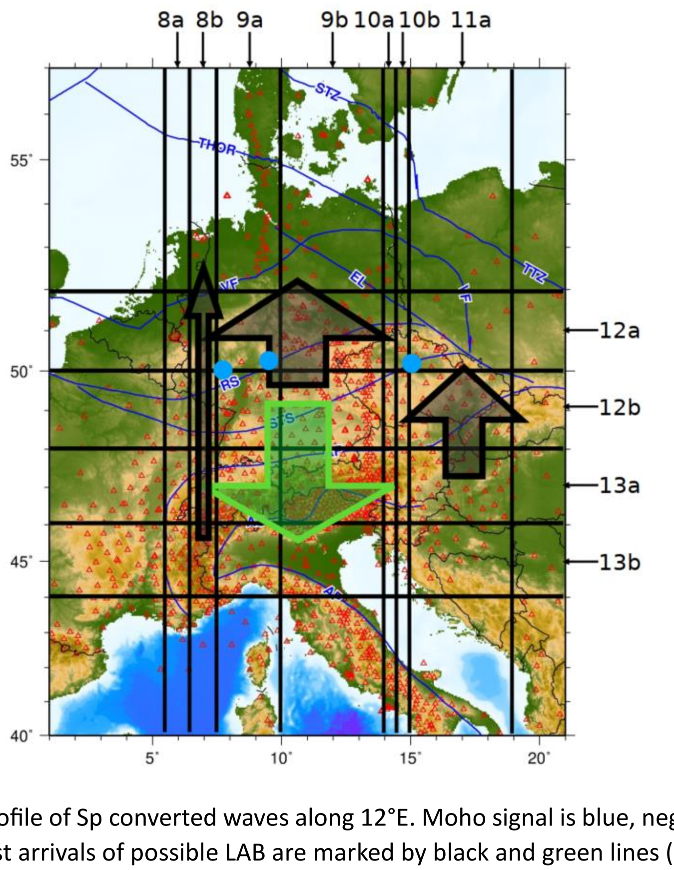

Figure 1b: North-south profile of Sp converted waves along 12°E. Moho signal is blue, negative velocity gradients are red (possibly LAB). First arrivals of possible LAB are marked by black and green lines (BM Bohemian Massif).

Devonian to Permian intrusions in the Zentralgneis Supersuite of the eastern Tauern Window constrained by U-Pb zircon geochronology and geochemistry

Chiara Költringer[1], Benjamin Huet[1], Ralf Schuster[1], Christoph Iglseder[1], David A. Schneider[2]

1. GeoSphere Austria – Bundesanstalt für Geologie, Geophysik, Klimatologie und Meteorologie, Vienna, Austria
2. Department of Earth and Environmental Sciences, University of Ottawa, Canada

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In the course of comprehensive geological mapping, the Geosphere Austria (formerly Geologische Bundesanstalt – Geological Survey of Austria) initiated a systematic geochemical and geochronological characterization of the metamorphic granitoids forming the Zentralgneis Supersuite in the eastern Tauern Window. Three dozens of samples from already defined units (Sonnblick, Siglitz, Romate, Göss, and Hochalm orthogneiss) as well as newly defined units (Säuleck, Kampleck, and Grübelwand orthogneisses) were sampled in four different nappes of the Venediger Nappe-System (Sonnblick, Romate, Hochalm, and Göss nappe).

Major and trace element geochemical analyses indicate three groups. Most of the Sonnblick orthogneiss samples, the Siglitz orthogneiss and other non-leucocratic orthogneisses derive from high-K, calc-alkaline granite with a peraluminous and magnesian composition. The analyzed samples classify as I-type (subordinately S-type) granites formed in volcanic arcs and show no negative Eu-anomaly. The Kampleck, Säuleck, and Grübelwand orthogneiss as well as leucocratic orthogneisses derive from high-Si, calc-alkaline granite, aplite and pegmatite, with a peraluminous ferroan composition. This group classifies as S-type granites formed in a within-plate setting and samples show a clear negative Eu-anomaly as well as comparably low Ba and Sr concentrations. The Romate orthogneiss and one analyzed Sonnblick orthogneiss sample derive from shoshonitic, quartz-monzonite to syenite with metaluminous and magnesian composition. This group classifies as syn-collisional A-Type granites and shows no negative Eu-anomaly with comparably high Eu, U and Th concentrations. The three distinguished groups are found in different nappes of the Venediger Nappe System; however, note that single orthogneiss units can host elements of different characteristics.

U-Pb zircon geochronology further constrains some of the orthogneiss units. A sample of coarse-grained Sonnblick orthogneiss with an augen microstructure yields a Late Devonian age. An atypical fine-grained Sonnblick orthogneiss with small K-feldspar yields a late Carboniferous age and a Siglitz orthogneiss sample yields an early Carboniferous age. Samples from Kampleck, Säuleck and Grübelwand yield middle Permian ages.

Our findings illustrate the complex and long lived intrusion story over 100 Myrs hidden in what is called the Zentralgneis Supersuite. The dominant group corresponding to I-type calc-alkaline plutonism contemporaneous to the Variscan Orogeny took more than 30 Myrs to form. At least in the Sonnblick orthogneiss, this group hosts younger intrusions that remain undefined and unmapped. Later Permian S-type intrusions are for the moment only attested in the Hochalm Nappe. However, based on lithological characteristics these can also be expected in other nappes (e.g. Sonnblick and Göss nappe). Finally, geochronological characterization of the Romate orthogneiss underpins any interpretation of its exotic chemistry. These results stress the importance of combined geochemical and geochronological analyses together with geological mapping for a more comprehensive understanding of the complex geological situation in the eastern Tauern Window.

AdriaArray – a passive seismic experiment to study plate deformation in the central Mediterranean: Status in September 2023

Petr Kolínský[1], Thomas Meier[2], and the AdriaArray Seismology Group

1. Czech Academy of Sciences, Prague, Czechia
2. CAU Kiel, Germany

DOI: http://dx.doi.org/10.17169/refubium-41049

The densely populated area around the Adriatic Sea is prone to strong multi-geohazards including earthquakes, tsunamis, landslides, flooding and volcanic activity as the Adriatic Plate is presently consumed in a tectonically active belt spanning from Sicily, over the Apennines to the Alps, the Dinarides and Hellenides. The Adriatic Plate and its active margins, which regularly generate earthquakes up to magnitude 7, represent a natural laboratory to study geodynamic causes of geohazards. To identify drivers of associated plate deformation, the plate configuration including slabs and plate boundaries, properties of active fault systems and of the acting stress field have to be determined. AdriaArray, a dense plate-scale regional array deployed in the central Mediterranean, will provide data necessary for passive seismic imaging of the crustal and upper mantle structure and for the analysis of seismic activity. AdriaArray consists of 995 broad-band stations (corner period: 30 s and larger) and 446 broad-band temporary stations from 24 mobile pools. Currently, 390 of the planned temporary stations, corresponding to 87 %, have already been installed. The average station spacing amounts to about 50 km. For the first time, a homogeneous coverage by broad-band stations in an area from the Massif Central in the west to the Carpathians in the east, from the Alps in the north to Sicily and the Kefalonia Fault Zone in the south will be achieved. The backbone network - operated between 2022 and 2025 - is complemented by several locally densified and LargeN networks for example in the western Carpathians, Croatia, in the Vrancea region, and Albania. Recorded data is archived at 8 EIDA nodes mostly by transmission of real-time data streams. Regular data quality checks ensure high data availability and data quality. AdriaArray, the largest passive seismic experiment that has been performed in Europe so far, is based on intense cooperation between local network operators, mobile pool operators, field teams, ORFEUS, EPOS and interested research groups. Altogether, more than 60 institutions are participating in the AdriaArray experiment and are forming the AdriaArray Seismology Group founded in 2022. Currently, Collaborative Research Groups are established to coordinate the data analysis.

Ligurian Ocean Bottom Seismology and Tectonics Research (LOBSTER)

Heidrun Kopp[1], Dietrich Lange[1], Anke Dannowski[1], Martin Thorwart[2], Ingo Grevemeyer[1]

1. GEOMAR, Marine Geodynamics, Helmholtz Centre for Ocean Research Kiel, Kiel, Germany
2. Institute of Geosciences, Kiel University, Kiel, Germany

DOI: http://dx.doi.org/10.17169/refubium-41050

The LOBSTER project constitutes the offshore component of the DFG Priority Program "Mountain Building Processes in Four Dimensions" (SPP 2017, 4DMB) and aimed to expand the densely spaced AlpArray broadband seismic network to the offshore domain in the Ligurian Sea. The LOBSTER program encompassed research cruises on the French RV *Pourquoi Pas?* in 2017 to deploy a long-term ocean bottom seismology network that was recovered using the German RV *Maria S. Merian* in 2018 (Fig. 1). The LOBSTER long-term seismic network consisted of 7 French (from IPGP) and 22 German (from the DEPAS pool and from GEOMAR) stations. During the second cruise an active seismic experiment was conducted to complement the passive seismology study. The refraction seismic data acquisition was conducted along two wide-angle profiles: P01 runs from the Gulf of Lion to Corsica and P02 trends parallel to the center of the Ligurian Basin in a NE-SW direction. Both profiles were analyzed using a travel time tomography (Dannowski et al., 2020 and in prep). The combined data set in addition to high-resolution bathymetry data shed light on today's active deformation of the Ligurian Sea (Thorwart et al., 2021). In addition, the 3-D crustal and upper mantle structure of the Ligurian Basin was inferred from surface wave tomography (Wolf et al., 2021). The main technical aim of the LOBSTER project is to provide consistent data that can be smoothly integrated with the onshore seismology data. Key features in the data pre-processing are the correct timing, determining of the orientation of the horizontal seismometer components, and the searchability and availability of the data based on FAIR data standards.

LOBSTER studied the Ligurian Sea at the transition from the western Alpine orogen to the Apennine system. This complex geodynamic setting is manifested in pronounced variations in crustal thickness. Topographic gradients in the area are the largest for the entire Alpine-Mediterranean domain, rising from -2500 m in the Ligurian basin to > +3000 m in the Alpine-Apennine orogen over a distance of less than 100 km. The Ligurian Basin is a back-arc basin opened by the south-eastward trench retreat of the Apennines-Calabria-Maghrebides subduction zone, which also triggered the opening of the adjacent western Mediterranean basins. The recent deformation in the Ligurian Sea results from compression along its northern margin (0.3 - 1.5 mm/year shortening), but no significant convergence is evident from GPS data, and rates of deformation are very low.

The LOBSTER data set offers a better understanding of the complex geodynamic setting of the Ligurian Sea, which is characterized by pronounced variations in crustal thickness. Based on the LOBSTER data the following conclusions were documented:

- Extension in the Ligurian Basin led to stretched and very thin continental crust or exhumed, partially serpentinised mantle.
- Continental crustal thinning from north to south is related to the increase of extension with increasing distance from the rotation pole of the anticlockwise rotation of the Corsica–Sardinia block.
- Seafloor spreading and formation of mantle-derived oceanic crust was not initiated during the extension of the Ligurian Basin.
- The Ligurian Sea is currently closing while Africa and Eurasia are converging. Part of the stresses are taken up in the basin center through re-activation of extension-related faults.

Data analysis is still ongoing and further results are expected from local earthquake tomography in the area of the Alps-Ligurian Junction conducted with the data from the long-term ocean bottom seismometer deployment.

Figure 1: Ship track of RV Maria S. Merian cruise MSM 71 from Las Palmas de Gran Canaria (07.02.2018) to Heraklion (27.02.2018) with profiles acquired in the Ligurian Sea northwest of Corsica.

The Alps Paleoelevation and Paleoclimate Experiment (APE): Neogene Paleoelevation and Paleoclimate of the Central Alps

Emilija Krsnik[1,2], Svetlana Botsyun[3,4], Katharina Methner[5], Sebastian G. Mutz[3,6], Todd Ehlers[3,6], Andreas Mulch[1,2]

1. Senckenberg Biodiversity and Climate Research Centre, Frankfurt am Main, Germany
2. Institute of Geosciences, Goethe University Frankfurt, Germany
3. Department of Geosciences, University of Tübingen, Germany
4. Institut für Meteorologie, Freie Universität Berlin, Germany
5. Institute of Geophysics and Geology, University of Leipzig, Germany
6. School of Geographical & Earth Sciences, University of Glasgow, UK

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Stable isotope paleoaltimetry takes advantage of the relationship between orogen elevation and the stable isotope ratios in meteoric water, which are ultimately recorded in geological archives like foreland basins or orogen-internal shear zones. The δ-δ approach relies on contrasting time-equivalent δ18O and δD records from high- and low-elevation sites to constrain the height of the orogen at the time these geologic archives were formed. However, at the same time, different boundary conditions such as changing paleogeography, atmospheric CO2 concentrations or sea surface temperatures result in complex paleoclimate model outputs, which predict significant changes in the isotopic composition of meteoric water. These changes may be recorded in geological archives and thus complicate the reconstruction of past elevations. The 4DMB Phase 1 project APE aimed at generating a first quantitative estimate for the paleoclimatic signal in Alpine stable isotope records, so that these records may be corrected for and ultimately yield more accurate paleoelevation estimates. We addressed this challenge by integrating isotope-tracking climate model (ECHAM5-wiso) simulations with stable isotope and clumped isotope data from the foreland basin and high-elevation regions of the central Alps.

ECHAM5-wiso simulations have been conducted with 1) boundary conditions based on paleogeographic reconstructions of the Last Glacial Maximum (LGM) and the mid-Pliocene (PLIO), and 2) different topographic scenarios for the Alps. The simulations show that modifying environmental conditions can produce similar magnitudes of δ18O change as changes in alpine topography. For example, the climatically induced δ18O changes in the PLIO and LGM experiments correspond to the magnitude of changes created by setting the entire orogen to 50% and 150% of its modern height, respectively (Botsyun et al., 2020). Our modelling results stress the need for the paleoaltimetry community to correct isotopic signals in geologic archives for climate-induced changes in isotope ratios.

Pedogenic carbonate proxy data from alluvial megafans of the Swiss Molasse Basin revealed that 1) low-elevation, distal δ18O values are higher than previously assumed and thus, more adequately reflect low-elevation δ18O values required for paleoelevation estimates; 2) Mid-Miocene megafans had considerable topography and an internal elevation gradient; 3) clumped isotope-derived carbonate formation temperatures yield low-elevation paleoclimate estimates and help to embed δ18O data into global climate models. Under consideration of previous work and our modelling results, we conclude that the Central Alps, more specifically the region surrounding the Simplon Fault Zone, attained surface elevations of >4000 m no later than the mid-Miocene (Krsnik et al., 2021).

In summary, our approach represents an important methodological advance that allows the disentangling of climatic and surface uplift signals in the geologic stable isotope record. Furthermore, new insights into the Alps elevation history can help to constrain the timing of slab inversion and/or break-off in the Western/Central Alps.

Phase 1 publications:

Botsyun et al., 2020, GRL, doi:10.1029/2019GL086046

Botsyun et al, 2022, Paleoceanography and Paleoclimatology, doi:10.1029/2022PA004442

Krsnik et al., 2021, Solid Earth, doi:10.5194/se-12-2615-2021

Methner et al., 2020, Scientific Reports, doi:10.1038/s41598-020-64743-5

Mutz et al., 2019, ESurfD, doi:10.5194/esurf-7-663-2019

Anisotropy and XKS-splitting from geodynamic models of double subduction: Testing the limits of interpretation

J. P. Kruse[1], G. Rümpker[1], F. Link[1,2], T. Duretz[1], H. Schmeling[1]

1. Institute of Geoscience, Goethe University Frankfurt, Germany
2. Department of Geology and Geophysics, Yale University, United States

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In this study, we develop three-dimensional geodynamic models to predict XKS-splitting for double subduction scenarios characterized by two outward dipping slabs. These models are highly relevant in various realistic settings, such as the central Mediterranean. We focus on the analysis of XKS-splitting, a key geophysical observable used to infer seismic anisotropy and mantle flow patterns predicted from these geodynamic models. Our geodynamic models simulate the concurrent subduction of two identical oceanic plates which are separated by a continental plate. The variation of the separating plate strength, cause a transition from a retreating to a stationary trench. The models provide detailed insights into the temporal evolution of mantle flow patterns, especially the amount of trench parallel flow, induced by these double subduction scenarios. In a second step, we use the well-known D-Rex model (Kaminski et al., 2004) to efficiently estimate the CPO development in response to plastic deformation produced by mantle flow. Based on the results of the D-Rex model, which includes the full elastic tensor of a deformed multiphase polycrystalline mantle aggregate within the three-dimensional model, we obtain synthetic apparent splitting parameters at receivers placed at the surface by applying multiple-layer anisotropic waveform modeling. Employing analytical techniques, we show the ambiguous nature of apparent splitting parameters, as already suggested by previous studies based on numerical modeling. In the light of the results, we postulate that a meaningful inversion, based on the commonly applied 2-layer anisotropic model, requires additional constraints on fast-axis orientation or strength of anisotropy (delay time). Finally, we show that constraints from our texture simulations (i.e., the integrated delay time) can be used to achieve unique 2-layer models that perfectly fit the synthetic observables. Such models could serve as reference for the interpretation of the observations. Our study highlights the necessity of combining geodynamic modeling and XKS-splitting analysis to shed light on complex upper mantle flow patterns such as those that might occur around subduction zones.

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Role of lithospheric-scale geological heterogeneity in continental lithosphere dynamics

Ajay Kumar[1], Mauro Cacace[1], Magdalena Scheck-Wenderoth[1,2]

1. GFZ German Research Centre for Geosciences, Potsdam Germany
2. Faculty of Georesources and Materials Engineering, RWTH Aachen University, Aachen, Germany.

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Starting from our analysis of the Alpine orogen in 4D-MB (Spooner et al. 2022), we analysed how the Alps compare to other parts of the Alpine-Himalayan collision zone (AHCZ). We find that all orogens in the AHCZ exhibit characteristic diffused seismicity compared to the intraplate regions (Storchak et al. 2013). Interestingly, they also show a thicker-than-average silica-rich upper crust and total crustal thickness, while their lithosphere thickness has been shown to be similar to that of stable continental interiors (e.g., Tibet, Zagros Priestley et al. 2018). These observations provide a metric for the lithospheric-scale geological inheritance, the role of which we aim to understand in continental lithosphere dynamics over geologic timescales. We use data-driven modelling to compute the present-day thermomechanical state of the AHCZ lithosphere (Cacace & Scheck-Wenderoth 2016). To do so, we first compute 3D steady-state temperature distribution in the AHCZ considering variations in the crustal layers from published models with representative radiogenic heat production and thermal properties. The temperature boundary condition is fixed at the surface to 15°C and at the base of the model (200 km) is derived from the conversion of seismic tomography models. We then compute the differential stress distribution for the AHCZ using equilibrium 3D temperature distribution and laboratory-derived rheological properties representative for each layer in the model.

Our results (Kumar et al. 2023) indicate the existence of a critical crustal thickness, which is thermodynamically controlled by the internal energy and chemical composition of the crust. The value of this critical crustal thickness matches the global average of continental crust thickness. Orogenic lithospheres with thicknesses above this critical value possess higher potential energy and are weakened by the internal energy from heat-producing elements, whereas continental intraplate regions with thicknesses close to the critical crustal thickness are stronger. Weaker orogenic lithospheres deform via dissipating this energy in a diffused deformation mode, leading to zones of deformation in contrast to focused deformation at the plate boundaries.

The observed crustal differentiation in the AHCZ could be understood as perturbations to the critical crustal thickness caused by plate-boundary forces. The dynamic evolution of these perturbations (Houseman & Houseman 2010) indicates that the critical crustal thickness is a stable fixed-point attractor in the evolutionary phase space of the continental lithosphere. The exact characteristics of the evolutionary path depend on the amplitude of perturbations, the source of the initial driving energy, and the relaxation time scale of the active dissipative process (thermal diffusion and/or viscous deformation). Typical ranges of thermal properties and viscosities of the continental lithosphere suggest that the thermal diffusion always lags the viscous relaxation giving rise to a thermodynamic feedback loop between thermal and mechanical relaxation of the out-of-balance energy in the orogenic lithosphere. Exponentially growing energy states, leading to runaway extension are efficiently dampened by enhanced dissipation from radioactive heat sources. This eventually drives orogens with their thickened radiogenic crust towards a final equilibrium state.

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DEFORM – Deformation patterns in relation to the deep configuration of the lithosphere of the Alps and their forelands

Ajay Kumar[1], Denise Degen[2], Mauro Cacace[1], Magdalena Scheck-Wenderoth[1,3], Judith Bott1, Hans-Jürgen Götze[4], Boris Kaus[5]

1. German Research Centre for Geosciences, Potsdam, Germany
2. Computational Geoscience, Geothermics and Reservoir Geophysics (CG3), RWTH Aachen University, Aachen, Germany
3. Faculty of Georesources and Materials Engineering, RWTH Aachen University, Aachen, Germany.
4. Institute of Geosciences, Christian-Albrechts-University of Kiel, Kiel, Germany
5. Institute of Geosciences, Johannes Gutenberg University of Mainz, Mainz, Germany

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Present-day surface deformation in the Alps in terms of uplift and crustal seismicity has been attributed to surface (i.e., climatic) and tectonic processes (i.e., subduction, slab detachment/break-off, mantle flow). Quantifying the relative contribution of these forces and their interplay is fundamental to understand their role in mountain building. The present-day 3D configuration of the lithosphere and upper-mantle is a prerequisite to assess the contribution of tectonic processes.

In the first phase of 4D-MB, INTEGRATE project produced a multidisciplinary data-integrated crustal model of the Alps and its forelands (Spooner et al., 2019, 2020, 2022). In the follow-up project DEFORM, we use these results to quantify how the active forces originating from the internal heterogeneity in the lithosphere and upper-mantle (i.e., lithospheric thickness and slabs in the asthenosphere) can provide some insights into the present-day mechanical set-up of the study area. To objectively interpret the upper-mantle configuration, we convert the results of regional shear-wave tomography models to temperature using an in-house developed tool (Kumar, 2022) based on Gibbs-free energy minimization algorithm (Connolly, 2005). Our results showcase a shallow/attached slab in the Northern Apennines as a common feature in the different tomography models, as also consistent with recent AlpArray seismic data-derived tomography models. They also highlight some differences among the different tomography models beneath the Alps. We quantitatively address these differences by statistically clustering tomography models into three end-members corresponding to the mean and 67% confidence intervals. These end-member models represent scenarios ranging from shallow/attached slabs to almost no slabs in the northern Apennines and Alps.

