ALPINE

15TH WORKSHOP

12-14 September 2022

LJUBLJANA, SLOVENIA

15TH Emile Argand Conference
on Alpine Geological Studies

ABSTRACT BOOK & FIELDTRIP GUIDE

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Abstract book

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Dating a long-lived lake in an intermontane basin: Late Miocene Lake Turiec in the Western Carpathians

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Lake Turiec existed from Late Middle Miocene to Pliocene in the heart of the Western Carpathians in the intermontane Turiec Basin. Despite the long-lasting lacustrine deposition, which formed a muddy succession up to 900 m thick. The specific history of this basin in Western Carpathians has been a puzzle due to the missing geochronological proxies. Authigenic ^{10}Be/^{9}Be dating method was applied to determine the existence duration and regression of the long-lived Lake Turiec. Altogether 35 samples were collected from 11 different localities of the basin representing different sedimentary environments such as lacustrine, fan delta, alluvial fan and braided river. Four different localities, the Late Pleistocene alluvial fans Veľký Čepčín and Malý Čepčín, and the Holocene river floodplains Košťany and Kalamová were considered for determining the initial ratio. The initial ratio from the Veľký Čepčín alluvial fan was used for all other localities representing lacustrine, fan delta, alluvial fan and braided river to determine ages, because it is the only N0 in agreement with the independent age proxies indicating that the lacustrine deposits cannot be older than 11.6 Ma. Another explanation of the suitability of the Veľký Čepčín initial ratio is its rapid deposition settings, preventing it from alteration by post-depositional processes and interaction with ground water, in contrary to the remaining intial ratio sites. Weighted mean depositional ages calculated using N0 from Veľký Čepčín imply that the Lake Turiec existed from ~9.96 Ma for more than ~3.25 Myr and regression of the lake begun nearly ~6.71 Ma.

Determining the precise timing of the lake existence has important implications for geodynamic phases of the Western Carpathians, since it mirrors rapid increase of accommodation followed by intense increase of sediment supply during regression. The presented application of authigenic ^{10}Be/^{9}Be yielded a first radiometric age of the long-living Lake Turiec as compared to roughly estimated ages described in previous studies of the Turiec Basin. This novel method also appeared as a promising dating tool to determine the beginning of regression of the lake in an intermontane settings with complicated tectonic and sedimentary history.

Multistage tectono-stratigraphic evolution of the Canavese Zone (Western Alps)

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The Canavese Zone (CZ) in the Western Alps represents the remnant of the distal passive margin of the Adria microplate, which was stretched and thinned up to mantle rocks exhumation during the Jurassic opening of the Alpine Tethys. Through detailed geological mapping, structural analysis, stratigraphic and petrographic observations, and documentation of relationships between tectonics and sedimentation, we redefine the multistage tectono-stratigraphic evolution of the CZ, which consists of a Variscan basement, post-Variscan magmatic bodies and a Late-Carboniferous to Cretaceous sedimentary succession (Festa et al., 2020, and references therein). The Variscan basement includes a Lower Unit, wherein micaschist and orthogneiss were metamorphosed under amphibolite-facies conditions and partly transformed into migmatitic gneiss during a post-Variscan high-temperature metamorphic event, and an Upper Unit, consisting of a metasedimentary succession metamorphosed under greenschist- to amphibolite-facies conditions during the Variscan orogeny. The two basement units were intruded by post-Variscan plutons and hypabyssal dykes of both mafic to acidic composition. The Late-Carboniferous to Cretaceous sedimentary succession starts with continental fluvial deposits (Upper Carboniferous Basal Conglomerate *Auct.*) unconformably overlain by Permian volcanic and volcanoclastic rocks (Collio Formation), and it continues upward with Upper Permian to Lower Triassic conglomerates and sandstones (Verrucano *Auct.* and Servino Formation), which are followed by pre-rift Middle Triassic dolostone. The latter is overlain by Lower to Middle Jurassic synrift sediments (Muriaglio Formation) and by Middle Jurassic to Early Cretaceous post-rift sediments, consisting of Radiolarites, Maiolica micritic limestones and Palombini shale. We point out that (i) the whole CZ succession, since the Late Carboniferous, shows significant thickness and facies variations, documenting long-lived tectonic control on sedimentation, and (ii) Late Paleozoic – Triassic structural inheritances playing a significant role in the localization of faults that accommodated both the Jurassic rifting of the Alpine Tethys and the subsequent convergent tectonics.