End-member scenarios of the mantle configuration are tested with the new pan-Alpine gravity anomaly by 3D density modelling (IGMAS+, Götze et al., 2023), surface uplift from GNSS, AlpArray seismicity catalogue, mantle flow inferred from the shear-wave splitting measurements of the AlpArray seismic experiment, and resulting topography. As a first step, we model topography and deformation velocities as resulting from buoyancy-forces driven by a quasi-instantaneous flow resulting from the first-order rheological structure of the lithosphere-asthenosphere system using the open-source geodynamic simulator LaMEM (Kaus et al., 2016). We found that detached slab beneath the Alps, but attached beneath the Northern Apennines captures first-order patterns in topography, vertical surface velocities, and mantle flow (Kumar et al., 2022). The presence of an attached slab beneath the northern Apennines can also explain the observed sub-crustal seismicity compared to the upper-crustal seismicity in the Alps.

Data-derived scenario-based modelling approach allowed us to capture the first-order characteristics of the lithosphere and upper-mantle configuration in the Alps and corresponding forelands. Although we have been able to explain first-order observations with respect to the end member variations in viscosity and density contrasts, we additionally carried out a global sensitivity analysis to quantify associated uncertainties as well as the degree of parameter correlation within a solid density-effective viscosity phase space. This was done using physics-preserving surrogate models (model order reduction via reduced basis, Degen et al., 2022) to effectively run ensemble models of the dynamic state of the system (Denise et al., 2023). Using surrogate models, we explore deformation velocities and stresses, guiding boundary conditions to reconstruct the loading/unloading history of the last glacial cycle.

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Anisotropy along a N-S profile of mica rich lithologies in the western Tauern Window (Eastern Alps, Austria)

Dustin Lang[1], Rebecca Kuehn[1], Rüdiger Kilian[1], Michael Stipp[1]

1. Institute of Geosciences and Geography, University of Halle, Halle (Saale), Germany

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Anatomy and internal structure of the Alpine orogens are difficult to decipher as structural information is usually limited to surface and seismic data. Seismic results very much depend on the elastic wave velocity model of the rocks. Simple velocity models depend strongly on the rock composition. Seismic properties are directionally dependent. Anisotropy can be subdivided into intrinsic (CPO of minerals and alignment in rock/texture) and extrinsic (compositional layering or fractures) anisotropy. In the investigated rock samples, phyllosilicates are by far most decisive for the elastic anisotropy due to their platy shape. We present here the first results of fabric analysis in a N-S profile of phyllosilicate-rich samples (mainly Innsbruck quartzphyllite and Bündner schist) from the Brenner Base Tunnel Project in order to obtain a refined anisotropy and velocity model.

Phyllosilicate-rich sections were selected from borehole and tunnel samples, from which 1.5 – 3.5 mm wide columns were drilled out from layers of different composition and structure. The CPO of phyllosilicates and graphite was measured using high energy X-ray diffraction at German Electron Synchrotron (DESY) and European Synchrotron Radiation Facility (ESRF). Pole figure data were directly extracted using single peak evaluation and compared to the optical microstructure and compositional distributions using µXRF measurements.

Texture strength is variable along the section with peak values at the transition from the Innsbruck quartzphyllite to the upper Bündner schist. The texture strength correlates positively with the content and distribution of phyllosilicates and graphite. By measuring the smallest representative volume element, we estimate the upper bound of expected intrinsic velocity anisotropies. The effect of (micro)structure-based upscaling on these anisotropies will be discussed.

Early Miocene tectono-sedimentary shift in the eastern North Alpine Foreland Basin and its relation to changes in tectonic style in the Eastern Alps

Eline Le Breton[1], Anne Bernhardt[1], Robert Neumeister[1,2], Claudia Heismann[1], Arthur Borzi[1], Julian Hülscher[1,3], Richard Sanders[1], Patrick Grunert[4], Mark R. Handy[1], Peter McPhee[1]

1. Institute of Geological Sciences, Department of Earth Sciences, Freie Universität Berlin, Berlin, Germany
2. DEEP. KBB GmbH, Bad Zwischenahn, Germany
3. Basalt-Actien-Gesellschaft, Linz am Rhein, Germany
4. Institute of Geology and Mineralogy, University of Cologne, Germany

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A striking difference along the Alpine Orogen is the style of collisional tectonics during the Oligo-Miocene, with the onset of escape tectonics in the Eastern Alps (Fig. 1A). The indentation of the Adriatic Plate into the Eastern Alpine Orogen resulted in the formation of conjugate dextral and sinistral strike-slip faults in the vicinity of the Tauern Window. Moreover, major changes occurred in the foreland of the Eastern and Southern Alps in the Early Miocene, with the cessation of the northern Alpine front propagation and the onset of thrusting along the Southern Alpine Front. In this study, we present new results from structural, stratigraphic and subsidence analyses of the eastern North Alpine Foreland Basin (NAFB; Fig. 1B) as part of the "Mountain Building in 4 Dimensions" project, German branch of the European AlpArray initiative, which aims at better understanding the deep crustal-mantle structures of the Alpine Orogen and their relation to surface processes.

Our results show a first phase of onset of foreland sedimentation in the eastern NAFB between c. 33-28 Ma, followed by a strong tectonic-driven subsidence between c. 28-25 Ma ending by a phase of erosion and the formation of a basin-wide Northern Slope Unconformity (NSU; Fig. 1C & 1D). During this time period, the rift-related Mesozoic normal faults of the European platform were reactivated and are capped by the NSU (Fig. 1D). We interpret this phase as an increase in the flexure of the subducting European Plate under the growing Alpine Orogen. Between 25-19 Ma, the eastern NAFB remained in a deep-marine, underfilled state with a gently increase in subsidence. A major shift took place around 19-17 Ma with strong tectonic-driven uplift, ranging from 200 m (absolute minimum) to 1200 m depending on uncertainties on paleo-water depths, and rapid sedimentary infill of the basin (Fig. 1C & 1D). We discuss the possible causes for this major tectono-sedimentary shift in the eastern NAFB in relation to contemporaneous changes in collisional tectonics within the Eastern and Southern Alps, and with a potential Early Miocene slab break-off event beneath the Eastern Alps.

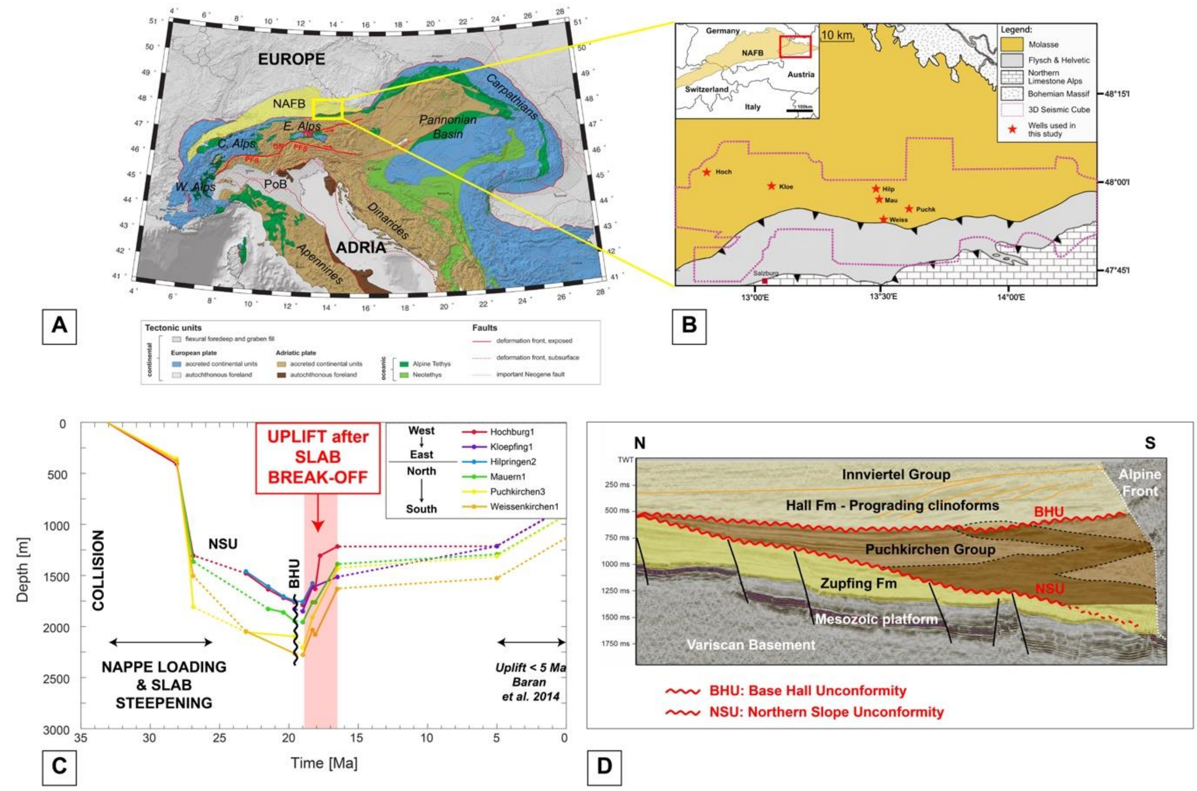

Figure 1. A: Tectonic map modified from M.R. Handy based on sources listed in Handy et al. (2019), yellow box shows location of our Study Area, **B:** Location of 3D seismic cube and wells used for subsidence analysis, modified after Masalimova et al. (2015), **C:** Tectonic subsidence curve (mean) for all wells (location in B.), and **D:** Seismic profile through the eastern NAFB showing the general stratigraphy of the eastern NAFB. Note the normal faults (black lines) in the Zupfing Fm, which reactivated Mesozoic rift-related normal faults and are capped by the NSU. Abb.: GF: Giudicarie Fault, NAFB: North Alpine Foreland Basin, PFS: Periadriatic Fault System, PoB: Po Pain, TW: Tauern Window.

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Stress transfer and Quaternary faulting in the northern Alpine foreland

Mader, S.[1], Reicherter, K.[2], Ritter, J.[1] and the AlpArray Working Group

1. KIT, Geophysical Institute, Karlsruhe, Germany
2. RWTH Aachen, Neotectonics and Natural Hazards, Germany

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Within the SPP *Mountain Building Processes in Four Dimensions* (MB-4D) we studied postglacial and present seismic rupturing in the northern Alpine Foreland to better understand the impact and forces of mountain building. We started a seismological field experiment to densify the permanent monitoring networks and the AlpArray Seismic Network. The later was also supported as well as its predecessor UNIBRA (Hetényi et al., 2018; Schlömer et al., 2022). Our StressTransfer network consisted of five recording stations in the Upper Rhine Graben, five in the Molasse Basin and five around the Albstadt Shear Zone (Mader et al., 2021a). The latter are still operating due to the increased seismicity during the last years below the western Swabian Alb. We determined local minimum 1-D seismic velocity models to relocate known events in the study regions (Mader et al., 2021b). Waveform cross-correlation was done to detect hitherto unknown events and recover earthquake sequences around the Albstadt Shear Zone (Mader et al., subm.). To determine fault planes and rupture mechanisms we used relative event locations (hypoDD) and FOCMEC for fault plane solutions.

For the Albstadt Shear Zone (ASZ), an NNE–SSW striking left-lateral strike-slip rupture zone, we determined a direction of the maximum horizontal stress (*SHmax*) of 140°–149°. Down to ca. 7–8 km depth, *SHmax* is bigger than *SV* (vertical stress); below this depth, *SV* is the main stress component. Beneath the shallow Hohenzollerngraben (ca. 2-3 km depth), which is nearly perpendicular to the ASZ, we found an NW-SE striking dextral strike-slip fault zone with very weak micro-seismicity in 11-15 km depth (Figure 1). This zone is possibly a reactivated old upper-crustal tectonic structure. At the interception of the ASZ and the NW-SE striking fault zone we observe NNW-SSE striking sinistral strike-slip and normal faulting micro-earthquakes which belong to a heterogeneous deformation zone with complex faulting. In Figure 1 we summarize our current model for the ASZ and its surroundings. The detection of many micro-earthquakes and the related active faults was only possible with the help of the additional temporal recording stations in the region and the studies of a PhD student (S.M.).

We thank the DFG for funding our project and the State Earthquake Service Baden-Württemberg in Freiburg for providing data (Az. 4784//18_3303).

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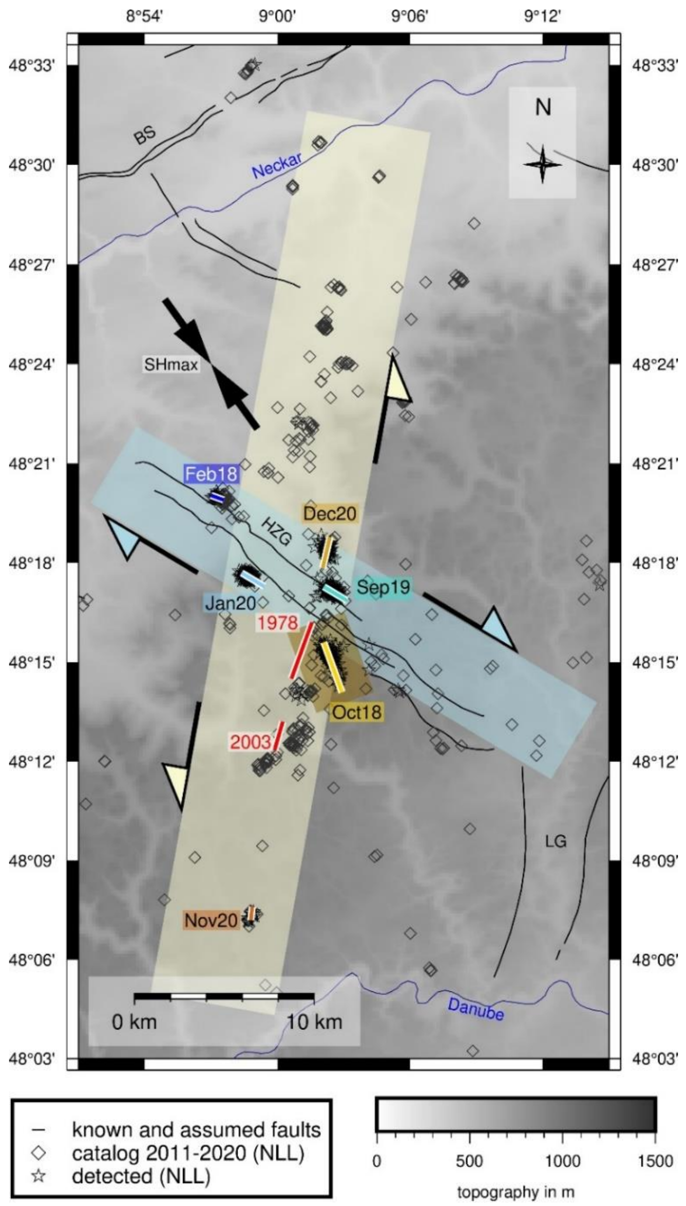

Figure 1: New tectonic model of the western Swabian Alb around Albstadt after Mader et al. (subm.). Colored lines indicate active faults of earthquake sequences. Their lengths are based on HypoDD hypocenter distributions. Red lines show rupture planes of the 1978 and 2003 earthquakes (after Stange and Brüstle, 2005). Blue (NW-SE dextral strike-slip) and yellow (ASZ) shaded areas represent the two active fault zones on the western Swabian Alb. Colored arrows indicate the movement of the strike slip faults. Stars represent NonLinLoc hypocenter locations of detected events (uncertainty < 2 km and at least six phase picks). Best located events (squares) from 2011 to 2018 are from Mader et al (2021b) complemented with new located events in 2019 to 2020 (Mader et al., subm.) using the minimum 1D seismic velocity model ASZmod1 and station corrections in NonLinLoc (Mader et al., 2021b). Black arrows show the direction of the maximum horizontal stress (*SHmax*) after Mader et al. (2021b). Topography is based on SRTM15+ (Tozer et al, 2019).

Investigating the post-collisional reorganization of the Eastern Alps using a 4D reconstruction

Peter J. McPhee[1], Mark R. Handy[1], Eline Le Breton[1]

1. Institute of Geological Sciences, Freie Universität Berlin, Germany

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In Neogene time, the Eastern Alps underwent a profound post-collisional tectonic reorganisation. This featured indentation of the Alpine orogenic wedge by the Adriatic upper plate, eastward lateral extrusion between conjugate strike-slip faults, and a shift from thrust propagation on the European lower plate to the Adriatic upper plate, accreting the eastern South Alps fold-thrust belt. The triggers and driving forces of this tectonic reorganisation remain hotly debated.

We present new sequentially restored orogen-scale cross sections along the TRANSALP (12°E) and EASI (13.3°E) transects, plus an E-W orogen-parallel section (46.5°E) to investigate the kinematic evolution of the Neogene tectonic reorganisation in 4D. These transects were affected by eastward lateral extrusion, and so we used a map-view reconstruction to restore out-of-section transport of rock at the onset of rapid extrusion (23 Ma), and the onset of thick-skinned thrusting in the eastern South Alps fold-thrust belt (14 Ma). We then compared our results with V_p LET and teleseismic models of the crust and upper mantle.

The geologic record reveals two phases of indentation in the Tauern Window: (Phase 1, 23-14 Ma) The Adriatic crust acted as a coherent indenter, with northward motion relative to Europe accommodated by shortening within the Eastern Alps orogenic wedge as well as sinistral motion along the Giudicarie Fault. Initially, upright folding of Penninic units, including the Venediger nappes, in the Tauern Window accommodated most shortening, but by middle Miocene time, eastward lateral extrusion of the entire metamorphic edifice and NCA was the primary mechanism accommodating N-S shortening. This shortening required ongoing subduction of the European lithosphere, ruling out previous models involving north-dipping Adriatic subduction. A purported detachment below the Venediger Duplex is inferred to have served as the base of the laterally extruding wedge, which comprised the previously subducted and exhumed European crust.

(Phase 2, 14 Ma-Present): Since the middle Miocene, the leading edge of the Adriatic indenter has been deforming, forming the thick-skinned South Alps fold-thrust belt. The onset of S-directed shortening is recorded by Langhian-Serravallian rocks beneath the Valsugana Thrust. In contrast, the Adriatic lower crust of the fold-thrust belt was decoupled and transported northwards into the orogenic wedge. In the TRANSALP section, the European lithospheric mantle currently extends beneath the orogenic wedge, whereas in the EASI section the subducted European lithosphere has detached. The Adriatic lower crust indented the deeply buried equivalents of the European Venediger rocks exposed in the Tauern Window. A high-velocity (6.8-7.25 km/s) bulge in LET models of the TRANSALP section images this indenter, and possibly includes accreted European lower crust.

We find that when the European slab detached beneath the Eastern Alps, shortening, exhumation, and lateral extrusion of the Eastern Alps orogenic wedge became increasingly important in accommodating Adria-Europe convergence. This culminated in the accretion of the South Alps which now forms the southern part of the orogenic wedge and primarily accommodates ongoing convergence. We note that in the E-W orogen-parallel section, a vertical gap within the slab anomaly, interpreted as a horizontal slab detachment, occurs east of the western boundary of the Tauern Window and the north projection of the Giudicarie Fault. Slab detachment (Handy et al., this volume) is an appealing explanation for the Neogene evolution by eliminating slab pull and redirecting the shortening into the south part of the orogenic wedge.

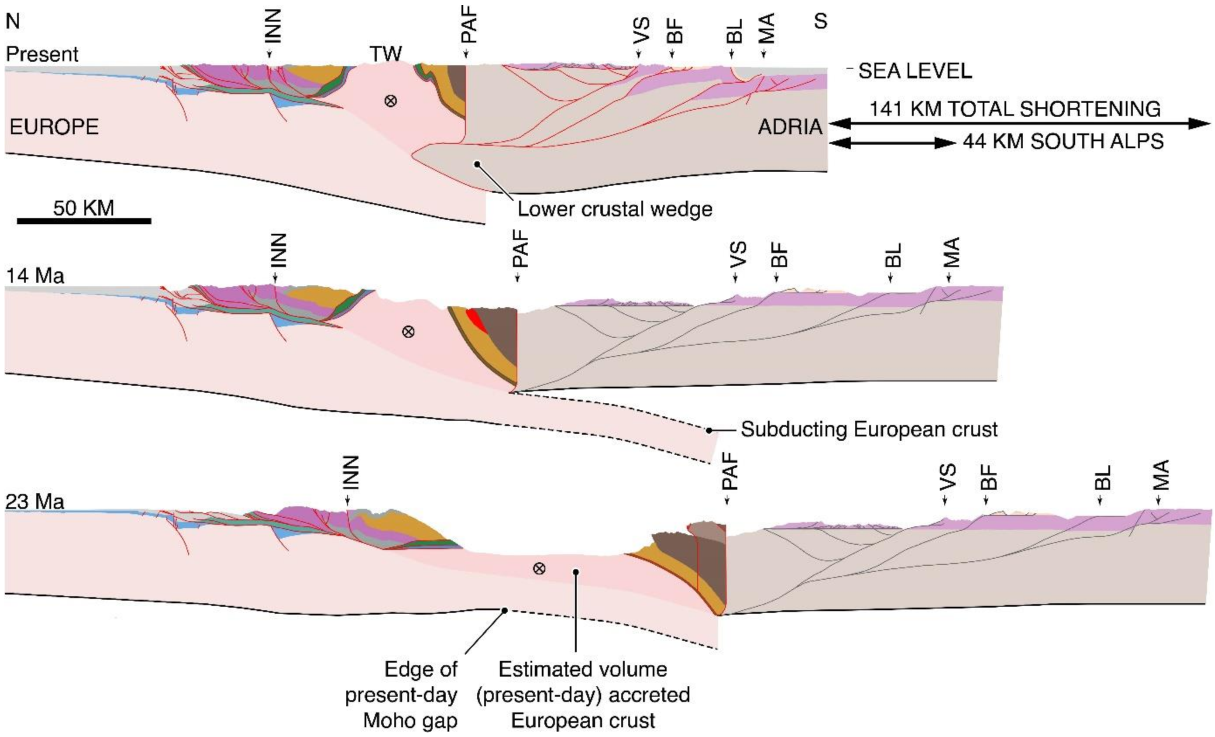

Figure 1A: Restored profiles along the TRANSALP section. Red = active faults during time slice.

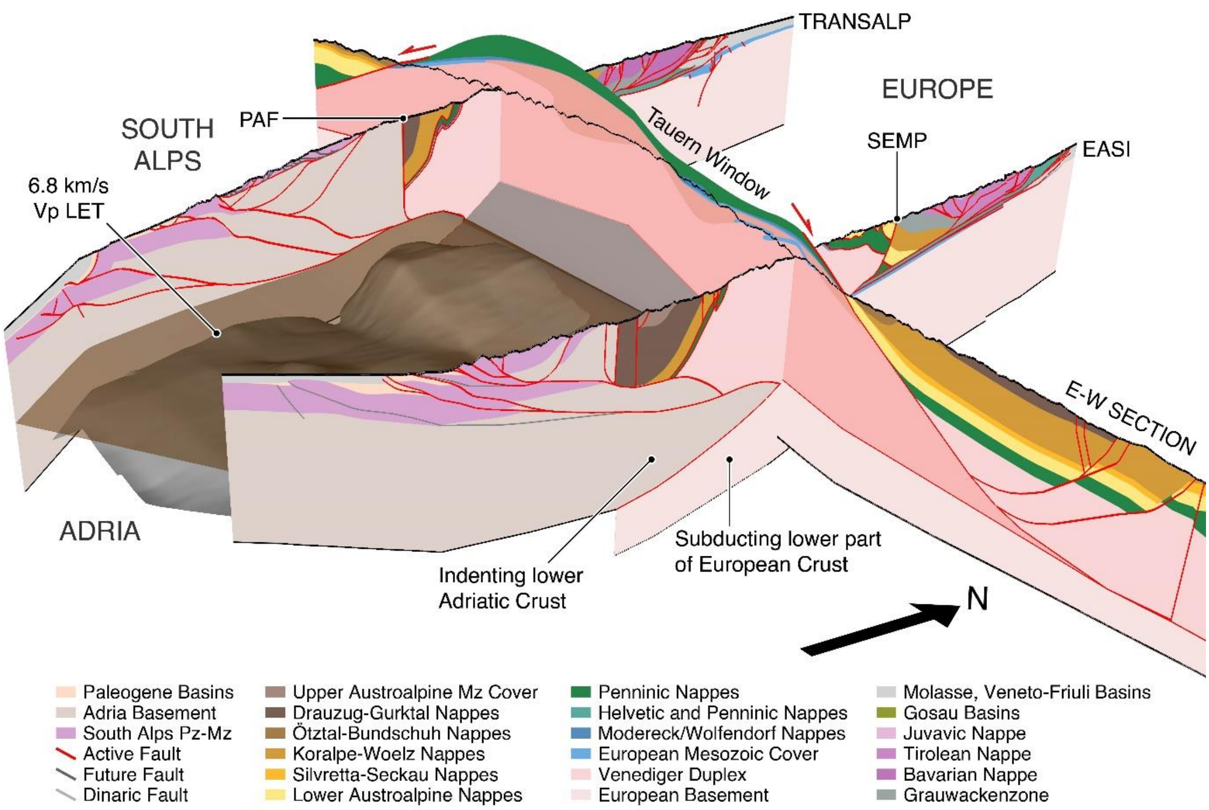

Figure 1B: Fence diagram showing the TRANSALP, EASI, and EW cross sections at the Present-day, and sequential restoration of the TRANSALP section.

Slabs in the Alpine region: inferences down to 300 km depth from surface wave tomography and receiver functions

Thomas Meier[1], Amr El-Sharkawy[1], Ben Heit[2], Emanuel Kästle[3], Rainer Kind[2,3],
Stefan Mroczek[2], Mate Timko[4], Frederik Tilmann[2], Xiaohui Yuan[2]

1. CAU Kiel, Germany
2. GeoForschungsZentrum Potsdam, Germany
3. FU Berlin, Germany
4. Hungarian Academy of Sciences, Hungary

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Mountain building in the Alps is driven by a complex interplay between (i) subduction of oceanic lithosphere and/or continental mantle lithosphere and (ii) exhumation of crustal material. A major challenge represents passive seismic imaging of the various slab segments crucial for shaping the Alpine orogen. AlpArray and Swath-D provide the necessary dense station distribution for high-resolution surface wave tomography using earthquake and ambient noise data as well as for detailed P-to-S and S-to-P receiver function analyses.

Absolute shear-wave velocity models of the crust and upper mantle down to 300 km depth have been obtained from stochastic particle-swarm-optimization inversion of a large data set of more than 200,000 Rayleigh wave phase velocity curves (4 -300 s period). This allows for imaging the slabs and their connection to the forelands with a lateral resolution of about 50 km to 75 km in the Alpine area.

Moreover, about 300,000 P-to-S and about 80.000 S-to-P receiver functions have been obtained for the wider Alpine area. The common conversion point stacks of the P-to-S and S-to-P waveforms, concentrated in the Eastern Alps, provide high resolution images of the crustal structure as well as velocity discontinuities in the mantle at the interface between the European, Adriatic, and Pannonian domains. Moho topography indicating the tops of slabs as well as negative velocity gradients in the mantle beneath the Moho have been imaged. Thermochemical modelling provides evidence that the bottom of the negative velocity gradient causing S-to-P conversions is located close to the lithosphere-asthenosphere boundary. These conversions are thus hinting at the geometry of the bottom of mantle lithosphere and slabs, respectively.

Beneath the northern Apennines, Adriatic lithosphere is subducting nearly vertically southwards down to at least 200 km depth as supported by the spatial distribution of a few intermediate-depth earthquakes. A short Eurasian slab subducting eastwards down to about 150 km depth and a slab gap beneath are present beneath the western Alps. Interestingly, the Eurasian slab is almost colliding with the east-west oriented Adriatic slab beneath the southwestern Po Basin. An attached Eurasian slab subducting to at least 250 km depth is imaged beneath the central Alps, whereas beneath the eastern Alps a short Eurasian slab is found down to only about 150 km depth. A short slab of continental mantle lithosphere is also present beneath the northern Dinarides. It is extending towards the Alps east of the Guidicaria fault. Broken-off Eurasian or Adriatic lithosphere may be indicated by high-velocity anomalies at depth larger than 250 km beneath the south-eastern Alps and the Adriatic Sea. Next, digital slab interface models are to be set up accounting for the various geophysical observations in order to create realistic input models for numerical geodynamic forward modelling of observed deformation rates.

Surface Wavefield Tomography of the Alpine Region to Constrain Slab Geometries, Lithospheric Deformation and Asthenospheric Flow

Amr El-Sharkawy[1], Marcel Tesch[1], Manuel Ditz[2], PIs: Thomas Meier[1], Wolfgang Friederich[2], Jörg Ebbing[1]

1. CAU Kiel, Germany
2. Ruhr-Universität Bochum, Germany

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Surface waves radiated by teleseismic earthquakes are ideally suited to constrain isotropic and anisotropic elastic properties of the upper mantle down to about 300 km depth beneath dense networks of broad-band stations. Rayleigh wave phase velocities were automatically determined in a broad period range from 8 s to 300 s and a very strict quality control was applied. This resulted in a data set of more than 200,000 inter-station phase velocity curves. Local dispersion curves, extracted from phase velocity maps were inverted for a 3D shear-wave velocity model (MeRE2020) using a newly developed stochastic inversion algorithm based on particle swarm optimization. It was shown that the presence of small and highly segmented slabs can be resolved by surface wave tomography in case of a high station density.

In the western Alps, a short Eurasian slab was imaged down to about 150 km depth, whereas at larger depths a pronounced low velocity anomaly indicates slab break-off. In the northern Apennines, a nearly vertical south-dipping slab connected to the Adriatic mantle lithosphere beneath the Po Basin is observed. In the central Alps, the presence of Eurasian mantle lithosphere is found down to the bottom of the model at 300 km depth. Whereas in the eastern Alps, a short Eurasian nearly vertical dipping slab is found down to only 150 km depth. The presence of a short slab consisting of Adriatic mantle lithosphere is also indicated beneath the northern Dinarides extending towards the Alps east of the Giudicarie fault.

Anisotropic phase velocity maps show at 25 s period (lower crustal depth) mostly fast orogen parallel directions, whereas in the western Alps azimuthal anisotropy is more inclined with respect to the Alpine arc. At 100 s period, azimuthal anisotropy beneath the western Alps indicates asthenospheric flow towards the Ligurian Sea and beneath the northern Dinarides towards the Pannonian Basin through slab gaps.

Moreover, seismic wavefields were analysed using AlpArray and Swath-D data. Wavefield animations illustrate the considerable spatio-temporal variability of the wavefield's properties at a lateral resolution down to about 100km. Within denser station distributions like those provided by Swath-D, even shorter period body and surface wave features can be recovered. Considerable amplifications of the Rayleigh wave in the Alpine area are observed for several earthquakes. To analyse Rayleigh wave quantitatively, an algorithm has been developed to extract their phase and amplitude fields using cross correlation between synthetic waveforms and recordings of a dense array. Phase fields are unwrapped by solving a linear system of equations. Phase and amplitude fields are quality controlled and interpolated to determine structural phase velocity fields using Helmholtz tomography. It is shown that the observed amplitude fields depend heavily on lateral heterogeneity outside the array. Often, linear amplifications in the propagation direction are observed. In order to model the observed wavefields, the AxiSEM-SPECFEM Coupling algorithm has been improved and adapted concerning flexibility and efficiency, reducing the necessary wavefield interpolation significantly and allowing topography as well as existing 3D Models of the Alpine region to be easily implemented.

Reconstructing Neogene surface uplift of the Alps: Integrating stable isotope paleoaltimetry and paleoclimate modelling

Maud J.M. Meijers[1] & Sebastian G. Mutz[2,3]

1. Department of Earth Sciences, NAWI Graz Geocenter, University of Graz, Austria
2. Department of Geosciences, University of Tübingen, Germany
3. School of Geographical & Earth Sciences, University of Glasgow, UK

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Paleoaltimetry - the reconstruction of the elevation of mountain ranges in the geological past - is key to understanding the geodynamic drivers of surface uplift. Simultaneously, surface uplift of Earth's major mountain ranges redirected atmospheric flow and impacted climate globally. At a smaller scale, mountain building affects regional climate and biodiversity.

Stable isotope paleoaltimetry is a powerful tool to quantify the past elevation of mountain ranges. It is based on the inverse relationship between the stable isotopic composition of meteoric waters and elevation, which is represented by the so-called isotopic lapse rate. However, variations in climatic parameters modify isotopic lapse rates and impact moisture transport over the continents and consequently affect paleoelevation reconstructions.

Here, we show the results of a combined stable isotope paleoaltimetry and paleoclimate modeling approach in the European Alps. This approach allows for an improved and more realistic estimation of isotopic lapse rates, large-scale isotope-in-precipitation patterns over Europe and hence Alpine paleoaltimetry calculations. The European Alps are an ideal target for a combined paleoaltimetry - climate modeling approach, given that they are (a) one of the most-studied mountain ranges for which many geoscientific data are available, and (b) sufficiently small and oriented near-parallel to dominant atmospheric circulation patterns. The latter implies that no major global climatic changes are expected in response to Alpine surface uplift, as opposed to e.g. the Andes or the Tibet-Himalaya mountain ranges.

Results from 4D-MB SPP phase 1 and 2 show that: (1) Changing the surface elevation of even a small orogen can complicate stable isotope paleoaltimetry by mixing the elevation and climate signal in a more complex way than commonly assumed. Climate models can help separate these signals and constrain surface uplift histories. (2) The Central Alps were already high during the Early and Middle Miocene, whereas the Eastern Alps were still at significantly lower elevations, thereby confirming that surface uplift propagated from west to east, as would be expected from oblique continent-continent collision. Together, the results highlight the importance and viability of this combined, interdisciplinary approach.

Based on the results from 4D-MB SPP phase 1 and 2, we propose that future efforts to reconstruct surface uplift of mountain ranges follow this state-of-the-art approach, while keeping local limitations to proxy material availability and access to facilities in mind.

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Present-day kinematics of the Southern Eastern Alps

Sabrina Metzger[1], Milan Lazecký[2]

1. Helmholtz Centre Potsdam, German Research Centre for Geosciences, Germany
2. COMET, School of Earth and Environment, University of Leeds, UK

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The European Alps exhibit extremely low (<2 mm/yr) horizontal deformation rates caused by the anticlockwise rotation of the Adriatic lithosphere. Uplift peaks in the Central Alps at 2-3 mm/yr due to post-glacial isostatic rebound, slab tearing and erosion. The subducted Adriatic plate causes N-S shortening on ~E-W trending frontal thrust faults separating the Southern-Eastern (SE) Alps from the densely-populated foreland. Regional seismicity is abundant and includes M6+ earthquakes such as the 1975 M_w6.5 Friuli event. Further north the Eastern Alps extrude towards the Pannonian basin at sub-millimeter rates.

Global Navigation Satellite System (GNSS) rates provide a first-order constraint on plate locking, a vital component in seismic hazard assessment. But the geometry of the active faults remains unclear. I present recent deformation rate maps of the SE-Alps in unprecedented resolution (~400 m, 6 days). The rate maps were derived from interferometric (InSAR) small-baseline (SBAS) time-series collected by the European Sentinel-1 radar satellite mission since 2017. Each of the assembled eight 240-km-wide radar tiles contains 300+ acquisition images, resulting in 2000+ interferograms (per tile), which were automatically generated, phase-unwrapped, and corrected for atmospheric and topographic signal contributions. I used the LiCSBAS time-series analysis software that applies a small-baseline (SBAS) approach, accounting for spatio-temporal coherence and seasonality. After tying the individual rates maps into a Eurasian reference frame defined by published GNSS rates I decomposed the rates originally observed in two look directions into east and vertical components. Field surveys, originally scheduled to densify the GNSS network in Slovenia were unfortunately canceled due to the pandemic.

The rate maps provide insight on the InSAR signal-detection limit of a challenging region like the heavily vegetated and snow-covered SE-Alps, overprinting subtle deformation signals along N-S, to which radar antennas are least sensitive: The vertical rates reflect a mixture of isostatic, and anthropogenic processes, overlaid by significant soil-moisture bias (Figure 1). The long-wavelength tectonic signal, remained below the detection threshold of the east rates. In comparison, considering only persistent scatterers (PS) produces more significant InSAR signals (cf. Areggi et al., 2023).

Based on recently updated GNSS rates (Pintori et al., 2022) I designed a kinematic model of the most active faults of the SE-Alps. I embedded an inter-connected chain of five dislocations in an elastic half-space and activated them in back-slip mode with no constraints on geometry or slip. Using simulated annealing I first scanned the parameter space randomly (Monte-Carlo) then gradually preferred parameter sets with a promising data fit. Such a multi-parameter model would add valuable new information on the unknown geometry of the active faults, also, because accurate earthquake locations of other 4D-MB projects (e.g., Najafabadi et al., 2020; Hofmann et al., 2023) provide ambiguous information on the fault dip. My tests resulted in unstable solutions, suggesting that geometric constraints (cf. Serpelloni et al. 2016) are compulsory in this particular case.

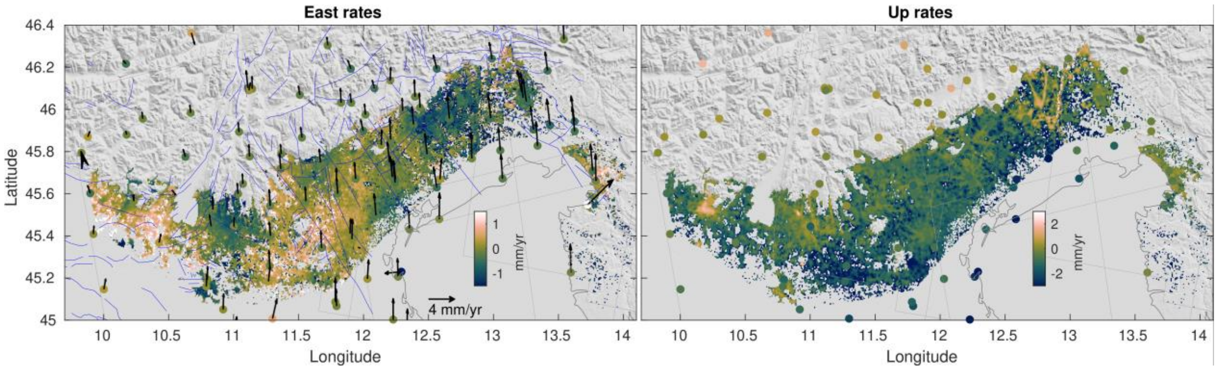

Figure 1: InSAR rate maps, masked, tied to the Eurasia-stable GNSS reference frame, and decomposed into east (left) and vertical (right) rates.

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Applying scattered wave tomography and joint inversion of high density (SWATH D) geophysical and petrophysical datasets to unravel Eastern Alpine crustal structure

Frederik Tilmann[1], Wolfgang Friederich[2], Timm John[3], Jan Pleuger[3], Stefan Mroczek[1], Anne Mohr[2]

1. GFZ Helmholtz Centre Potsdam, Germany
2. Institute for Geology, Mineralogy und Geophysics, Ruhr University Bochum, Germany
3. Institute of Geological Sciences, Freie Universität Berlin, Germany

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This project harnesses the high density of seismic stations in AlpArray and the AlpArray complementary experiment SWATH D to significantly improve the resolution and reliability of the subsurface models by enabling the use of many different inversion methods to obtain and integrate the different results. These advanced models are vital for resolving the complex Alpine plate configuration and understanding how the crustal structure seen today reflects the dramatic changes in mountain building style and reorganisation of plate boundaries at about 20 Ma. We employ the joint inversion of seismological and petrophysical data sets in order to understand the intra-crustal structure, temperature, and petrophysical properties of crustal layers by inverting seismic data directly for the crust's constituent mineral assemblages. Teleseismic full waveform inversion (FWI) provides a powerful tool for illuminating both the crustal and, complementing the joint inversion, intra-crustal structure. In our application of FWI, we increase the frequency content with the progression of the inversion.

To perform FWI with teleseismic data at low frequencies, we couple the 1D code Gemini (Friederich and Dalkolmo, 1995) with the 3D code SPECFEM3D Cartesian for forward modelling and use the FWI code ASKI (Schumacher and Friederich, 2016) for computing waveform sensitivity kernels and performing the inversion. At higher frequencies we opt for a ray theory-based approach rather than full waveform modelling due to its high computational cost. We calculate high frequency P-phase synthetic seismograms by coupling various codes to obtain travel times, amplitudes and source time functions. ObsPy TauP, a 1D code, is used to determine travel times and ray paths in the bulk earth, while FM3D (de Kool et al., 2006), a 3D code, is employed in the study area. Subsequently, the ray paths are used to calculate amplitudes via dynamic ray tracing. Source time functions are obtained by fitting the recorded data. We intend to use the P-phase synthetic seismograms within the framework of ASKI to compute waveform sensitivity kernels. Subsequent inversion with these kernels could improve the resolution of the resulting models.

First results of FWI at low frequencies up to 0.1 Hz (using the coupled Gemini-SPECFEM3D code for forward modelling) demonstrate a good agreement with the P-wave velocity models obtained from teleseismic travel time tomography by Paffrath et al. (2021) as part of the first phase of the SPP. Though derived from Fourier-transformed waveform data and currently only 24 events, the FWI model reduces the variance of the P-wave travel time residuals data set by 60 percent. Moreover, the FWI models exhibit surprisingly high resolution in the crust and uppermost mantle with a superb image of the Alpine and Apennine orogenic root and the Ivrea body probably by virtue of the presence of reflected and converted P- and S-phases in the considered time windows.

Receiver functions and surface wave dispersion curves, calculated in partner projects, are usually jointly inverted for elastic properties. By utilising the strengths of Markov Chain Monte Carlo inversion, we are able to instead parameterise our model by temperature and mineral assemblage. This allows the introduction of geological-mineralogical constraints, in a probabilistic self-consistent manner, to the inversion. A further significant advantage is in interpretation where the probabilities of certain lithologies being present allows for a more seamless integration of qualitative geological data and a reduction in interpretation biases present when only seismic velocities are presented.

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Resolving the Eastern Alpine puzzle: Illumination of crustal structure with receiver functions and ambient noise autocorrelations

Stefan Mroczek[1,2], Frederik Tilmann[1,2], Jan Pleuger[2], Xiaohui Yuan[1], Ben Heit[1], the SWATH-D Working Group, and the AlpArray Working Group

1. GFZ German Research Centre for Geosciences, Germany
2. Freie Universität Berlin, Germany

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The tectonic structure of the Eastern Alps is heavily debated with successive geophysical studies that are unable to resolve areas of ambiguity (e.g., the presence of a switch in subduction polarity and differing crustal models). In order to better understand this area, we produce a high resolution Moho map of the Eastern Alps based on a dense seismic broadband array deployment (SWATH-D). Moho depths were derived from joint analysis of receiver function images of direct conversions and multiple reflections for both the SV (radial) and SH (transverse) components, which enables us to map overlapping and inclined discontinuities. Autocorrelations, derived from ambient noise, recover zero-offset reflections for a subset of stations located in the Bohemian Massif (part of the EASI transect) and provide an independent measurement of Moho depth and corroborate the receiver function results. Autocorrelations also give potential for a combined analysis to better constrain crustal average P velocities. Furthermore, an associated petrological study informs us on the implications of the eclogitisation of crustal rocks for these imaging techniques (see poster John et al "The effect of eclogitization of crustal rocks on the seismic properties on variable scales"). We observe the European Moho to be underlying the Adriatic Moho from the west up to the eastern edge of the Tauern Window. East of the Tauern Window, a sharp transition from underthrusting European to a flat and thinned crust associated with Pannonian extension tectonics occurs, which is underthrust by both European crust in the north and by Adriatic crust in the south. The Adriatic lithosphere underthrusts northward below the Southern Alps for a short distance of a few tens of km at most, and becomes steeper and deeper towards the Dinarides where it dips towards the north-east. Our results suggest that the steep high velocity region in the mantle below the Eastern Alps, observed in tomographic studies, is likely to be of European origin.