Festa, A., Balestro, G., Borghi, A., De Caroli, S. & Succo, A. (2020). The role of structural inheritance in continental break-up and exhumation of Alpine Tethyan mantle (Canavese Zone, Western Alps). *Geosciences Frontiers*, 11, 167–188.

The inversion of a passive continental margin portrayed by a 2D balanced kinematic forward model across the Velebit Mt. in the northern external Dinarides fold and thrust belt

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The Dinarides fold and thrust belt resulted from the collision of the Adriatic Microplate with Eurasia and shows an overall SW-vergent and in-sequence structural architecture. In the Paleocene the ophiolite-bearing internal Dinarides were exclusively affected by crustal shortening. The outward SW propagation of the deformation front reached the eastern Adriatic passive continental margin mainly composed of Mesozoic carbonate platform rocks in Mid-Eocene times. This led to high crustal Mid Eocene to Oligocene shortening and the formation of the external Dinarides. Two balanced crosssections across the external Dinarides show an along-strike contrasting deformation style observed in two orogenic segments separated by the 250 km long dextrally transpressive Split-Karlovac Fault: the southern segment dominated by SW-vergent forethrusts, and the northern segment dominated by NE-vergent backthrusts, located to the SE and NW from the Split-Karlovac Fault, respectively. So far, it is not known why the regionally rather uniform Mesozoic Adriatic carbonate platform sequence had undergone such contrasting along-strike deformation. To improve the understanding of the initiation of the NE-vergent backthrusts and to assess the amount of crustal shortening in the NW segment, a 2D kinematic forward model across the central Velebit Mt. was set up. The Velebit Mt. extends for about 130 km along the eastern Adriatic coast and form a SW-dipping monocline with topographic elevations reaching close to 1800 m. This faultrelated monocline is formed in the hanging wall of a NE-vergent backthrust system. The 2D kinematic forward model approach applied to a pre-deformed lithostratigraphic template scaled to reported stratigraphic thicknesses enabled us to test various geometries and temporal successions of fault activity not only for the Mid Eocene – Oligocene contraction, but also for the Mesozoic passive margin extension. Through an iterative trial-and-error method, we were able to reproduce the present-day deformed reference section across the Velebit Mt. and the Lika Plateau in its northeastern hinterland.

Our best-fit balanced kinematic model suggests that the reactivation of Middle Triassic and Upper Jurassic basement-rooted half grabens played a key role in the initiation of the backthrusts. These half grabens were mainly reactivated by hanging wall shortcuts. This inversion of normal faults led to predetermination of the thin-skinned NE-vergent back thrusts, forming the upper part of a complex 68 km wide triangle structure. The structurally lower part comprised of a SW-vergent antiformal stack involving Paleozoic basement. We assessed a crustal shortening for the triangle structure of 47 km and a shortening of 98 km for the entire cross-section. Our results show that the differences in both the lithostratigraphic and Mesozoic half grabens along the eastern Adriatic passive margin played a crucial role in the Mid Eocene – Oligocene deformation of the external part of the Dinarides fold and thrust belt, which led to the contrasting along strike deformation styles to the NW and SE of the Split-Karlovac Fault.

Two types of peridotites in the area of Banovina, Croatia and their Petrogenesis

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Numerous outcrops of ultramafic rocks consisting mostly of peridotites occur in the area of Banovina, in Croatia. These rocks were formed as parts of the former Earth's mantle and belong to the Central Dinaride Ophiolite Belt (CDOB), which is direct proof of the existence and closure of the Neothetys ocean in the northern part of the Balkan area. Previous studies have considered these peridotites as fertile, subcontinental parts of the mantle with complex chemistry. This research presents a more detailed petrographic and chemical analysis, with the intention to sort between different types of Banovina peridotites and offer the model for their petrogenesis.