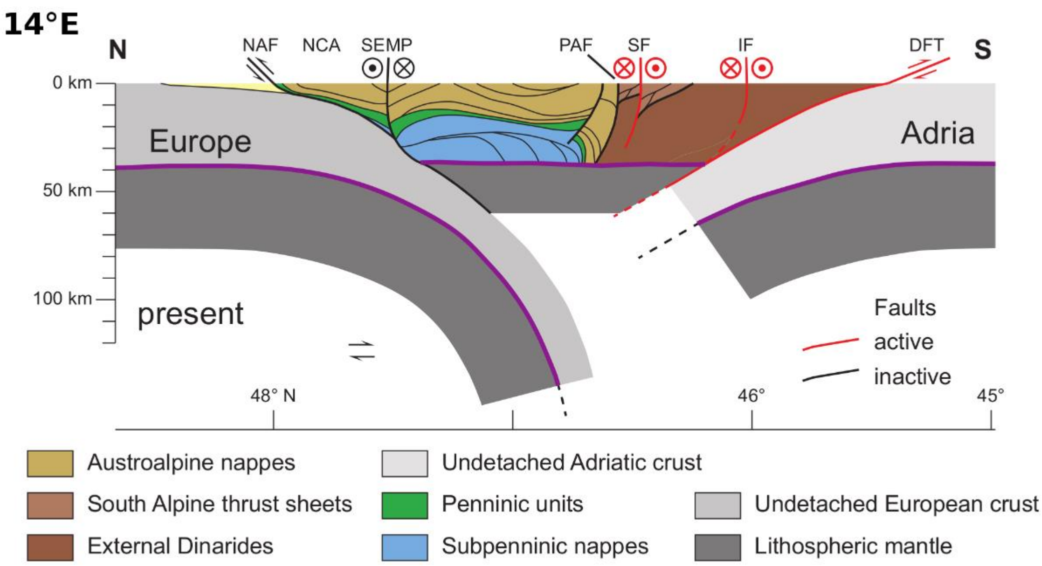

Figure 1: The north-south transition from European to Adriatic crust, through the central Pannonian domain, is captured in the schematic cross section (present day) through the Alps at 14°E based on Moho depths derived from receiver functions.

Joint inversion of seismic data for temperature and lithology in the Eastern Alps

Stefan Mroczek[1,2], Frederik Tilmann[1,2], Sascha Zertani[3], Emanuel Kästle[2], and Timm John[2]

3. GFZ German Research Centre for Geoscience, Germany
4. Freie Universität Berlin, Germany
5. University of Oslo, Norway

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The high density SWATH-D and AlpArray seismic networks provide a unique opportunity in the Eastern Alps to resolve the complex plate configuration and investigate how the crustal structure seen today reflects the dramatic changes in mountain building style and reorganisation of plate boundaries at about 20 Ma. This study complements the partner project where scattered wave tomography is applied to the same area (presented in the poster 'Applying scattered wave tomography and joint inversion of high-density (SWATH D) geophysical and petrophysical datasets to unravel Eastern Alpine crustal structure', Tilmann et al).

In order to bring together the seismological and geological-mineralogical constraints in a probabilistic self-consistent way, we employ the joint inversion of seismological and petrophysical data sets. Receiver functions and surface wave dispersion curves, calculated in partner projects, are usually jointly inverted for elastic properties. By utilising the strengths of Markov Chain Monte Carlo inversion, we are able to instead parameterise our model by temperature and mineral assemblage. By inverting seismic data directly for the crust's constituent mineral assemblages, we are led to a deeper understanding of intra-crustal structure, temperature, and petrophysical properties of crustal layers. A further significant advantage is in interpretation where the probabilities of certain lithologies being present allows for a more seamless integration of qualitative geological data and a reduction in interpretation biases compared to when only seismic velocities are presented.

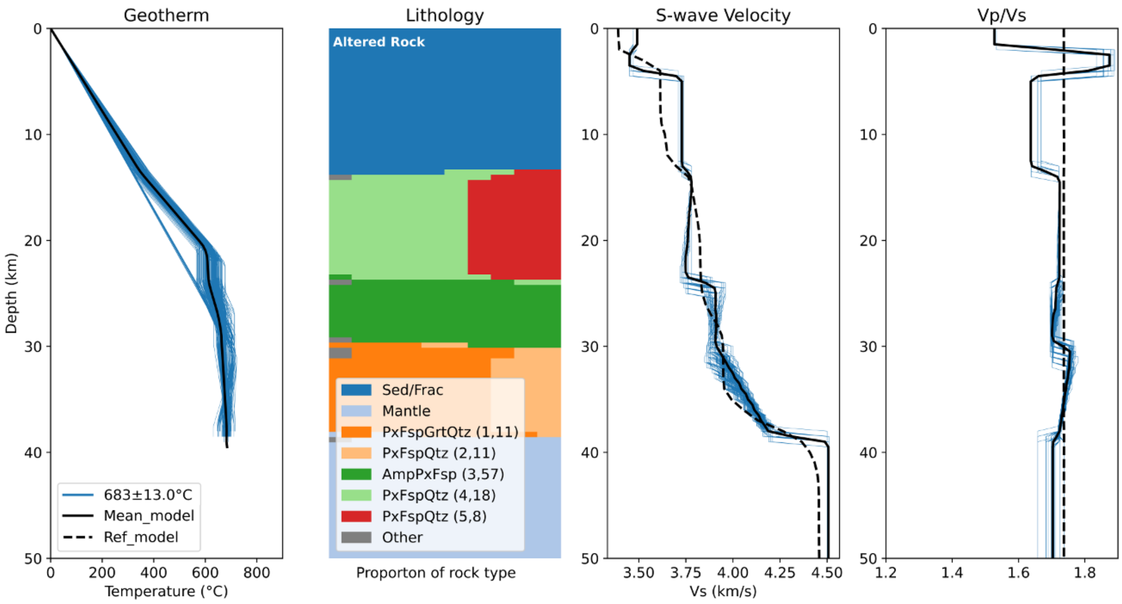

Figure 1: Result from a test station of a joint inversion for temperature and lithology compared to a reference model (dashed line) calculated with a usual joint inversion. Blue lines represent the best 5,000 models. Each colour in the *Lithology* panel represents a different mineral assemblage (the legend gives shorthand for their main constituents). The proportion of different assemblages at each depth in this panel represents the proportion of models with that rock type at that depth. This can be interpreted as the probability of particular assemblage being present (given the model assumptions).

The Potential and Limitations of 2D Seismic Experiments for 3D Tomography

L. Murray-Bergquist[1], A. Dannowski[1], D. Lange[1], H. Kopp[2,1], M. Thorwart[2]

1. GEOMAR Helmholtz Center for Ocean Research Kiel, Germany
2. Christian-Albrechts-University of Kiel, Germany

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The Liguro-Provençal Basin is located in a complex tectonic area, at the junction of the Western Alps and Northern Apennines. Despite its central location within Europe, much about the basin, including the character of the crust, and the continuation of the Alpine orogen offshore, remain ambiguous.

The basin began opening in the late Oligocene as a back-arc basin related to the retreat of the Apennine subduction zone. Opening continued into the early Miocene with the counter-clockwise rotation of the Corsica-Sardinia block to its current position. In the southern part of the basin where this rotation opened the widest, seismic tomography has shown evidence of oceanic crust, however, the extent of this spreading zone northward into the Ligurian Sea is poorly mapped. The nature of the crust in the basin, whether atypical oceanic crust or partially serpentinized mantle overlain by sediments or highly thinned continental crust is still a matter of debate.

At a larger scale there are still open questions as to the continuation of the alpine orogen offshore, and the change in polarity between the Alp and Apennine subduction zones. As well, present day seismicity with thrust-faulting focal mechanisms have been observed in the basin, indicating that the stress field is now compressive. This could potentially reactivate rift-structures in the basin, which are difficult to map due to thick sediment cover including a layer of Messinian salt with variable thickness.

These open questions, and the accessibility of the basin in the heart of Europe, have led to the collection of at least 18 active seismic profiles, and even more multi-channel seismic lines. Each of these studies have contributed to understanding the tectonics of the area through 2D tomography along the profile, but these are small snapshots of a complex setting. The amount of data that has been collected provides a unique opportunity to combine data sets and examine the possibility of gaining new information in the form of 3D tomography from existing 2D data sets.

In this project we use active seismic data from the LOBSTER-AlpArray Experiment, the GROSMarin Experiment, and the SARDINIA Experiment, as well as passive seismic data from the AlpArray Experiment and the ISC Bulletin. We explore the potential and limitations of these data sets for use in 3D tomography using two new methods. We first use off-profile stations along a 2D seismic line combined with passive seismicity to provide back-shots for the stations, then in the Gulf of Lion we use two parallel seismic profiles where stations recorded shots from both profiles. This project is part of the DFG Priority Program “Mountain Building Processes in Four Dimensions (4DMB)”.

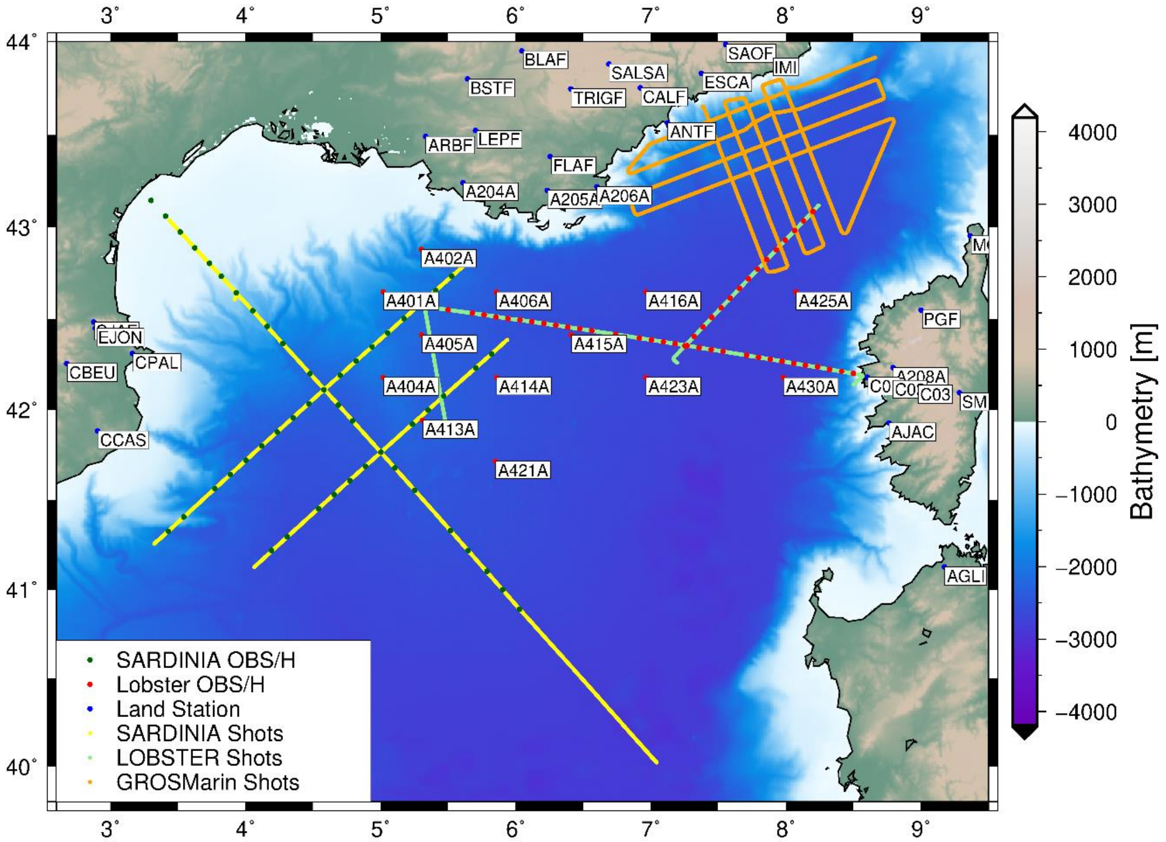

Figure 1: Overview of data used: Yellow and dark green dots show shots and Ocean Bottom Seismometers (OBS) from the SARDINIA Experiment, light green and red dots show shots and OBS from the LOBSTER—AlpArray Experiment, and orange dots show shots from the GROSMarin Experiment, OBS not shown as we do not have access to the data. Blue dots show land stations at which shots were recorded.

Imaging structure and geometry of Alpine slabs by full waveform inversion of teleseismic body waves

Marcel Paffrath[1], Johannes Stampa[2], Wolfgang Friederich[1], Thomas Meier[2], Boris Kaus[3]

1. Ruhr-Universität Bochum, Germany
2. CAU Kiel, Germany
3. JGU Mainz, Germany

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The primary goal of this project was to use records of distant earthquakes from the AlpArray Seismic Network to contribute to the controversial debate about the structure, origin, and fate of subducted lithospheric plates in the deeper mantle beneath the Alps, such as possible slab detachments or changes in subduction polarity, to expand our understanding on mountain-building processes.

Originally intended as a preliminary step before full-waveform inversion, we performed a teleseismic P-wave travel-time tomography (Paffrath et al., 2021b) based on waveforms recorded at over 600 temporary and permanent broadband stations of the AlpArray Seismic Network. An algorithm using a combination of automatic picking, beamforming and cross-correlation was developed to extract teleseismic travel times of direct P-waves from 331 events of magnitude > 5.5 recorded between 2015 and 2019 resulting in a database of over 162 000 highly accurate absolute P-wave travel times and travel-time residuals (Paffrath et al., 2021a).

In addition, we developed an automatic picking algorithm based on multi-component autoregressive prediction and properties of the analytic signal. This algorithm was applied to a global data set of waveforms from over 6000 events of magnitude < 6 recorded between 1990 and 2019 at more than 25000 stations to obtain about 3.8 million P- and 3.2 million S-phase arrival times.

We obtained models of P-wave velocities on a grid with 25 km lateral and 15 km depth spacing, encompassing the entire Alpine region, from the Massif Central to the Pannonian Basin and from the Po Plain to the river Main, down to a depth of 600 km. Hardly resolvable crustal heterogeneities were taken into account by a novel approach of direct incorporation of an external 3D a priori model of the crust and uppermost mantle into the starting model of the inversion. For forward travel-time predictions, a hybrid method was developed by combining ObsPy-Taup with the fast-marching code FM3D.

The resulting model provides a detailed image of slab configuration beneath the Alpine and Apennine orogens that differs from previous studies. Major features are: (1) A partly overturned Adriatic slab beneath the Apennines reaching down to 400 km depth exhibiting progressive detachment towards the southeast; (2) a fast anomaly beneath the western Alps indicating a short western Alpine slab that ends at about 100 km depth; (3) a complex deep-reaching coherent fast anomaly beneath the Central Alps generally dipping to the SE down to about 400 km, detached from the overlying lithosphere in its eastern part but suggesting a slab of European origin; (4) a further deep-reaching, nearly vertically dipping high-velocity anomaly beneath the Eastern Alps, laterally well-separated in the upper 200 km from the slab beneath the central Alps but merging with it below, suggesting a slab beneath the eastern Alps of presumably European origin completely detached from the orogenic root so that a change in subduction polarity is not necessary.

Very recent P-wave velocity models from teleseismic full-waveform inversion based on hybrid coupling of GEMINI and SPECFEM3D exhibit, in contrast to travel time tomography, surprisingly high resolution in the crust and uppermost mantle with a superb image of the Alpine and Apennine orogenic root and the Ivrea body; they confirm the general distribution of high-velocity anomalies found by traveltime tomography in the mantle below, but might allow new conclusions about the connection of the subducted slabs.

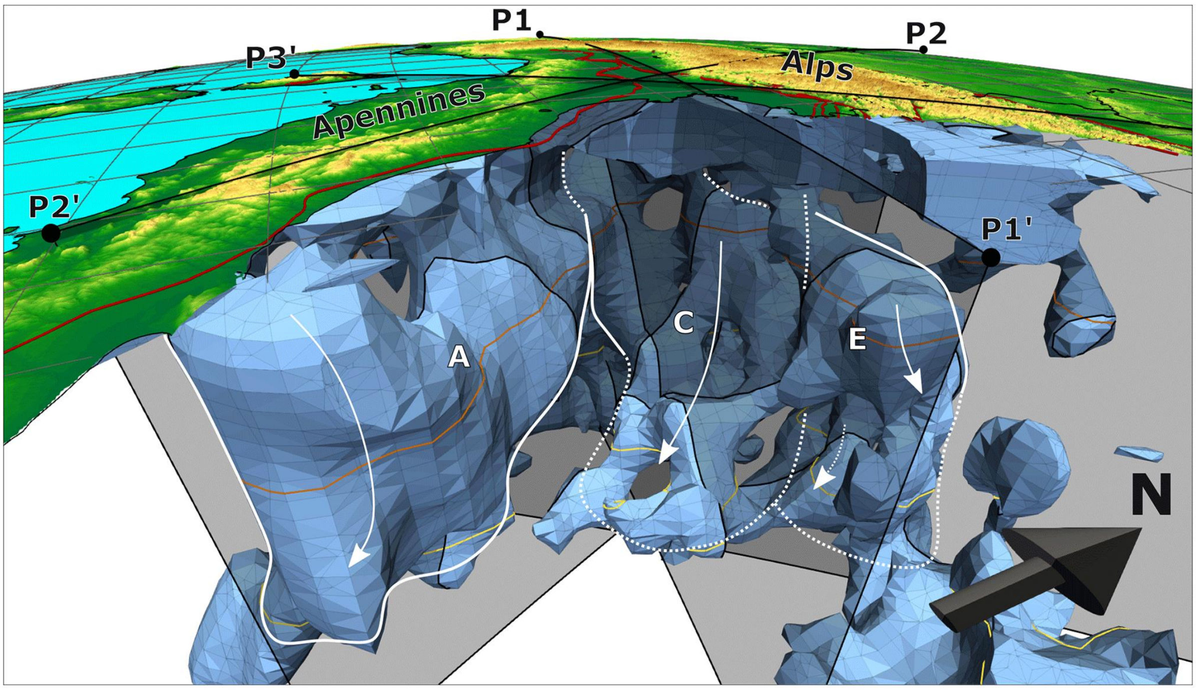

Figure 1: Paffrath et al. (2021b), Fig. 17

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Seismotectonics of the Eastern Alps: New insights from earthquake studies within 4D-MB

Gesa Petersen[1], Laurens Hofman[2], Simone Cesca[1], Jörn Kummerow[2], Thomas Plenefisch[3], Joachim Wassermann[4]

1. GFZ Potsdam, Germany
2. Freie Universität Berlin, Germany
3. BGR Hannover, Germany
4. LMU München, Germany

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The recent installation of the dense SWATH-D network in the Eastern Alps, integrated into the broader AlpArray, provides the basis for new detailed and consistent studies of small to moderate seismicity. In the SPP project *'From Top to Bottom – Seismicity, motion patterns and stress distribution in the Alpine crust'* and the follow-up project *'Constraints on quaternary processes in the Eastern Alps from a new detailed image of seismicity'*, we have focused on event detection, precise location, analysis of seismicity clustering and detailed source parameter studies, involving methodological advancements and subsequent application to the seismological SWATH-D and AlpArray data.

Here, we summarize the main results of our completed and ongoing work:

1. We have developed a new, python-based tool for automated station quality control of dense seismic networks and arrays and applied it successfully to the permanent and temporary AlpArray networks as well as to the denser SWATH-D network (AutoStatsQ, [Petersen et al., 2019]). The toolbox uses a combination of observed and synthetic teleseismic event data to identify and quantify errors in amplitude gain and sensor orientation and to correct the stations accordingly.
2. Based on methodological tests adapted for the complex tectonic setting in the Alps, we have performed centroid moment tensor inversion of seismicity with MW ≥ 3.0 recorded by the AlpArray network and compared the solutions to historical earthquakes, recent seismicity, published focal mechanisms, and GNSS deformation data ([Petersen et al., 2021]). We additionally applied epicenter clustering to resolve in detail the heterogeneity of tectonic movement. Thrust faulting is dominant in the Friuli area of the eastern Southern Alps, related to the N–S convergence of the Eurasian and Adriatic plate and counterclockwise rotation of Adria relative to Europe. Strikeslip faulting with similarly oriented P- axes is observed along the northern margin of the Central Alps and in the northern Dinarides, consistent with right-lateral strike-slip faults and high shear strain rates. The NW Alps exhibit deviant behavior, with NW–SE-striking normal faulting events and NE–SW-oriented T- axes. Faulting styles in the SW Alps are more heterogeneous, with a majority of earthquakes related to an extensional stress regime.
3. We have designed a workflow which combines a priori information from local catalog and waveformbased event detection, subsequent GPU-based event search by template matching, P & S arrival time pick refinement and location in a regional 3-D velocity model. Application to the SWATH-D data provided for the first time a consistently processed seismicity catalog for the Eastern and Southern Alps, which has a magnitude of completeness of −1.0 ML, involves event classification and includes > 6, 000 earthquakes [Hofman et al., 2023a]. The newly revealed clusters better illuminate the fault structures at depth, and we detected and located additional, mostly weak events, a part of them pointing to small, but active upper crustal deformation in the Dolomite indenter, along the Pustertal-Gailtal Fault and in the Tauern window.
4. In our ongoing work, we characterize the earthquake distribution in more detail, using novel approaches from Graph theory, waveform similarity-based clustering and stacked- waveform moment tensor Inversion [Hofman et al., 2023b], [Petersen et al., 2020], [Petersen et al., 2023].

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Reflection of mantle flow in the tectonics of Europe: stress, strain, and induced seismic anisotropy.

Alexey Petrunin[1]

1. Deutsches GeoForschungsZentrum GFZ, Potsdam, Germany

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Mantle flow is one of the key factors influencing the lithosphere's loading, including both normal and tensile basal tractions. This flow dominantly controls the dynamics of the lithosphere and the distribution of stress within continental plates. To account for both far-field stresses, e.g. caused by ocean spreading, and the influence of plumes, the computation of regional patterns of mantle flow requires the development of a global convection model that is consistent with GPS measurements and local stress field data. To achieve this goal, we first developed a refined density-temperature model for the lithosphere. This model is based on the latest findings from tomographic, gravity, and crustal structure data, which have been used for the joint density inversion. This approach allows us to significantly reduce uncertainties due to the influence of the crust and to refine the primary tomographic inversion results for the density structure of the upper mantle and lithosphere.

As a result, we have derived a density distribution map beneath the Alpine region and its surroundings for the lithosphere and upper mantle. Figure 1(left) demonstrates the refined density anomaly map for the depth of 100 km.

Using our spectral code ProSpher 3D (Petrunin et al., 2013) and the results of the density model, we computed mantle flow patterns, stresses, and estimates of seismic anisotropy at 1x1 degree resolution. The most revealing result, demonstrating the reliability of our model, is the map of calculated maximum principal stress directions, Figure 1 (right). It shows good agreement with observations of SKS splitting (red dashes). We also calculate the tectonic regimes of the lithosphere (compression-tension) for the study area.

One of the causes of seismic velocity anisotropy is the finite strain accumulated in the lithosphere and/or upper mantle. This parameter is not calculated in our snapshot model. However, since the direction of the main forces in the lithosphere has not changed significantly since at least 10-15 Ma, we assumed that the directions of the principal axes of the finite strain tensor should correlate with those of the stress tensor.

In order to identify the main factors controlling the mantle flow beneath the European lithosphere and induced by the flow stresses, we constructed a three-dimensional model of the flow lines in the mantle. According to this model, we can assume that the main factors are the Island, Canary Islands, and Azores plumes and they interplay with the subduction of the African plate under Europe. Thus, our model provides a 3D map of density, viscosity, stress, and seismic anisotropy distribution for the European lithosphere and upper mantle down to depths of 400 km, taking into account both local body forces and traction forces as well as far-field stresses.

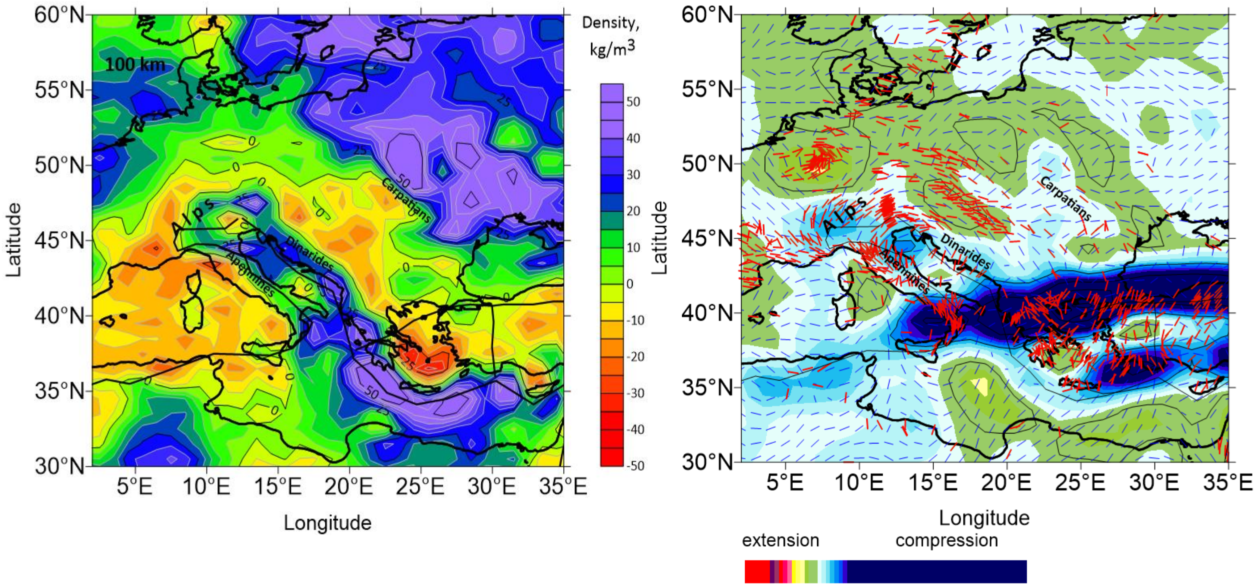

Figure 1: The new map of density anomaly (left) and maximum principal stress directions for the depth of 100-150 km (blue dashes). The red dashes indicate the SKS splitting observations and show the fast seismic velocity azimuth averaged by co-located stations (Wüstefeld et al., 2009, Becker et al., 2012). Colors denote tectonic settings from the modeling.

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Slab detachment dynamics: Insights from 0D to 3D numerical experiments

Andrea Piccolo[1], Marcel Thielmann[1], Arne Spang[1]

1. Bayreuth Universität, BGI, Bayreuth, Germany

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Slab detachment is a process that has been invoked to explain rapid uplift, deep seismicity, and magmatic activity in several active orogens (e.g., Alps, Himalaya). However, it is not yet clear to which extent slab detachment is the primary cause of these phenomena. Thus, deciphering the physical processes controlling detachment is important to understand its impact on the post-collisional evolution of orogens.

Here we employ numerical models to investigate the nonlinear coupling between mantle flow and slab detachment. Due to the three-dimensional nature of slab detachment and the variety of involved processes, it is daunting to pinpoint the first order controls on the time scale of this process. We therefore investigated this issue by first developing a simplified 0D necking model that describes the temporal evolution of the thickness of a detaching slab.

Our 0D numerical experiments highlight the importance of slab temperature and activation volume of the slab and upper mantle. The combination of these two parameters can delay the detachment process and yield different transient surface and stress signals. These results have been confirmed with 2D numerical experiments The same insights have been furtherly validate with 3D numerical experiments, allowing us to focus our attention on the radius of curvature of the subduction zone and on the lateral heterogeneities. Based on these findings, we then used 2D and 3D numerical models to further determine higher dimensional geometrical effects on slab detachment. For more complex slab geometries, higher dimensional results deviate from the 0D predictions. Nevertheless, the combination of 0D and 2D/3D numerical models allows to determine first order controls on slab detachment.

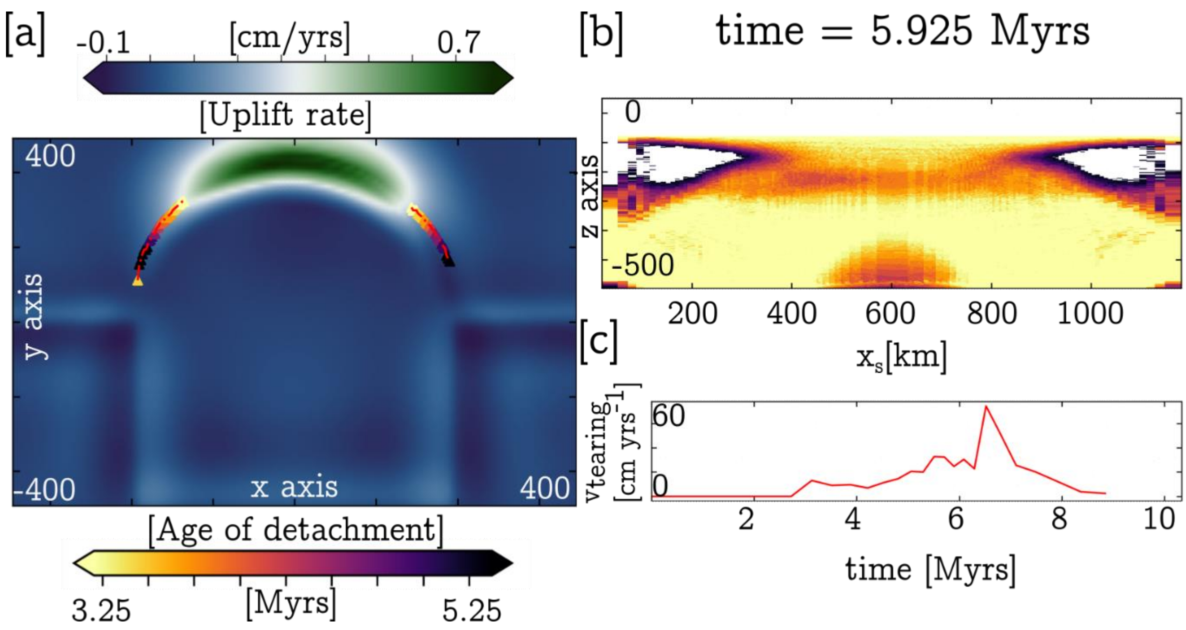

Figure 1: a) This map displays a 3D numerical simulation featuring a slab with an average temperature of 900°C and a curvature of 0.0026 km^{-1}. The colored triangles depict the propagation of tearing and are shaded based on the age at which tearing occurs at specific coordinates. **b) Thickness of the slab:** This figure represents the actual slab below the surface, and how the tearing propagates along the slab. **c) Tearing velocity vs time**

The evolution of a thrust belt within a continental indenter: Investigating the internal deformation of the Dolomites Indenter (Southern European Alps) using low-temperature thermochronology

Hannah Pomella[1], Thomas Klotz[1], Anna-Katharina Sieberer[1], Alexandra Wzietek[1], István Dunkl[2]

1. University of Innsbruck, Department of Geology, Innsbruck, Austria
2. University of Göttingen, Department of Sedimentology and Environmental Geology, Göttingen, Germany

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The Dolomites Indenter represents the front of the Neogene to ongoing N(W)-directed continental indentation of the Adriatic microplate into Europe. Concomitant shortening within the indenter is accommodated within a dominantly WSW – ENE striking and S-vergent thrust belt.

In this contribution, we present a new low-temperature thermochronological dataset (apatite U-Th/He (AHe) and apatite fission track (AFT)) over the Dolomites Indenter, with a north to south extent from the Periadriatic fault system (Pustertal-Gailtal fault) to the footwall of the Bassano thrust. In west-east direction, the AFT data cover the area from Lake Garda to San Martino di Castrozza. The AHe dataset, on the other hand, extents further east to Bled in Slovenia. The extensive dataset covers several major fault systems (from north to south): west of Lozzo di Cadore the Villnöß-, Truden-, Valsugana-, Belluno-, and Bassano-Valdobbiadene faults; east of Lozzo di Cadore the Fella-Sava-, Sauris-, Ampezzo-Tolmezzo-, Dof-Auda-, Pinedo-Uccea- and Barcis-Staro Selo faults. It includes several elevation profiles and aims to capture the cooling and exhumation history of the Dolomites Indenter.

The AFT data obtained range from Jurassic to Miocene age. The vast majority of modelled cooling paths show a plateau and a long residence time of the samples within the Apatite partial annealing zone (APAZ), often from the beginning of the Jurassic to the Miocene. The location of the plateau within the APAZ during the long residence time can be responsible for whether a sample gives a Mesozoic or Cenozoic AFT age without major faults being involved. The basement and Permian intrusive rocks in the northern part of the Dolomites Indenter show cooling below ZFT between ~140 and 110 Ma and Eocene AFT data (~50-40 Ma). The modelled cooling paths based on apatite confined length distributions indicate a flat plateau in the upper APAZ delimited by two phases of accelerated cooling, one predating the AFT data and one in the middle Miocene. The latter is present in nearly all modelled cooling paths of our dataset besides the southernmost samples located in the footwall of the Bassano fault. The bend point varies between 20 and 12 Ma, tending to be earlier in the north and later in the south. We assign this middle Miocene change in cooling rate to the Valsugana deformation phase. For the older accelerated cooling phase, a tectonic interpretation is still in elaboration.

Within the AHe dataset the most striking pattern is a significant trend towards younger ages in the direction east (lower Miocene in the west to upper Miocene to Pliocene in the east).

Quaternary Seismic Slip in the Eastern Alps: Dating Fault Gouges from the Periadriatic Fault System Using Trapped Charge Dating Methods

Erick Prince[1], Sumiko Tsukamoto[2], Christoph Grützner[1], Marko Vrabec[3], Kamil Ustaszewski[1]

1. Friedrich-Schiller University Jena, Germany
2. LIAG Hannover, Germany
3. University of Ljubljana, Slovenia

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The Periadriatic Fault System (PAF) is among the largest post-collisional structures of the Alps. Recent studies using GPS velocities suggest that Adria-Europe convergence is still being accommodated in the Eastern Alps. However, according to instrumental and historical seismicity records, earthquake activity is mostly concentrated along structures in the adjacent Southern Alps and adjacent Dinarides. Apart from ambiguous historical events, the PAF has little to no earthquake record. Electron spin resonance (ESR) and Optically Stimulated Luminescence (OSL) are dating methods that can be applied as ultra-low temperature thermochronometers (closing temperature below 100 °C), with a Quaternary dating range of a few decades up to ~2 Ma. Both are potentially applicable to date shear heating during earthquakes in slowly deforming fault zones. Since the saturation dose of the quartz ESR signals is larger than that of quartz and feldspar OSL, ESR enables establishing a maximum age of the events (assuming the resetting during seismic events was at least partial), while OSL allows finding their minimum age when the signal is in saturation. We analyzed fault gouge samples from 4 localities along the easternmost segment of the PAF (east of the Giudicarie Fault), and 5 localities along the southernmost segment of the Lavanttal Fault.

For ESR, we measured the signals from the Al center in quartz, comparing the results from the single aliquot additive dose (SAAD) and single aliquot regenerative dose (SAR) protocols. Different grain size fractions were measured (SAR protocol) to establish a grain-size age plateau. For OSL, we measured the Infrared Stimulated Luminescence (IRSL) signal at 50 °C (IR50) and the post-IR IRSL signal at 225 °C (pIRIR225) on potassium feldspar. Additionally, experiments of thermal activation of the OSL signal in quartz were performed to observe the shear heating effect in different grain size fractions.

For the PAF, the OSL shear heating sensitivity experiments show that quartz has been thermally activated to temperatures below 300 °C, corroborating that shear heating was sufficient for at least a partial system reset. The ESR grain size plateaus suggest that the most effectively reset fraction is 100-150 µm. In general, our dating results indicate that the studied segment of the PAF system accommodated seismotectonic deformation within a maximum age ranging from 1075 ± 48 to 349 ± 17 ka (ESR SAR) and a minimum age in the range of 196 ± 12 to 281 ± 16 ka (pIRIR225). The obtained ages and the current configuration of the structure suggest that the studied segment of the PAF could be considered a potentially active fault at least. In the case of the Lavanttal fault, the ESR dose-response curves were either close to or in saturation, allowing to obtain only minimum ages of ca. 4 Ma for the last total reset of the system. This could be the result of insufficient shear heating by low magnitude earthquakes, or the fault has not seen significant activity since then. Altogether, our results show that large structures in the Eastern Alps such as the PAF have accommodated part of the Adria-Europe convergence during the Quaternary and can potentially host earthquakes in the future.

Clustered activity of Intraplate Faults: The silent and slow active faults of southern Germany

Klaus Reicherter[1], Joachim R.R. Ritter[2], Stephane Baize[3], Vanessa Steinritz[1], Sara Pena-Castellnou[1], Jochen Hürtgen[1]

1. Institute of Neotectonics and Natural Hazards, RWTH Aachen University, Germany
2. Geophysical Institute, KIT, Karlsruhe, Germany
3. IRSN, Fontenay-aux-Roses, France

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Silent and slow faults pose a particularly fascinating challenge in the field of active tectonic studies, especially in regions characterized as Stable Continental Regions (SCR) or Active Intraplate Regions (AIR), such as Central Europe. The term "silent faults" encompasses a broad spectrum of meanings, with "silent" denoting either the absence of seismic activity, the lack of faulting that generates earthquakes (though possibly involving creep), or the limited visibility of these faults in terms of their geomorphological and geological features.

Slow active faults, generally defined by slip rates of ≤ 0.1 mm per year, typically do not produce noticeable topographic features in regions with a humid or moderate climate. The slip rate of a fault is a critical parameter governing the occurrence of earthquakes and seismic hazard in a given area. Lower slip rates result in longer intervals between earthquakes of a specific magnitude. Owing to these prolonged recurrence intervals, earthquakes occurring on low slip-rate faults are often absent from historical records and standard processes for assessing seismic hazard.

In our study, we present new fault data obtained from the AIR region of the Rhine Graben rift within the German SCR region. Generally, Holocene surface rupturing events are exceedingly rare in these areas, with recurrence intervals spanning approximately 1,000-10,000 years. The associated slip rates are notably low, often below 0.5 mm per year, or even ≤ 0.1 mm per year. We also observe secondary earthquake effects in a broader context, extending beyond our study regions.

However, some faults exhibit distinct linear scarps and topographic variations, as revealed through high-resolution Digital Elevation Models (DEMs) and geophysical field surveys. It is indeed puzzling how these small-scale scarps, with heights of around 50 cm and formed during single events, have managed to persist for 1,000-10,000 years, particularly in agricultural areas. Nevertheless, recurring paleo-earthquakes are recorded in surface deposits, as demonstrated by our trench excavations in the Upper Rhine Graben.

Geodetic techniques, such as GPS and Differential Interferometric Synthetic Aperture Radar (DInSAR), offer valuable tools for detecting silent faults. However, their signals can be influenced by factors like groundwater extraction, seasonality, vegetation, and other obstacles. Additionally, in the Upper Rhine Graben, some normal faults display evidence of "Clustering and Quiescence" in terms of earthquake occurrences, potentially explaining the persistence of these scarps over time. This contrasts with the "One Shot" hypothesis sometimes applied to SCR faults.

To further our understanding of the history of silent and slow faults, we propose the integration of high-resolution geodetic techniques, like GPS and DInSAR, with traditional paleoseismological investigations. Despite potential signal distortions caused by groundwater and vegetation, this combined approach holds promise in unveiling the hidden history of these slow and silent faults.

Paleoseismicity of the Alpine foreland: the Upper Rhine Graben

Klaus Reicherter[1], Joachim R.R Ritter[2], Jochen Hürtgen[1], Sara Pena-Castellnou[1]

1. Institute of Neotectonics and Natural Hazards, RWTH Aachen University, Germany
2. Geophysical Institute, KIT, Karlsruhe, Germany

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The Upper Rhine Graben faults in Central Europe are known for significant seismic activity within the Earth's crust, even though they are located within a tectonic plate, in an intraplate setting. This region has experienced destructive earthquakes throughout history, such as the 1356 Basel earthquake amongst others, which had a magnitude below 7 on the Richter scale. In recent decades, several research initiatives have assessed the seismic hazard associated with the Rhine Graben. These efforts primarily concentrated on investigating the western edges of the graben, where Late Pleistocene to Early Holocene faults that ruptured the surface during earthquakes were identified.

However, the use of "period and characteristic" fault models in earthquake geology has led to incomplete estimates of the faulting history and the seismic potential of these faults. Our research is designed to comprehensively characterize the seismogenic faults within the Rhine Graben by examining their recent geological activity and creating a chronological record of seismic events along each fault or fault segment. Our approach involves several methods, including geomorphological mapping of fault features, studying the deposits from the Quaternary period, trenching to investigate paleoseismic evidence, and employing various morphometric parameters to delineate the segmentation of these faults while considering long-term deformation.

The data we have collected provide compelling evidence regarding the dynamic behavior of these faults, allowing us to define specific areas with varying levels of tectonic activity formerly not known. We conducted trenching activities at several key sites for paleoseismological investigations, including comprehensive geophysical surveys conducted in the Upper Rhine Graben. Notably, our findings include the discovery of surface rupturing earthquakes near Karlsruhe (Ettlingen) and Freiburg (Tunsel), offering the initial evidence of tectonic activity during the Late Pleistocene and Holocene periods, with magnitudes exceeding M 6 on the Richter scale. Consequently, our research significantly, hence we contribute significantly to the completeness of the earthquake history in this region North of the Alps.

Rapid Miocene Exhumation to the East of the Tauern Window

Johannes Rembe[1], Edward R. Sobel[1], Willemijn S. M. T. van Kooten[1,2], Susanne Schneider[3,4]

1. Institute of Geosciences, University of Potsdam, Germany
2. Department of Digital Business & Software Engineering, MCI - The Entrepreneurial School, Austria
3. Bundesamt für die Sicherheit der nuklearen Entsorgung BASE, Germany
4. Institute for Geosciences, University of Freiberg, Germany

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The Eastern Alps were substantially shaped by northward movement of the Dolomites Indenter and eastward extrusion of the orogenic wedge in front of the indenter. A resulting sinistral wrench zone runs through the western Tauern Window (TW) and continues along the Salzach-Ennstal-Mariazell-Puchberg Fault (SEMP) eastward. Low-T thermochronological studies demonstrate rapid Miocene cooling of the TW units from ≥ 350 °C to below ~ 80 °C due to folding and coeval erosion. Thermochronologic ages in the Eastern Tauern Window range between 12 Ma to 22 Ma for the zircon fission track chronometer (partial annealing zone (PAZ) ~ 200 – 350°C, e.g., Tagami et al., 1996) and 5 Ma to 13 Ma for the apatite (U-Th)/He chronometer (partial retention zone (PRZ) ~ 40 – 80°C, Stockli et al., 2000). Ages for the zircon (U-Th)/He and apatite fission track chronometers fall in between.

Along the eastern margin of the TW, the extensional Katschberg Fault-System (KFS) decoupled the Gurktal Block (GB) in its hanging wall from folding. The KFS was active between 20 and 17 Ma, in the early Miocene (Scharf et al., 2016). A late reactivation phase is demonstrated by reset or partially reset zircon and apatite fission track ages within the footwall towards the fault, yielding Late Miocene to Pliocene ages (Bertrand et al., 2017). A similar younging trend is observed within the TW towards the Brenner Fault in the western TW. The GB in the hanging wall of the KFS preserves a rapid Cretaceous and Eocene cooling through the zircon fission track PAZ and rapid Oligocene to Miocene cooling through the apatite fission track PAZ (Wölfler et al., 2023).

The Niedere Tauern (NT), north of the GB and south of the SEMP line, seem to be structurally closely linked to the TW. They show a similar rapid Miocene cooling history and an intervening Cenozoic structure between the TW and the NT is missing. Published apatite fission track ages range between 14 Ma and 24 Ma (apatite PAZ ~ 60 – 100°C, Wagner et al., 1989). Published apatite (U-Th)/He ages from the southern boundary of the NT range between 6 Ma and 7 Ma, indicating a Late Miocene cooling below ~ 80 °C (Wölfler et al., 2016).

Our (U-Th)/He analysis from the interiour of the NT revealed ages of around 20 Ma to 23 Ma (zircon (U-Th)/He), and 11 Ma to 22 Ma (apatite (U-Th)/He). Published apatite fission track ages fall in between and partly overlap with our results. This demonstrates a rapid cooling pulse in the Miocene, exhuming at least the western part of the NT from ≥ 200 °C to below ~ 80 °C. Published AHe ages of ~ 6 Ma along the southern margin of the NT might relate to late Miocene normal faulting along the complex Murtal Fault-System (MFS). A pronounced jump towards older thermochronologic ages in the Seckauer Tauern, east of the Pöls fault and extensional structures along this fault indicate a structural decoupling of the western NT from the Seckauer Tauern.

In this contribution, we discuss the linkage between TW and N T and characterize in greater detail the exhumation history along the eastern wrench zone.