Detailed field work, mapping and petrographic analyses have revealed that Banovina peridotites occur as two texturally, lithologicaly and mineralogicaly different types, that crop out in two geographically different belts, the northern (N-belt) and the southern (S-belt). The N-belt contains mostly serpentinite breccias and serpentinized, depleted and mostly porphyroclastic spinel lherzolites that occur in the form of mélange, while S-belt comprises larger masses of peridotites which consist predominantly of fertile spinel lherzolites with equigranular to porphyroclastic textures. Bulk rock analyses have shown that spinel lherzolites from the S-belt have lower Cr# and Mg# and higher content of Al_2O_3, CaO, Na_2O, TiO_2 and REE than spinel lherzolites from N-belt, and same relations, excluding the REE, can be seen in the chemistry of clinopyroxenes and orthopyroxenes. Spinels from the N-belt spinel lherzolites have a significantly higher Cr# (12.7 – 50.7) then those from the S-belt spinel lherzolites (7.7 – 10.8). Two types of dunites, which were found only within S-belt peridotites, have very different petrographic and chemical characteristics. Pyroxene rich dunite is characterized by a coarse-grained protogranular to porphyroclastic texture, high modal pyroxenes (up to 10 vol. %) and spinels enriched in MgO, Al_2O_3 and NiO. The second type of dunite has smallgrained equigranular texture, contains amphibole (up to 1 vol. %), pyroxene (< 1 vol. %) and spinels enriched in Cr_2O_3 and FeO_T. Geochemical analysis of all peridotites indicate that the S-belt peridotites represent a subcontinental mantle which have been formed through the initial rifting phase during which they ascended to the upper crust. Peridotites from the S-belt are classified as orogenic peridotites. The geochemical characteristics of N-belt peridotites indicate their origin from a suboceanic mantle formed within mid ocean ridge environment and are classified as ophiolitic peridotites. Dunites show different geochemical characteristics and may have been formed by different geological processes. The diverse lithology of ultramafics in the limited space of the S-belt indicates very heterogeneous nature of the subcontinental mantle. As a part of the CDOBs, peridotites from Banovina indicate that the CDOB record three different phases of ocean evolution, the early phase of the initial rift and opening of the ocean (S-belt peridotites), later phase of the already developed ocean (N-belt peridotites) and also the phase of ocean closure which is evident from the mélange occurrences.

Barometric studies on different rock types from the Adula Nappe (Central Alps) by Raman spectroscopy of quartz inclusions in Garnet

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The Adula nappe in the Swiss-Italian Central Alps is a continental basement nappe from the former European margin that was subducted to depths indicating (ultra)-high-pressure conditions. Many studies were performed to understand the pressure-temperature-time evolution of the Adula nappe. However, the pressure data derived from classical thermobarometry from eclogite and garnet peridotite lenses cannot be correlated with the tectonic record without several difficulties. The pressure gradient is very high, the structural record for the often suggested extrusion model is missing and the directly surrounding nappes show consistently lower pressures. Furthermore, it was discovered that at least parts of the Adula nappe underwent eclogite-facies metamorphism during the Variscan and the Alpine orogenic cycles. These two cycles were distinguished by age dating and the chemical zonation patterns of garnet, although in some cases it can be ambiguous. Otherwise, the Variscan and Alpine parageneses are hardly, if at all, possible to tell apart. Therefore, existing pressure and temperature data that were obtained using classical geobarometers rely on mineral equilibria, which may not have yielded true Alpine metamorphic conditions. For this study, around fifty felsic and metabasic samples were collected from different lithologies on a N-S transect through the Adula nappe parallel to the direction of subduction. Raman spectroscopy on quartz inclusions (RSQI) in garnet was used as a geobarometer to measure minimum peak pressures. The advantages of this method are its independence of a chemical equilibrium and the ability to yield reliable pressure constraints even if the high-pressure mineral assemblage has been retrogressed. The Variscan and Alpine garnet domains were carefully identified using the Electron Microprobe (EMP) and the Scanning Electron Microscopy (SEM). Temperatures were determined by means of Zr-in-rutile thermometry by measuring the Zr content with EMP.