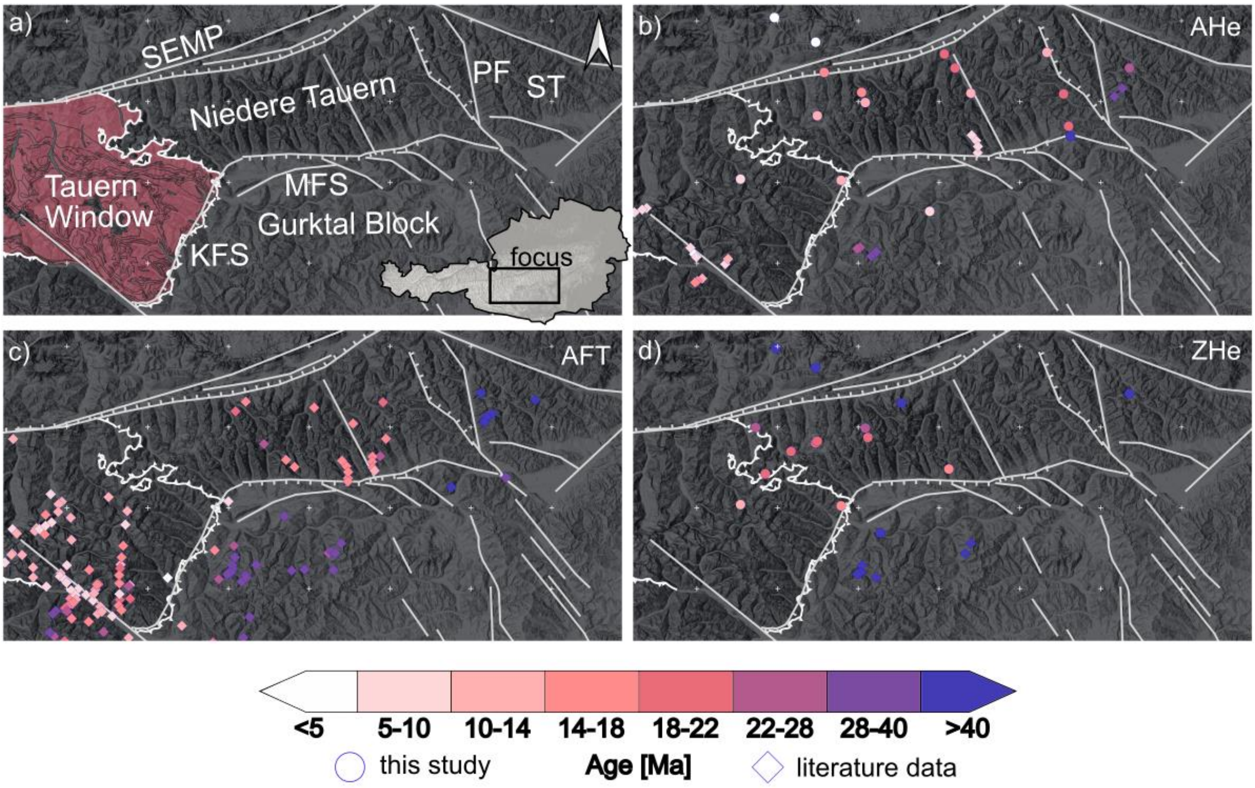

Figure 1: a) This map shows the location of major structural entities named in the text. The inlet shows the location of the maps of a)-d) within Austria. Abbreviations are: SEMP…Salzach-Ennztal-Mariazell-Puchberg Fault, PF…Pöls Fault, ST…Seckauer Tauern, MFS…Mur Fault-System, KFS…Katschberg Fault-System. Cross-grid distance is 20 km. b) Distribution of new and published apatite (U-Th)/He ages (AHe) in the study area. c) Distribution of published apatite fission track ages (AFT) in the study area. d) Distribution of new and published zircon (U-Th)/He ages (AHe) in the study area.

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2-D kinematic restoration of the western Tauern Window using thermochronological constraints

Julia Rudmann[1], David Colin Tanner[1], Michael Stipp[2], Hannah Pomella[3], Christian Brandes[4]

1. Leibniz Institute for Applied Geophysics, Stilleweg 2, 30655 Hannover, Germany
2. Martin-Luther-University Halle-Wittenberg, Von-Seckendorff-Platz 4, 06120 Halle (Saale), Germany
3. University of Innsbruck, Innrain 52f, 6020 Innsbruck, Austria
4. Leibniz University, Callinstraße 30, 30167 Hannover, Germany

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The Tauern Window (TW) in the European Alps has a high tectonic complexity. It is a key area to understand a number of important orogenic processes. During the Cretaceous, subduction and accretion of the Penninic realm beneath the northern margin of Adria (Austroalpine) began, which led to collision between Europe (Subpenninic) and the Adria margin, from Eocene to early Oligocene. This resulted in the Penninic and Subpenninic nappe stack in the southward-dipping orogenic wedge. After the “Tauernkristallisation”-event, indentation of the Dolomites Indenter (Eastern Southern Alps) is heralded in the last deformation stage, which bent the primarily W-E striking, dextral Periadriatic Fault System (PFS) separating the Eastern from the Southern Alps, and finally caused this fault system to be sinistrally offset by the NNE-SSW-striking Giudicarie fault system in the Miocene. This last deformation stage resulted in strong N-S shortening (ca. 70 km) of the western TW in front of the Dolomites indenter as well as W-E extension, which formed the Katschberg and Brenner Normal Faults (eastern and western border of the TW), and to lateral extrusion towards the east involving major strike-slip faults (e.g., Inntal Fault, PFS, SEMP). It is widely assumed that all these processes happened synkinematically exhuming the western TW up to ca. 20 km (derived from the throw of the Brenner Normal Fault and by the metamorphic conditions reached). However, the quantitative deformation history of the western TW, and in particular its Subpenninic core (Venediger Duplex, VD), has never been investigated in detail. Our goal is therefore to quantify the deformation and kinematics accommodated by the VD in a first step by restoring the Brenner Base Tunnel cross-section using the software MOVE (Ptx). Since standard balancing of this structure is not possible due to penetrative deformation, we integrate Zircon Fission Track data (partial annealing zone of 240 – 180°C and closure temperature ca. 210°C) as marker for the transition from brittle to viscous conditions in the felsic rocks of the VD: Any folding in the VD must be older than the ZFT age of the corresponding unit. For this reason, we first displaced the whole duplex structure down along the Sub-Tauern Ramp below the Zircon Fission Track annealing zone. We then unfolded the gneiss cores individually until a symmetrical duplex structure was modeled, which reached 20 km depth. Since the modeling of vertical exhumation, N-S shortening and displacement along the Sub-Tauern Ramp strongly depends on the geothermal gradient (GG), we tested different GG. Resulting exhumation rates related to a GG of 30°C/km and 50°/km fit well with former studies, which means that 30-50°C/km is a reasonable range for the GG during the last deformation stage.

Layered anisotropy and mantle flow beneath AlpArray from shear-wave splitting

Georg Rümpker[1], Frederik Link[1,2]

1. Institute of Geosciences, Goethe-University Frankfurt, Germany
2. Now at: Department of Planetary Sciences, Yale University, USA

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Seismic anisotropy provides a unique link between directly observable surface structures and the more elusive dynamic processes in the mantle below. The ability to infer the vertically- and laterally-varying anisotropic structures is of great significance for the geodynamic interpretation of surface-recorded waveform effects. In the first part of this presentation, we assess the capabilities of different observables for the inversion of XKS phases to uniquely resolve the anisotropic structure of the upper mantle (Rümpker et al., 2023). For this purpose, we perform full-waveform calculations for relatively simple models of upper-mantle anisotropy. In addition to waveforms, we consider the effects on apparent splitting parameters and splitting intensity. The results show that it is not generally possible to fully constrain the anisotropic parameters of a given model, even if complete waveforms are considered. However, inversions of both waveforms and apparent splitting parameters lead to similar models that exhibit systematic variations of anisotropic parameters. These characteristics may be exploited to better constrain the inversions. The results also show that splitting intensity has some significant drawbacks: First, even from measurements over a wide range of back-azimuth, there is no characteristic signature that would indicate depth variations of anisotropy. Secondly, identical azimuthal variations of splitting intensity for different anisotropic structures do not imply that the corresponding split waveforms are also similar. Thus, fitting of observed and calculated splitting intensities could lead to anisotropic models that are incompatible with the observed waveforms. In the second half, we present the first comprehensive analysis of layered anisotropy for the complete Alpine range based on apparent splitting parameters determined at 591 seismic stations of the AlpArray experiment (Link & Rümpker, 2023). Our findings suggest a combination of asthenospheric and distinct lithospheric contributions to the splitting observations, which can be seen as a refinement of previously reported models of single-layer anisotropy. The enhanced vertical resolution exposes the impact of successive Mediterranean tectonic episodes, such as the opening of the Provencal-Ligurian and Tyrrhenian Basins alongside the Adriatic slab retreat, as well as the Pannonian Basin opening and the Aegean slab retreat, resulting in deformation of the lithosphere and flow in the asthenospheric mantle. The dominant role of the larger scale Mediterranean subduction systems on mantle dynamics becomes evident. The observations provide supporting evidence that the European slab has broken off at its boundaries and that the resulting gaps channel flow from the mantle beneath the Eurasian plate to the Adriatic and Aegean subduction systems. The results provide important constraints on geodynamic processes involved in forming the European Alps, as previous and ongoing tectonic episodes can be inferred from the anisotropic fabric of the lithosphere-asthenosphere system.

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INTEGRATE-Integrated 3D structural, thermal, gravity and rheological modeling of the Alps and their forelands

Magdalena Scheck-Wenderoth[1], Judith Bott[1], Cameron Spooner[1], Jörg Ebbing[2], Hans-Jürgen Götze[2], Josef Sebera[2]

1. Helmholtz Zentrum Potsdam, Deutsches GeoForschungsZentrum, GFZ Telegrafenberg, 14473 Potsdam, Germany
2. Christian-Albrechts-Universität zu Kiel, Otto-Hahn-Platz 1, 24118 Kiel, Germany

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The aim of this project was to obtain a better understanding of the crust and the uppermost mantle beneath the Alpine orogen and its forelands and to test different hypotheses on the configuration of the subduction system as well as on the distribution of deformation and seismicity. Therefore, we have integrated the geoscientific observations publicly available so far on properties of the sediments and the crystalline crust (geometry, seismic velocities, and densities) with seismologically derived heterogeneities in the sub-crustal mantle into a consistent data-based 3D structural model that resolves the first-order contrasts in physical properties of the units composing the orogen and the forelands.

The derived structural model was additionally constrained by 3D gravity modelling and used as input to derive a lithospheric temperature field based on petrological assumptions on the composition of the crust and mantle. This is done to study the effects of regional heat-flow into the Alps and their foreland basins. Starting from these 3D density thermal and lithology models, the integrated strength was derived and discussed in the context of stress and deformation fields.

The project led to the successful completion of a dissertation by Cameron Spooner who obtained the highest possible grade ("summa cum laude") from the University of Potsdam and published 4 high-level papers. Also, a Master thesis was successfully completed by Max Lowe at CAU Kiel that also led to a publication (Lowe et al. 2021).

As members of the AAAGRG, the partners of CAU Kiel were significantly involved in the compilation of the new gravity maps for the Alps and their forelands (Zahorek 2021).

The project contributed to "Theme 3: deformation of the crust and mantle during mountain building", in providing the configuration of the different crustal units and of the lithospheric mantle. The project also contributed to "Theme 4: motion patterns and seismicity" in that it supported identifying spatial patterns of faulting and seismicity in relation to the rheological configuration. In response to its regional character, the project links with the different activity fields of the SPP and a continuous exchange of observations and modelling results with many working groups in the SPP and supported data processing and interpretation.

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Glacial and erosional contributions to Late Quaternary uplift of the European Alps (GEOLQUEA)

Dirk Scherler[1,2], Helen Werner[1], Ricarda Winkelmann[3,4], Guillaume Jouvet[5], Volker Klemann[1]

1. Helmholtz Centre Potsdam German Research Centre for Geosciences GFZ, Potsdam, Germany
2. Freie University Berlin, Berlin, Germany
3. Potsdam Institute for Climate Impact Research, Potsdam, Germany
4. University of Potsdam, Potsdam, Germany
5. University of Lausanne, Lausanne, Switzerland

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Isostatic adjustments of the Earth's surface to changes in water, ice, and sediment loading are important contributions to present-day uplift/subsidence rates in many regions on Earth. In the absence of significant horizontal tectonic shortening in the central and western parts of the European Alps, uplift rates larger than 2 mm/yr are difficult to explain by geodynamic processes and have been a matter of debate for many decades. Here we examine the likely contribution of glacial isostatic adjustment in the European Alps in response to changes in ice loading using state of the art ice flow and lithospheric numerical modeling. In contrast to a similar previous approach (Mey et al., 2016), we employ a transient ice sheet model over the last glacial cycle (100 kyr) in combination with a spherical viscoelastic solid earth model. We present ice model results using the Instructed Glacier Model (Jouvet et al., 2021), in which we tested the effect of spatial resolution on the growth and extent of the European ice cap. We found significant differences using a model resolution of 200 m compared to a resolution of 2000 m, which is commonly used in large-scale glacier modeling studies. These differences result in near-steady state volumetric differences at the maximum ice extent of +13% for the high compared to the low-resolution model. In addition, we observed periods of marked ice growth that initiated at significantly different times for the different resolution models. Therefore, we conclude that a realistic ice loading history requires a sufficiently high spatial resolution, which is significantly higher than used in previous models. Based on the modeled ice loading histories, we used the lithosphere and mantle model VILMA (Klemann et al., 2008, J. Geodyn.) to predict the vertical land motion. These estimates are based on a global 60 km thick elastic lithosphere, followed by a 200 km thick viscous layer with a viscosity of 10^{20} Pa s, which increases to 5 x 10^{20} Pa s down to 670 km depth, and 3.16 x 10^{21} Pa s to the core mantle boundary. Preliminary results indicate similar first-order lithospheric responses, with spatiotemporal differences in the magnitude of postglacial response. We hope to present more results based on further ice models that are forced by a more realistic climate history.

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The seismically active Mt. Hochstaufen, Bad Reichenhall (Germany)

Antje Schlömer[1], Joachim Wassermann[1], Sabrina Metzger[2]

1. Department of Earth and Environmental Sciences, Ludwig-Maximilians-University of Munich, 80333 Munich, Germany
2. GFZ German Research Centre for Geosciences, 14473 Potsdam, Germany

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For centuries, the Mt. Hochstaufen/Bad Reichenhall region in the Northern Alps has been affected by single earthquakes with magnitudes up to M3.2 or by irregular swarms. Most of the swarms occur during summer, often accompanied by strong precipitation, suggesting a direct correlation of seismicity and rainfall. A swarm in 2019 comprised many earthquakes with high magnitudes but a synchronous strong rain event is missing. Consequently, precipitation and tectonic background stress cannot be the sole explanation for the unusual high local seismicity. A trans-disciplinary study combining seismological analysis, meteorological and geodetic observations of the last years was proposed to identify the set of acting forces. Here, we present the first results of the seismological analyses and of the ground-based radar measurement performed at three measuring points surrounding Mt Hochstaufen. The relocation and clustering of earthquakes of the last decade, enables to distinguish between one-time occurrence of fault mechanisms limited to one swarm and faults reactivated with a distinct (yearly) periodicity. Beside a subsidence of the Bad Reichenhaller basin west of the Saalach river, the ground-based radar measurements show the opening of prominent fractures at both flanks of the mountain.

The Southern Alps east of the Giudicarie Belt: Did they really act as an indenter?

Stefan M. Schmid[1]

1. Institute of Geophysics, ETH Zürich

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According to Ratschbacher et al. (1991) the eastern part of the south directed fold and thrust belt of the Southern Alps located east of the Giudicarie Belt acted as a rigid indenter responsible for the exhumation of the Tauern Window and the eastward lateral extrusion of the Austroalpine nappe pile in the Miocene. However, there is an apparent contradiction in that the Dolomites indenter is itself part of the Southern Alps fold- and thrust belt and hence far from being rigid. Realizing that different parts of thus fold- and thrust belt became deformed during distinct deformation events during different time intervals helps to solve this dilemma.

In the Lombardian Southern Alps to the west, and along the kinematically linked sinistrally transpressive Giudicarie fold- and thrust belt, most of the south-directed thrusting occurred twice. Important thrusting occurred before the oldest intrusions of the Adamello pluton (before 45Ma), in the innermost parts of the Lombardian Southern Alps, very probably during the Late Cretaceous (94-78 Ma) as is suggested by the occurrence of flysch deposits whose detritus had its source in the Austroalpine units: the Late Cretaceous Lombardian flysch found along the foothills adjacent to the Po Plain and the remnants of this same flysch belt also found along the northern segment of the Giudicarie line. A second event occurred during the Miocene that postdates 22 Ma (age of the youngest marine sediments affected by sinistral transpression within the Giudicarie Belt), kinematically linked to the frontal-most thrust sheets of the Lombardian Southern Alps (figure 1). Schönborn (1992) quantified the amount of this post-Adamello Miocene N-S shortening to some 56km increasing eastward to some 87 km. Much of this Miocene N-S convergence is accommodated by northward wedging and underthrusting of the crystalline underpinnings of the fold-and thrust belt below the Central Alps and shallower parts parts of the preexisting about 30 Ma old Tonale Line (Schmid et al. 1996). The Giudicarie fold-and thrust belt, however, sinistrally displaced the entire crustal section of the eastern Southern Alps by about the same amount, i.e. some 72km (68km N-S component) to the north (Pomella et al. 2012). This resulted a sinistral offset of the pre-existing Tonale line in respect to the Pustertal segment of the Periadriatic line, associated with suspected indentation and rapid exhumation of the Tauern Window.

Deformation in the eastern part of the Southern Alps fold-and thrust belt (the Dolomites), however, occurred during entirely different time intervals. Parts of the Dolomites were affected by Dinaric SW-directed thrusting at 48-32Ma when the external Dinarides extended into the yet unfolded strata of the future Dolomites. After some 8 Ma of quiescence Miocene deformation in the Dolomites did initiate after the Langhian (i.e. after ca. 14 Ma) in the Dolomites as indicated by the youngest sediments involved along the Val Sugana thrust system (Castellarin et al. 1992, 1998). From a structural point of view the Val Sugana thrust system of the Dolomites ends westward before reaching the Giudicarie fold and thrust belt to which it is kinematically unrelated. The end of the suspected indentation of the Dolomites indenter, and hence sinistral transpression along the Giudicarie belt, can be estimated on the basis of the end of fast cooling in the Tauern window due to exhumation at around 14 Ma (Scharf et al. 2013).

In conclusion, it appears that indentation occurred during the 22-14 Ma time interval when the Dolomites east of the Giudicarie Belt remained undeformed and indeed acted as an indenter.

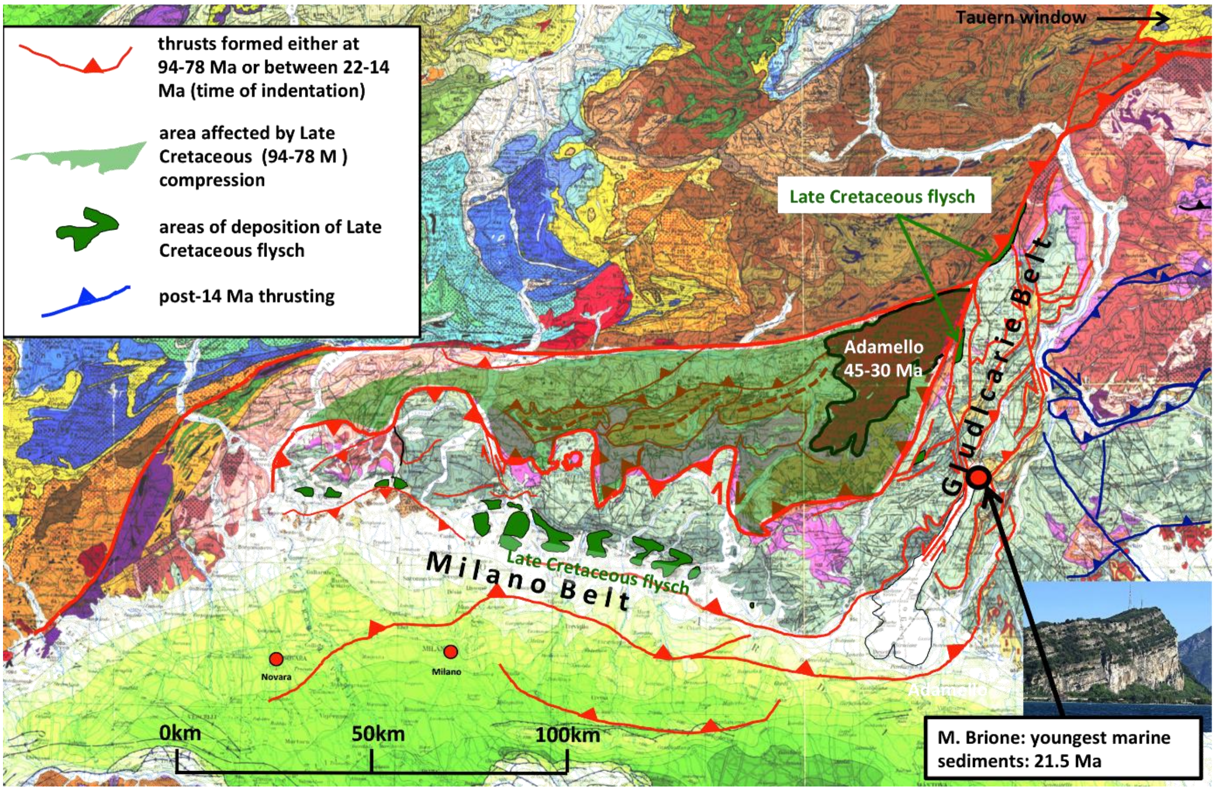

Figure 1: Note that the frontal part of the Lombardian Southern Alps (Milano Belt) south of the area deformed during Late Cretaceous times (green), deformed during the 22-14 Ma interval curves into the SSW-NNE striking Giudicarie Belt. Deformation of the indenter (blue lines) occurred after 14 Ma. Background map: Structural Model of Italy sheet Nr. 1 (Bigi et al. 1990).

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Investigating the plate motion of the Adriatic microplate by 3D thermomechanical modelling

Christian Schuler[1], Boris Kaus[1], Eline Le Breton[2], Nicolas Riel[1]

1. Institute of Geosciences, Johannes-Gutenberg University Mainz, Germany
2. Institute of Geological Sciences, Free University Berlin, Germany

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Mantle dynamics in the Alpine-Mediterranean area provides a complex geodynamic picture and is still subject of ongoing debate. The Adriatic microplate represents the central part of the Mediterranean and is affected by various subduction zones, like the Hellenic slab, the Calabrian slab or the Apenninic slab. These different processes pose challenges in making qualitative assumptions about the unique impact factors influencing the plate motion.

In this study, we conduct 3D thermomechanical forward simulations of the Alpine-Mediterranean area using the LaMEM (Kaus et al., 2016). Our simulations incorporate a viscoelastoplastic rheology and an internal free surface, enabling us to investigate both internal dynamics and surface response. The initial setup for the simulations is based on the kinematic reconstructions of Le Breton et al. (2021) at 35 Ma. Our objective is to determine the main driving forces behind the plate motion of the Adriatic microplate by examining the effects of different model parameters, such as the thermal structure, slab geometry, mantle viscosity, and brittle parameters of the crust.

Although these forward simulations do not yet precisely reproduce the present-day tectonic setting, they provide valuable insights into the parameters that influence the plate dynamics. Based on our findings, we have identified two distinct stages of plate motion affecting Adria over the past 35 million years. The initial phase is dominated by the northwards moving African plate, which pushes Adria to the north. However, as the Hellenic slab advances from the east and the Calabrian and Apenninic slabs propagate from the west, the Adriatic microplate is decoupling from the African plate which induces an anticlockwise rotation of Adria. The extent and the thermal structure of the Ionian oceanic lithosphere are significant parameters that influence the retreat of the Hellenic and Calabrian slab and therefore the rotation of Adria. Simultaneously, the northwards motion of Adria during the rotation is caused by the retreat of the Western Alpine slab.

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Control of inherited structures and mechanical heterogeneities on the internal deformation of the Dolomites Indenter, eastern Southern Alps: a multi-scale analogue modelling study

Anna-Katharina Sieberer[1], Ernst Willingshofer[2], Thomas Klotz[1], Hugo Ortner[1], Hannah Pomella[1]

1. Department of Geology, University of Innsbruck, Innsbruck, 6020, Austria
2. Department of Earth Sciences, Utrecht University, Utrecht, 3584 CB, Netherlands
3. Department of Infrastructure Engineering, University of Innsbruck, Innsbruck, 6020, Austria

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During the Cenozoic evolution of the Alps, the Adriatic plate is traditionally considered as a rigid indenter. The structure of the northernmost part of the Adriatic plate in the eastern Southern Alps of Italy and Slovenia, referred to as Dolomites Indenter (DI), however, demonstrates significant internal deformation. Mostly Miocene shortening is accommodated within a WSW-ENE striking, S-vergent fold-and-thrust belt overprinting a pre-existing platform-basin geometry related to Jurassic extension. In this contribution we present two new sets of physical analogue experiments, addressing the effect of lateral crustal heterogeneities on the internal deformation of the DI on crustal- and lithospheric scale.

The upper crust of the western Trento platform (western DI) is compositionally heterogeneous linked to Permian intrusives and extrusives (i.e., Athesian Volcanic Complex). Together with inherited basement structures this lateral heterogeneity, which strengthened the platform locally, is key for understanding upper crustal deformation and surface uplift patterns associated with Miocene basin inversion. We present brittle crustal-scale analogue experiments with inversion of pre-scribed platform-basin geometries, which indicate that variations in thickness, shape, and basement structure of especially the western platform (WP) have impact on timing and uplift of the DI's upper crust. The mentioned variations in crustal composition, lead, compared to the reference model with simple platform-basin geometry, to (i) overall fewer thrust sheets, (ii) footwall cut-offs of the frontal thrust further in the hinterland, and to (iii) longer and flatter flats of the frontal thrust. Regarding the topographic evolution, a variation in, e.g., basement structure shows strain localization at the margin of the basal plate and stronger uplift within the southern part of the WP compared to limited uplift of the northern WP, which is consistent with documented little vertical movement north of the Valsugana fault system since the Jurassic.

On the scale of the lithosphere, new analogue experiments with pre-scribed platform and basin geometries in the upper crust show similar lateral variations in thrust fault orientation across transfer zones as crustal-scale analogue models (Sieberer et al., 2023). Additionally, lateral variability of ductile lower crustal thickness predicts stronger uplift in areas of thicker lower crust. Documented thickening of the lower crust in some parts of the Southern Alps close to areas of higher uplift, tentatively interpreted being Miocene in age (Jozi Najafabadi et al., 2022), might support this finding.

Ultimately our crustal and lithosphere-scale modelling predictions will be validated by high resolution low-temperature thermochronological data which cover the entire Dolomites Indenter.

Jozi Najafabadi, A., Haberland, C., Le Breton, E., Handy, M. R., Verwater, V. F., Heit, B., and Weber, M.: Constraints on Crustal Structure in the Vicinity of the Adriatic Indenter (European Alps) From Vp and Vp/Vs Local Earthquake Tomography, Journal of Geophysical Research: Solid Earth, 127, 10.1029/2021jb023160, 2022.

Sieberer, A.-K., Willingshofer, E., Klotz, T., Ortner, H., and Pomella, H.: Inversion of extensional basins parallel and oblique to their boundaries: inferences from analogue models and field observations from the Dolomites Indenter, European eastern Southern Alps, Solid Earth, 14, 647-681, 10.5194/se-14-647-2023, 2023.

Seismic wavefield visualizations with AlpArray and AdriaArray

Johannes Stampa[1], Thomas Meier[1]

1. Institut für Geowissenschaften, Christian-Albrechts-Universität Kiel, Germany

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The dense network of broadband seismometers in the alpine region is making it possible to resolve the seismic waves moving across the array in fine detail. These animations allow for an insight into the wave field dynamics, but processing the data poses several challenges, especially in bringing the amplitudes across the array into a range where they can be usefully shown alongside each other, and filtering the data to bring out the seismic phases visually from the shorter period noise.

Here, we use a normalisation method based on the envelopes of the long-period lowpass filtered waveforms. The waveforms are then also band-pass filtered. The amplitudes are represented in color, with red being positive and blue being negative, as well as marker sizes in the animations for vertical component data. An estimate for the wave propagation of the most important seismic phases is performed via TauPy, and this estimate is drawn into the animation as coloured lines of theoretical wavefronts to facilitate the association of the visible wavefronts with them.

The horizontal component is shown as well, but here the color is used to represent horizontal direction, while the marker size still corresponds to amplitude. The colour wheel encoding the directional information is shown in the top right, with white and black corresponding to radial polarisation and red and blue to transversal polarisation of the seismic waves.

These animations can provide an intuitive, visual way to gain an understanding of seismic waves. They can also showcase the data quality, and might represent an early step in identifying specific problems at a glance over the whole array, like polarity errors or strong station noise level.

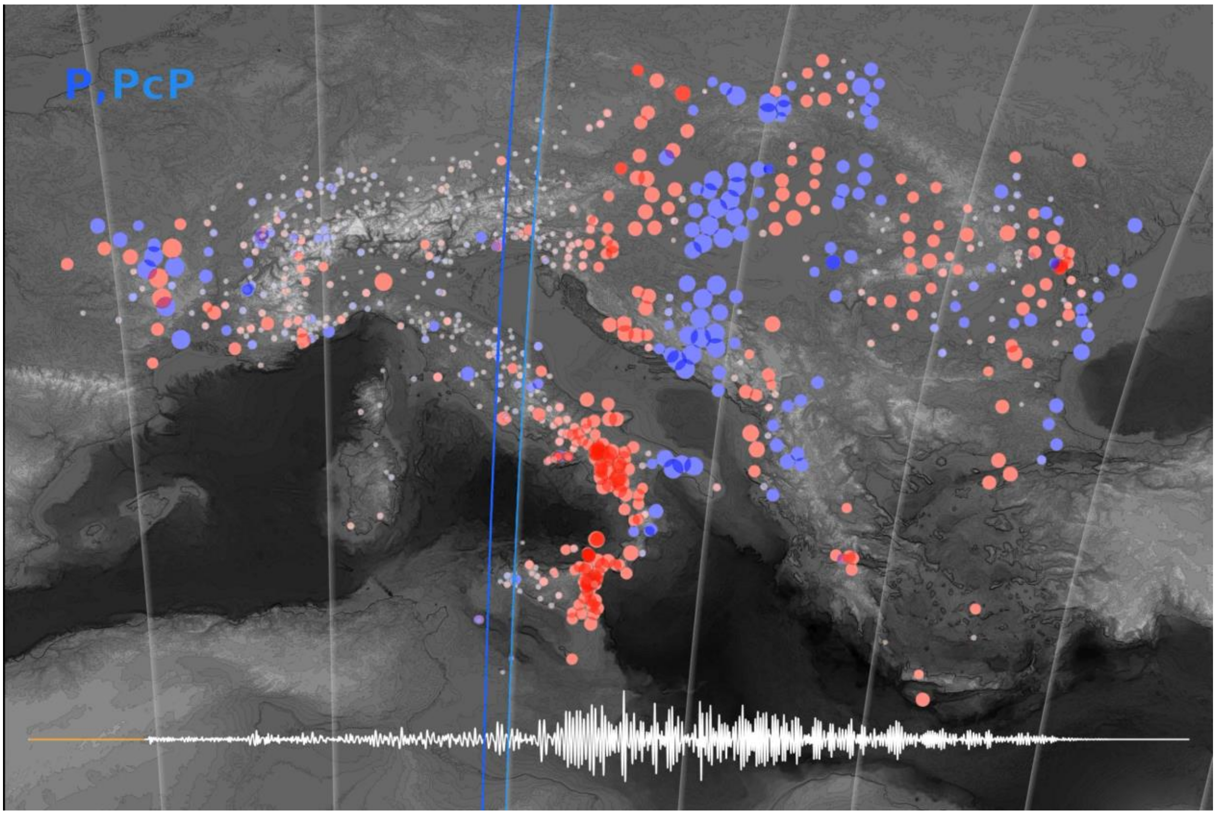

Figure 1: Screenshot of the vertical component wave field animation at the time of the arrival of the teleseismic P- and PcP-phase from a strong event that originated 171 km South-South East of Teluk Dalam, Indonesia, on the 24th of April 2023. The reference trace shown on the bottom was recorded at station FUSIO in the western alps.

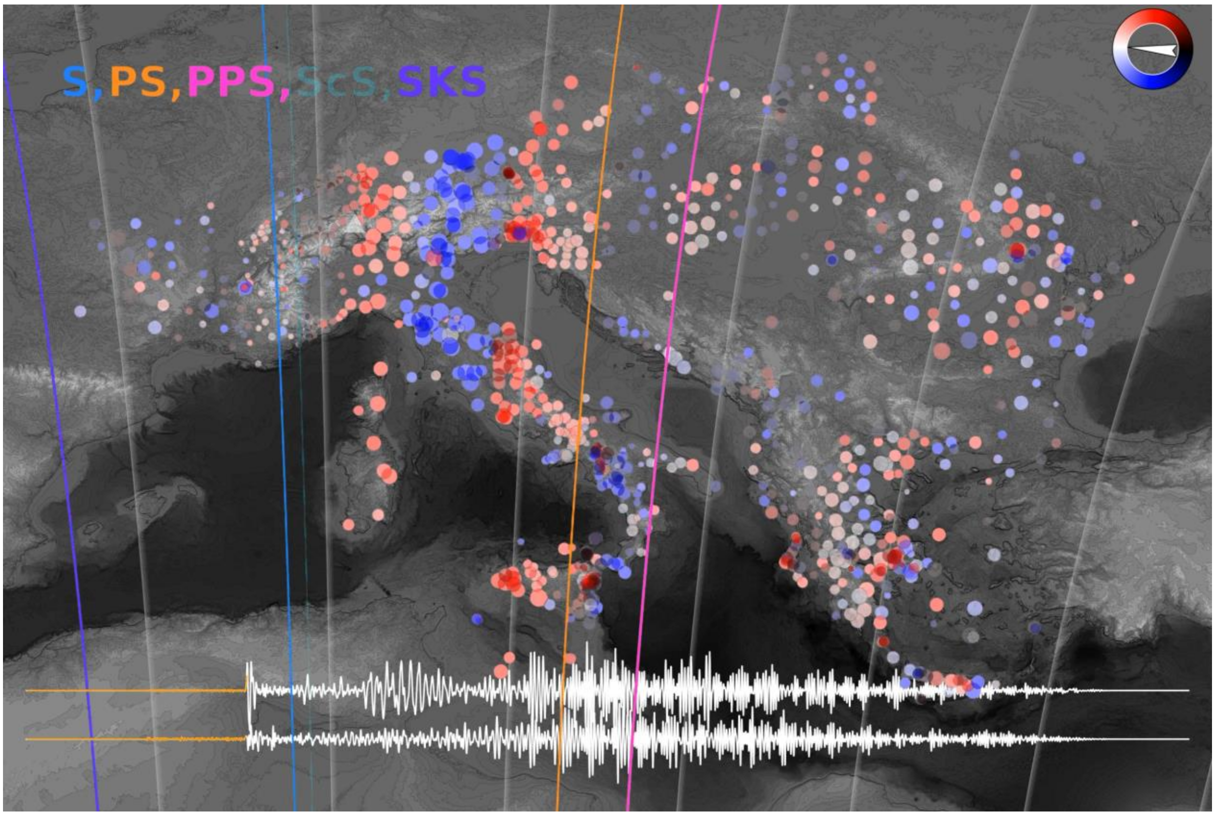

Figure 2: Screenshot of the horizontal component wave field animation at the time of the arrival of the teleseismic S-phase and some related phases.

Processes and repercussions of slab detachment

Marcel Thielmann[1]

1. Bayerisches Geoinstitut, Universität Bayreuth

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The European Alps are a result of the convergence between the European and the Adriatic plate, where the oceanic part of the European plate subducted beneath the Adriatic plate until continental collision occurred and slowed down subduction. This stalling of subduction then resulted in strong extensional stresses in the subducting slab and ultimately in slab detachment. Based on geological and seismological arguments different slab detachment/lithosphere delamination events have been proposed to have occurred in the last 40 Ma. These delamination events have severe effects on surface processes, such as rapid rock uplift, potentially enhanced magmatic activity and significant changes in erosion/deposition processes.

However, the direct link between slab detachment and its surface expression has still not been sufficiently quantified. On the one hand, the processes governing the detachment and in particular its time scale are still incompletely understood while on the other hand quantitative links between the detachment and shallow processes are still missing. Next to the uncertain geometry and configuration of slabs beneath the European Alps, our incomplete understanding of the detachment process is one of the reasons why timing, duration and number of detachment events beneath the European Alps are still debated.

Here, I summarize the results of different studies within the framework of MB4D that have addressed these issues from a numerical perspective. I show how numerical modelling has increased our quantitative understanding of the slab detachment process and the physical mechanisms governing its temporal evolution. With the increased computational capabilities, high resolution three-dimensional models of slab detachment have also increasingly become feasible, thus enabling us to study three-dimensional effects such as convergence obliquity and slab curvature to an unprecedented degree. By coupling these models of deep detachment processes with stratigraphic modelling, it has also become possible to create synthetic datasets that can then be compared to observed data. In addition to these more generic models, large-scale models of the European Alps have shown that to properly model the evolution of the European Alps, effects of neighbouring slabs have to be taken into account.

Finally, creating present-day models of the Alps has been complicated by the fact that the exact slab configuration and geometry is still debated. Depending on interpretations of seismic tomographies, uplift velocities and overall dynamics may change considerably. This has led to technical developments such as the GeophysicalModelGenerator (https://github.com/JuliaGeodynamics/GeophysicalModelGenerator.jl) and the accompanying graphical user interface GeoDataPicker.jl (https://github.com/JuliaGeodynamics/GeoDataPicker.jl) that are designed to significantly facilitate the process of data interpretation and geodynamic model generation.

The Geophysical Model Generator: A tool to unify and interpret geophysical datasets

Marcel Thielmann[1], Boris J.P. Kaus[2], Thomas Meier[3]

1. Bayerisches Geoinstitut, Universität Bayreuth
2. Institut für Geowissenschaften, Johannes-Gutenberg-Universität Mainz
3. Institut für Geowissenschaften, Christian-Albrechts-Universität zu Kiel

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Geophysical datasets and their interpretations form the basis of geodynamic simulations of the Earth's mantle and lithosphere. Yet, going from data to models is often non-trivial, particularly in complex regions such as the Alps. This is because creating consistent three-dimensional models from these datasets is often challenging due to technical discrepancies such as different data set formats, different spatial resolutions or discrepancies between different data sets. At the same time, the different datasets obtained through initiatives such as AlpArray contain a wealth of data that can help to constrain subsurface models to an unprecedented extent. Yet interpreting these different data still involves subjective steps and ideally different datasets are combined in the process.

To facilitate the joint interpretation of these datasets and the generation of geodynamic model setups, we therefore developed an open-source package - the Geophysical Model Generator (GMG) - to assist with unifying these datasets in a common data format that can then be further used to visualize, compare and interpret data. Within this package, we provide a set of routines to import different datasets, convert them to a common data format and to process them further (e.g., to create vote maps from different tomographies). These unified datasets can then be exported as vtk-files for further 3D visualization (e.g., Paraview). Moreover, with the Geophysical Model Generator it is also possible to create model setups for numerical models (such as the 3D geodynamic code LaMEM). This package thus covers the entire workflow from data import to numerical model generation. Key features of the Geophysical Model Generator include 1) the creation of 3D volumes from seismic tomography models, 2) the import of 2D data (e.g., surface or Moho topography or screenshots from published papers) and 3) the incorporation of point data such as earthquake locations or GPS measurements. Both scalar and vector data can be handled. With these tools, one can then create a consistent overview of the entire data available for a given region.

The package is written in Julia and hosted as a public open-source repository on GitHub (https://github.com/JuliaGeodynamics/GeophysicalModelGenerator.jl). To assist the joint interpretation of different geophysical datasets, we furthermore provide a graphical user interface that allows to view and compare them (https://github.com/JuliaGeodynamics/DataPicker). The GUI works provides an interactive webpage, allows loading different datasets and facilitates the manual interpretation of different structures (such as subducting slabs) along profiles and visualize them in 3D while taking different data into account. An example of the current version is given in Figure 1.

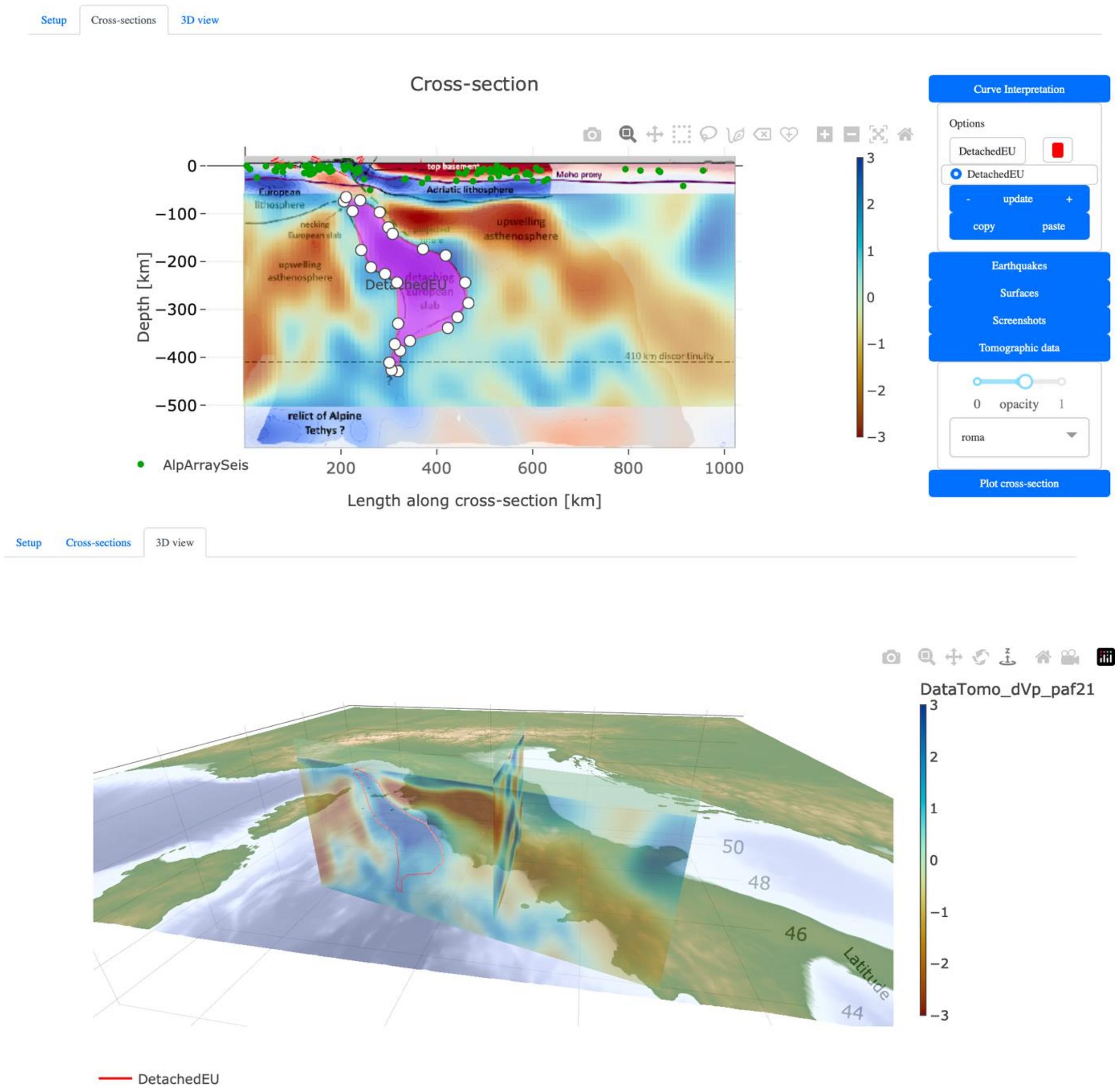

Figure 1: Snapshots of the GMG GUI with which Data processed with the Geophysical Model Generator can be analyzed and interpreted (provided in the GMG DataPicker package).

Basin inversion: reactivated rift structures in the central Ligurian Sea revealed using ocean bottom seismometers

Martin Thorwart[1], Anke Dannowski[2], Ingo Grevemeyer[2], Dietrich Lange[2], Heidrun Kopp[2]

1. Institute of Geosciences, Kiel University, Kiel, Germany
2. GEOMAR, Marine Geodynamics, Helmholtz Centre for Ocean Research Kiel, Kiel, Germany

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The Alpine orogen and the Apennine system are part of the complex tectonic setting in the Mediterranean Sea caused by the convergence between Africa and Eurasia. Between 30 Ma and 15 Ma, the Apennines-Calabrian-Maghrebides subduction retreated in a southeast direction pulling Corsica and Sardinia away from the Eurasian landmass, opening the Ligurian Sea. In this extensional setting, the Ligurian Sea was formed as a back-arc basin. The northern margin of the Ligurian Basin shows notable seismicity at the Alpine front, including frequent magnitude 4 events. Seismicity decreases offshore towards the basin center and Corsica, revealing a diffuse distribution of low-magnitude earthquakes.

Within the framework of the AlpArray research initiative, a long-term amphibious seismological experiment was conducted in the Ligurian Sea to investigate the lithospheric structure and the seismicity in the Ligurian Basin. The passive seismic network consisted of 29 broad-band ocean bottom stations from Germany and France next to permanent and temporary broad-band land stations. The ocean bottom stations were in operation between June 2017 and February 2018.