As a result, the obtained temperatures exhibit a gradient increasing from the north at ca. 500-550 °C to the south at around 700 °C. The minimum peak pressures in the northern and central Adula nappe range between 2.09 GPa and 2.17 GPa for metasediments and 1.41 GPa and 2.02 GPa for metabasites. 1.53 GPa were determined for an orthogneiss from the central part of the nappe. Lower pressures between 1.14 GPa and 1.31 GPa in the southern Adula nappe were potentially caused by viscous relaxation of the quartz inclusions during the high-temperature Lepontine metamorphism. Our new pressure data imply a very weak pressure gradient. Therefore, it is in contrast to the results of previous works, in which barometers based on a chemical equilibrium were applied. Additionally, no systematic difference in minimum peak pressures is observable for the different lithologies.

The arc of the western Alps: a review and new kinematic model

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The arc of the western Alps forms the western termination of the Alpine Chain. The E-W striking Austro-Italian-German and Swiss Alps turn into a N-S direction along the western margin of the Po plain, finally rotating back to an E-W strike along the Italian-French Mediterranean coast. The origin of this enigmatic shape was originally attributed to a variscan inheritance (Argand, 1916), but the vast majority of the present-day literature suggests that it results from the indentation of Adria during collision, as a result of a significant W-directed component of convergence. We briefly review previous interpretations and suggest a new kinematic model based on retrodeformation of syncollisional shortening, on paleomagnetic results, on structural analysis of maps on the arc-scale, and on field-based structural investigations.

Retrodeformation of syn-collisional shortening around the arc of the Western Alps points to the existence of an arc of significant amplitude before the onset of collision. Paleomagnetic results from the External Zone (Dauphinois) suggest that most rotations around vertical axes only affect the Mesozoic cover above the Triassic, hence they do not provide an information on the kinematic of the entire crust. In the area of the Argentera Massif, where paleomagnetic data were derived from Permian beds, hence allowing to interpret rotations of the entire crustal block, it is shown that no significant rotations around vertical axes affected the area during Alpine orogeny. Structural analyses of maps indicate that the transition between the N-S and E-W striking parts of the arc in the External Zone is abrupt, taking place along the Var Valley. No progressive rotations of structures are observed there, instead N-S striking folds and thrusts appear to be interrupted by the E-W striking ones which continue all along the southern coast of France until the Pyrenees. In several localities, stratigraphic and structural evidences show that these E-W structures were initiated before the onset of Alpine collision, and amplified during Alpine collision.

Our field-based structural data and compiled ones point to the occurrence of a large-scale widely distributed system of sinistral shear zones, striking ENE-WSW, which affect the area north of the Argentera Massif including part of the Internal Zone. Such structure was often assumed to be the prime site accommodating the west-directed indentation of Adria. In spite of its significant extent, its newly mapped location within the Arc precludes such such a 1st order kinematic role of this structure during collision.

To conclude, we suggest that the arc of the Internal Zone (Penninic Units) showing a progressive rotation of structures is not similarly observed in the External Zone, and we infer that this progressive, continuous curvature largely existed or formed during subduction. The arc of the western Alps as observed in the External Zone mainly reflects the existence of such a structure at the end of subduction and the transition between the Alps s.s. and the Pyrenean Chain, reactivated during Miocene time.

Argand, E., (1916). “Sur l’arc des Alpes Occidentales”. *Eclogae geologicae Helvetiae*, 14, 145-192.