Two clusters consisting of 18 earthquakes occurred between ~ 10 km to ~ 16 km depth below the sea surface, within the lower crust and uppermost mantle, in the centre of the basin. Thrust faulting focal mechanisms indicate compression and tectonic inversion of the Ligurian Basin, which is an abandoned Oligocene–Miocene rift basin. The basin inversion is suggested to be related to the Africa–Europe plate convergence. The locations and focal mechanisms of seismicity suggest reactivation of pre-existing rifting-related structures. Slightly different striking directions of presumed rifting-related faults in the basin center compared to faults further east and hence away from the rift basin may reflect the counter-clockwise rotation of the Corsica–Sardinia block.

Mantle refractions Pn and Sn have apparent velocities of 8.2 km/s and 4.7 km/s. The low Vp-Vs-ratio of 1.72 indicates a more brittle behavior of the mantle material. This supports the hypothesis of strengthening of crust and uppermost mantle during the Oligocene–Miocene rifting-related extension and thinning of continental crust.

This project is part of the DFG Priority Program "Mountain Building Processes in Four Dimensions (4DMB)". This research has been supported by the Deutsche Forschungsgemeinschaft (grant nos. TH_2440/1-1, KO_2961/6-1, and LA_2970/4-1) and the Agence Nationale de la Recherche (grant no. ANR-15-CE31- 0015).

Foreland dynamics as a measure of mountain building processes

Christoph von Hagke[1], Elco Luijendijk[1,2], Sarah Louis[3], Sofia Brisson[1,4], Kevin Frings[5], Florian Wellmann[4]

1. Department of Biodiversity and Environment, Geology and Physical Geography, Salzburg University, Austria
2. Department of Earth Science, University of Bergen, Norway
3. Gruppe Forschung & Entwicklung Standortauswahl, BGE Bundesgesellschaft für Endlagerung mbH, Germany
4. Computational Geoscience, Geothermics and Reservoir Geophysics, RWTH Aachen University, Germany
5. Geologisches Institut, RWTH Aachen University, Germany

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Forelands record the uplift and exhumation history of mountain belts. The alpine foreland basin is particularly exciting, as is shows late-orogenic exhumation, possibly as a reaction to mantle-driven, plate convergence, or climatic forcings. However, inferring the contribution of the individual drivers to exhumation from stratigraphic or thermochronological data is challenging. The reason for this are along strike variability basin of stratigraphy, different degree of exhumation, as well as structural style of the Subalpine Molasse (i.e., the fold-thrust belt at the southern fringe of the basin). Furthermore, the influence of fluid flow on the thermochronological ages is unknown.

Exhumation estimates in the central part of the basin are mostly based on stratigraphic arguments. Thermochronological data is scarce and limited to local studies. As the Molasse has also been uplifted in the central part of the basin since the Miocene, it is probable that it also responds to deep-seated processes, but to a lesser extent than the western part of the basin. This may be a result of different slab dynamics along strike the orogen. To test this, we used detrital and in situ low-temperature thermochronological age dating to shed light on the surface expression of the underlying geodynamic process (Figure 1). Data shows that most ages in the central part of the basin are unreset, while resetting occurs in the southernmost tectonic slices of the Subalpine Molasse. Generally, Miocene shortening in the Subalpine Molasse progressively decreases from west to east. The pattern coincides with slab geometries at depth (Mock et al., 2020). A general trend of lesser erosion from west to east is also visible in the flat lying Molasse based on vitrinite reflectance data. This suggests that a geodynamic driver is required for explaining basin exhumation on basin scale.

Locally, the pattern is more complex. Particularly in the Subalpine Molasse, exhumation may be associated with plate convergence. To test the influence of faulting on exhumation, we constrained the geometries of the fold-thrust belt. Using a new compilation of stratigraphy and structures along the entire Alpine deformation front (Ortner et al., 2023), we identified two key regions: the Bregenzerach south of the eastward termination of the Jura Mountains, and the Hausham Syncline southeast of Munich. The Bregenzerach region lies at the surface boundary between Eastern and Western Alps. Furthermore, previously published thermochronological data indicate thrust activity in the mid-Miocene. Structures at depth are reasonably well-constrained due to good outcrop conditions and seismic data. The Hausham Syncline represents the region where structures at depth are less well constrained, and additionally the frontal triangle zone of the Subalpine Molasse tapers out. Structural modeling shows that it is possible to quantify the uncertainty of structures at depth, paving towards thermo-kinematic modeling including structural uncertainty (Brisson et al., 2023; Frings et al., 2023).

The extensive thermochronological dataset offers the opportunity to identify local particularities not in line with the general trends observed in the data. Using thermal springs as proxy for heat flow (Luijendijk et al., 2020), we show that fluid flow may at least locally influence the cooling pattern. This is important for translating cooling into exhumation, particularly in regions where less data is available and thus outliers may be overlooked.

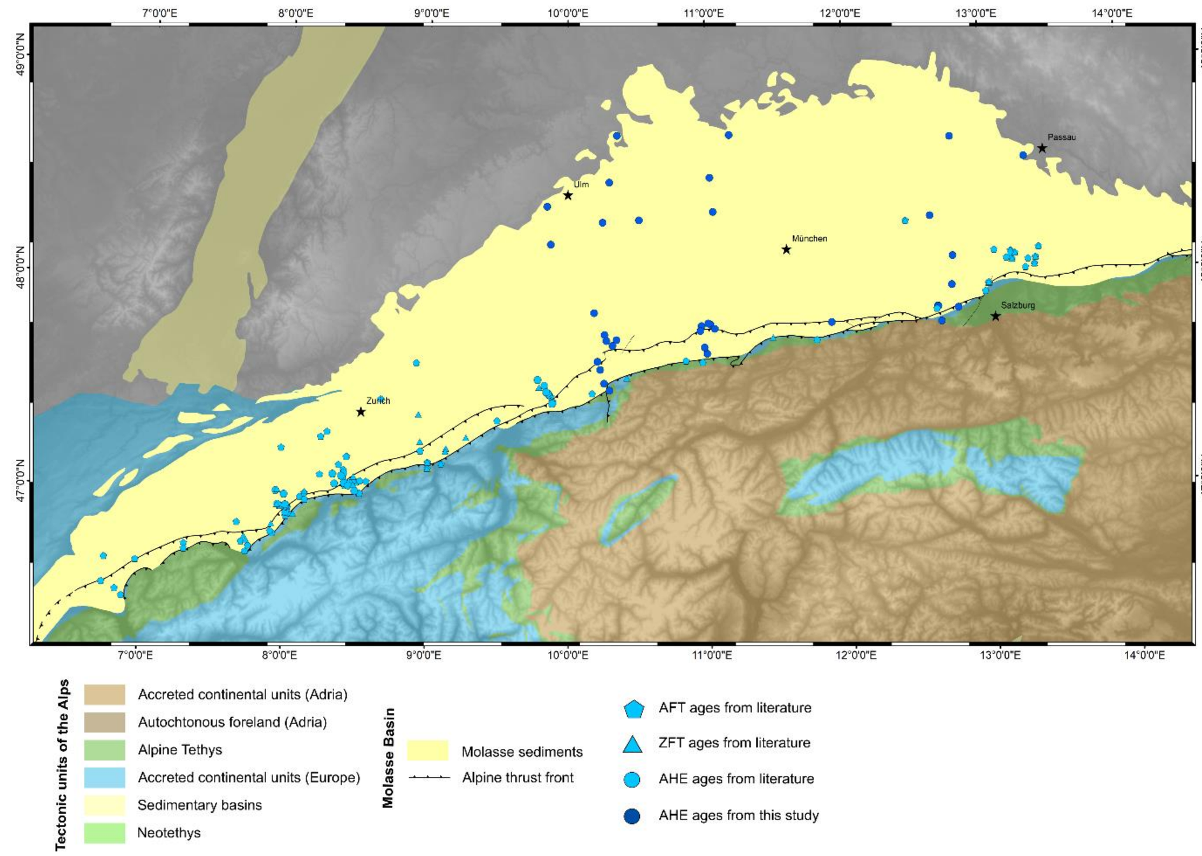

Figure 1: Thermochronological data from the Molasse Basin collected at the surface and from borehole data (western Molasse).

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A petrological and geochronological study of the Koralpe-Saualpe-Pohorje (KSP) Complex (Eastern Alps)

Iris Wannhoff[1], Jan Pleuger[1], Xin Zhong[1], Timm John[1], Leo J. Millonig[2], Axel Gerdes[2]

1. Institute of Geological Sciences, Freie Universität Berlin, Germany
2. Institut für Geowissenschaften, Goethe-Universität Frankfurt, Germany

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The KSP Complex in the Eastern Alps stretches from SE Austria to NW Slovenia and is a lithologically heterogenous (U)HP nappe with abundant eclogite lenses embedded in gneissic and metasedimentary rocks. An increase of metamorphic peak pressure-temperature (PT) conditions from NW to SE with UHP conditions for Pohorje was previously proposed based on thermodynamic modelling. The formation history of the KSP Complex is still debated. Here, we investigate in detail the PT conditions during the formation of the complex along a NW-SE transect following the direction of subduction with a new combined approach for this area of Raman spectroscopy of quartz inclusions in garnet, Zr-in-rutile thermometry and U/Pb dating on garnets. This is the first study within the KSP complex where quartz inclusions in garnet elastic barometry was conducted to determine the entrapment pressures, which correspond to the minimum pressure conditions present during the entrapment of quartz inside garnet. Approximately 5000 quartz inclusions inside the inner part of the garnets were investigated. The garnet rims contain almost no inclusions. The eclogites yield pressures of max. 1.9 GPa across the KSP complex, indicating no pressure increase from the NW to SE (Fig. 1). The metasediments and gneisses show overall lower pressures with ca. 1.4 GPa. Temperatures based on Zr-in-rutile thermometry was conducted on 194 rutile grains in different microstructural positions. The results do not indicate a temperature increase from NW to SE, with ca. 640 (±30)°C across the whole KSP Complex (Fig. 1), based on very similar Zr contents of ca. 270 ppm. The new approach of insitu U/Pb dating on garnets allows the age determination of the different growth zones in garnet and makes it an ideal tool to decipher metamorphic processes. The metasediments provide the following ages (Fig. 1) for the Koralpe 101.3 ± 6.6 Ma (throughout garnet); Saualpe 224.6 ± 31 Ma (core) and 115.5 ± 17.7 Ma (rim); Pohorje 104.2 ± 7.1 Ma to 105.5 ± 17.2 (throughout garnet). Garnet in eclogite from Koralpe is 112.8 ± 9.9 Ma. In general, the garnets in eclogite from the KSP complex are very poor in U. The obtained ages are interpreted to be metamorphic peak ages with a Cretaceous event at c. 100 Ma and a Triassic/Permian event reported in garnet cores from metasediments from Saualpe which is in line with existing literature. Combined with results of previous studies of eclogite ages, we suggest, that the eclogites are former (probably Permian) gabbro intrusions that experienced HP conditions during the Eoalpine orogeny. Whereas garnet ages of metasediments from Saualpe provide evidence for a polymetamorphic history.

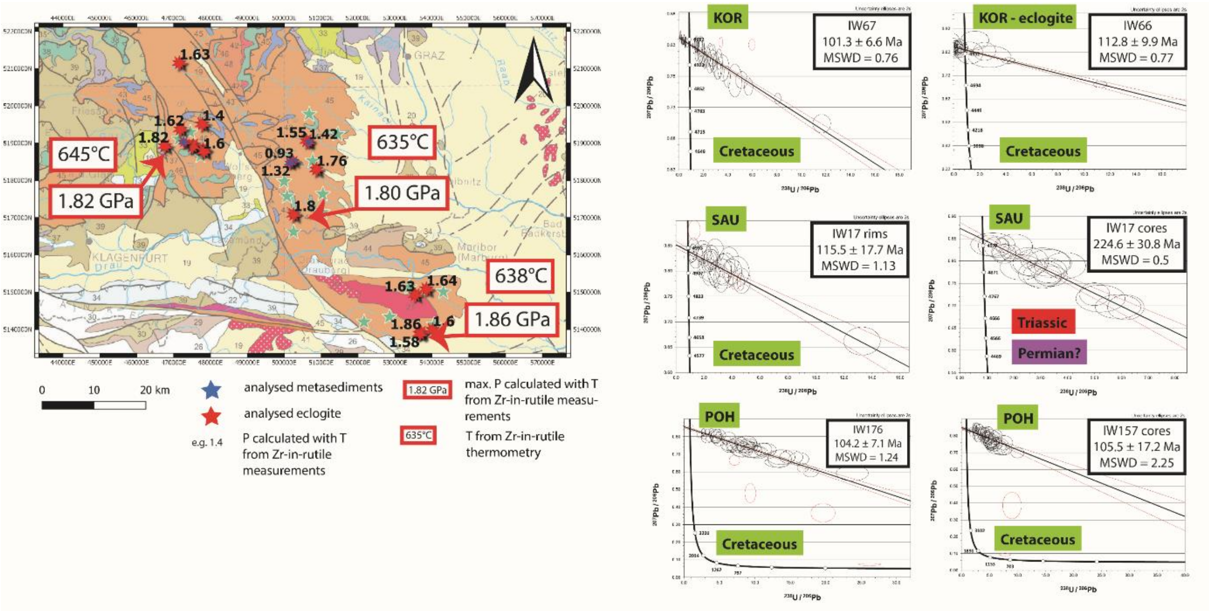

Figure 1: Left) Geological map from Schuster et al. (2015) with results for metamorphic peak PT of eclogites and metasediments. Right) U/Pb isochron plots for the dated metasediments and eclogites from the KSP complex.

Impact of spatial resolution on large-scale ice cover modeling of mountainous regions

Helen Werner[1], Dirk Scherler[1,2], Ricarda Winkelmann[3,4]

1. Helmholtz Centre Potsdam German Research Centre for Geosciences GFZ, Potsdam, German
2. Freie Universität Berlin, Berlin, Germany
3. Potsdam Institute for Climate Impact Research PIK, Potsdam, Germany
4. University of Potsdam, Potsdam, Germany

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For reconstructing paleoclimate or studying glacial isostatic effects on the Earth's lithosphere, increasingly more studies focus on modeling the large-scale ice cover in mountainous regions over long time scales. However, balancing model complexity and the spatial extent with computational costs is challenging. Previous studies of large-scale ice cover simulation in mountain areas such as the European Alps, New Zealand, and the Tibetan Plateau, typically used 1-2 km spatial resolution. However, mountains are characterized by high peaks and steep slopes - topographic features that are crucial for glacier mass balance and dynamics, but poorly resolved in coarse resolution topography.

The *Instructed Glacier Model* (IGM) is a novel 3D ice model equipped with a physics-informed neural network to simulate ice flow. This results in a significant acceleration of run times, and thereby opening the possibility of higher spatial resolution runs. We use IGM to model the glaciation of the European Alps with different resolutions (2 km and 200 m) over a time period of 160,000 years. We apply a linear cooling rate to present-day climate until 6 °C colder to mimic ice age conditions.

Preliminary results indicate systematic, resolution-related differences: At the beginning of cooling the 2 km resolution yields slightly more ice volume. However, this trend reverses when ice flows together from high elevations and fill large valleys with thick ice. When the Alps are fully ice covered, we find up to 14% more ice volume in the higher resolution models which, however, is not uniformly distributed in space.

3D crustal structure of the Ligurian Basin revealed by surface wave tomography using ocean bottom seismometer data

Felix N. Wolf[1], Dietrich Lange[1], Anke Dannowski[1], Martin Thorwart[2], Wayne Crawford[3], Lars Wiesenberg[2], Ingo Grevemeyer[1], Heidrun Kopp[1,2], and the AlpArrayWorking Group

1. GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany
2. Institute of Geosciences, Kiel University, Germany
3. Laboratoire de Géosciences Marines, Institut de Physique du Globe de Paris, France

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The Liguro-Provençal basin was formed as a back-arc basin of the retreating Calabrian–Apennines subduction zone during the Oligocene and Miocene. The resulting rotation of the Corsica–Sardinia block is associated with rifting, shaping the Ligurian Basin. It is still debated whether oceanic or atypical oceanic crust was formed or if the crust is continental and experienced extreme thinning during the opening of the basin. We perform ambient noise tomography, also taking into account teleseismic events, using an amphibious network of seismic stations, including 22 broadband ocean bottom seismometers (OBSs), to investigate the lithospheric structure of the Ligurian Basin. The instruments were installed in the Ligurian Basin for 8 months between June 2017 and February 2018 as part of the AlpArray seismic network. Because of additional noise sources in the ocean, OBS data are rarely used for ambient noise studies. However, we carefully pre-processed the data, including corrections for instrument tilt and seafloor compliance and excluding higher modes of the ambient-noise Rayleigh waves. We calculate daily cross-correlation functions for the AlpArray OBS array and surrounding land stations. We also correlate short time windows that include teleseismic earthquakes, allowing us to derive surface wave group velocities for longer periods than using ambient noise only. We obtain group velocity maps by inverting Green's functions derived from the cross-correlation of ambient noise and teleseismic events. We then used the resulting 3D group velocity information to calculate 1D depth inversions for S-wave velocities.

The group velocity and shear-wave velocity results compare well to existing large-scale studies that partly include the study area. We observe a high-velocity area beneath the Argentera Massif in onshore France, roughly 10 km below sea level. We interpret this as the root of the Argentera Massif. Our results add spatial resolution to known seismic velocities in the Ligurian Basin, thereby augmenting existing seismic profiles. The velocity model indicates that the southwestern and north-eastern Ligurian Basin are structurally separate (Figure 1, panel a). In agreement with existing seismic studies, our shear-wave velocity maps indicate a deepening of the Moho from 12 km at the south-western basin centre to 20–25 km at the Ligurian coast in the north-east and over 30 km at the Provençal coast. The lack of high crustal vp/vs ratios beneath the southwestern part of the Ligurian Basin precludes mantle serpentinisation there. The poster summarises the findings published in Solid Earth (Wolf et al. (2021).

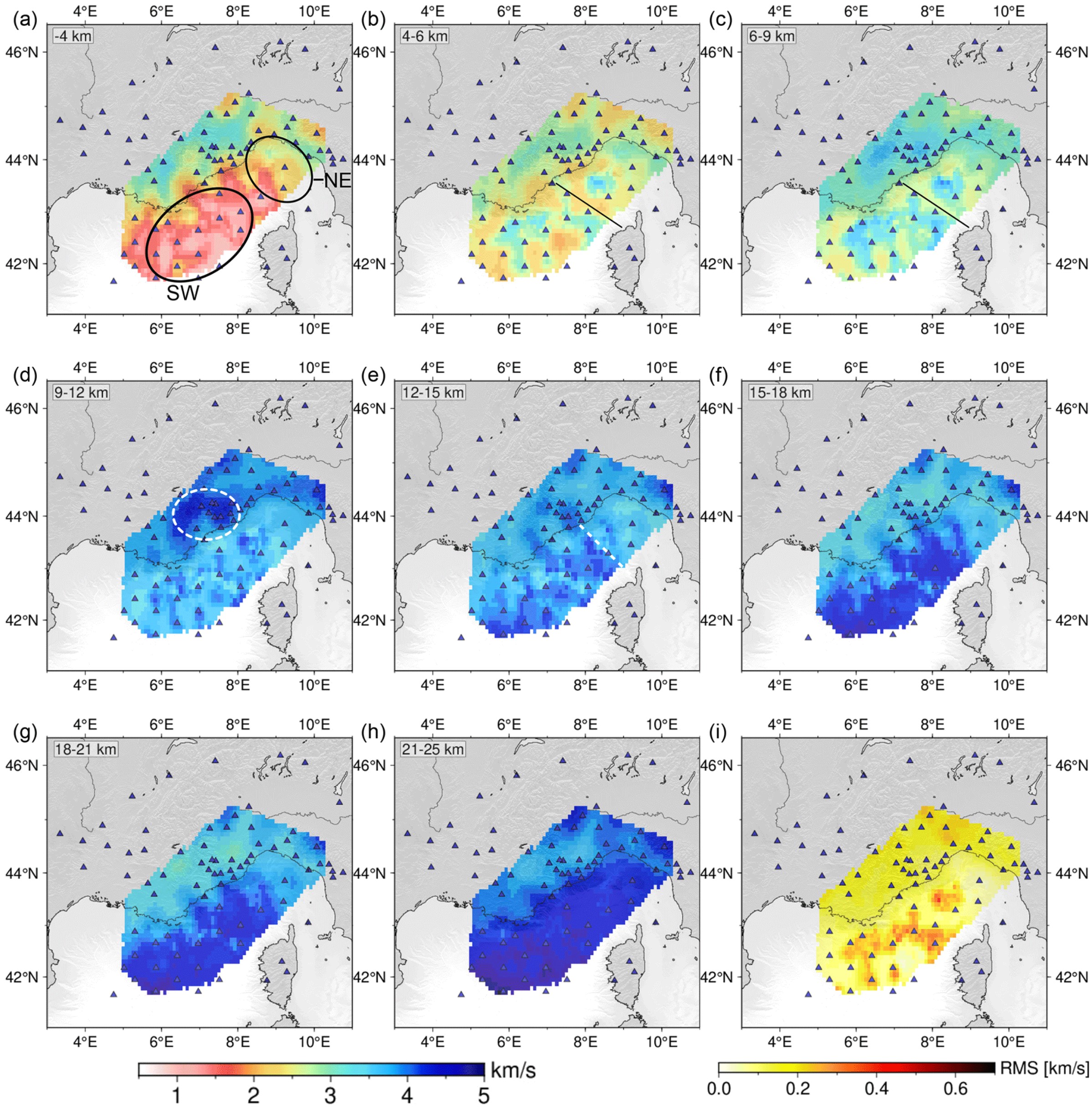

Figure 1: 2D shear velocity maps derived from the 1D inversion. Layer depth is stated in the upper left corner. Depths (in km) are relative to the sea surface. The annotations in (a) mark the southwestern and central (SW) and the north-eastern (NE) Ligurian Basin. The dashed circle in (d) marks a high-velocity area north of Nice, and the dashed white line in (e) represents the proposed prolongation of the Alpine front. Panel (i) shows the root mean square (RMS) value for the 1D shear-wave-inversion in map view (i.e., one RMS value per grid point). Blue triangles indicate stations.

Wolf, F.N., Lange, D., Dannowski, A., Thorwart, M., Crawford, W., Wiesenberg, L., Grevemeyer, I., Kopp, H., the AlpArray Working Group, 2021. 3D crustal structure of the Ligurian Basin revealed by surface wave tomography using ocean bottom seismometer data. Solid Earth 12, 2597–2613.