Hf isotopic constraints for Austroalpine basement evolution of Eastern Alps: review and new data

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The Alps, as part of the Alpine-Mediterranean Mountain chain, are one of the classical localities for orogenic studies, where the Mesozoic-Cenozoic tectonic evolution is well known. Many classical models have been proposed to explain the tectonic evolution from Mesozoic rifting and breakup to Late Mesozoic-Cenozoic subduction, plate collision and exhumation. However, the pre-Mesozoic tectonic evolution of the pre-Alpine basement remains poorly known because of the lack of sufficient age data due to complex polyphase deformation and multiple metamorphic overprints. New data from mainly amphibolite-facies pre-Alpine basement of the Austroalpine mega-unit indicates that this basement is composed of a heterogeneous series of continental units, island arcs, ophiolites, subduction mélanges, accretionary wedges, and seamounts affected by different metamorphic grades. This study presents new results of LA-ICP-MS U-Pb zircon dating and MC-ICP-MS Lu-Hf isotopic tracing of zircons from three key areas of Austroalpine basement, including the: i) Wechsel Gneiss and Waldbach Complexes, and Wechsel Phyllite Unit, (ii) Saualpe-Koralpe-Pohorje, and (iii) Schladming areas. We determine the Wechsel Gneiss Complex to be a continental magmatic arc formed during 500–560 Ma in the proximity to a continental block with a 'memory' of Late Archean to Early Proterozoic continental crust. The Wechsel Gneiss Complex has Hf model ages of 2.1 to 2.2 Ga and 2.5 to 2.8 Ga that indicate a close relationship to northern Gondwana, with depleted mantle Hf model ages as old as 3.5 Ga. The Wechsel Phyllite Unit structurally overlying the Wechsel Gneiss Complex has partly different sources, including juvenile crust formed at ca. 530 Ma. In contrast, the Waldbach Complex constantly added new crustal material during 490–470 Ma period and bears considerably more positive εHf(t) values than the underlying Wechsel Gneiss Complex and gives relatively young, depleted mantle model ages of 700 to 500 Ma. The Waldbach Complex is, therefore, interpreted to be part of a magmatic arc that formed during closure of the Prototethys and was metamorphosed during Variscan orogenic events at ca. 350–330 Ma. The Schladming-Seckau and Wechsel Complexes represent a Cambro-Ordovician magmatic arc system formed by Prototethys subduction processes with the associated Late Neoproterozoic to Early Ordovician ophiolitic Speik complex having formed in its back-arc basin or as Prototethyan lithosphere. The Plankogel Complex and structurally overlying micaschist and amphibolite units represent accreted ocean, ocean island, and continent-derived materials, interpreted to be an accretionary complex formed during the Permo-Triassic closure of the Paleotethys. Many granites with Permian ages (e.g., porphyric granite called Grobgneiss and other granite gneisses and associated pegmatites) were likely formed in an extensional environment that culminated in the opening of the Middle-Late Triassic Meliata oceanic rift. These granites formed by partial remelting of crust with mainly Middle Proterozoic Hf model ages. Taken all these data together, we find that the Austroalpine basement is heterogeneously composed and includes complexes of different ages, different tectonic evolutionary histories and different remolten sources representing different locations before final accretion. The composite of pre-Alpine complexes in the Austroalpine mega-unit likely assembled not earlier than Late Permian or Early Triassic.

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Multiscale lithological and structural heterogeneity control on the nucleation of a crustal shear zone: petro-structural investigation and U-Pb titanite dating from the Anzola shear zone (Ivrea-Verbano Zone, Southern Alps)

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The Ivrea-Verbano Zone (IVZ, Southern Alps) is a fossil exhumed passive margin section of the pre- Alpine middle to lower continental crust that escaped Alpine subduction. Following the Variscan orogeny, the IVZ was affected by Permian post-orogenic extension and Triassic-Jurassic polyphasic rifting stages. Rift-related deformation was accommodated by several km-scale shear zones active at different crustal levels (e.g., Beltrando et al., 2015). Due to the intrinsic importance of these tectonic structures, a detailed characterization of their compositional, metamorphic and structural patterns, as well as the timing of activity may provide key information for the models of shear development in relation to the evolution of the regional tectonics. In this contribution, we investigate one of these major extensional structures - the Anzola shear zone - with the aim to assess the conditions that promoted the strain localisation. We also provide Upb dating on titanite as an attempt to constrain the timing of the high-temperature crystal-plastic deformation occurring within the shear zone. Recent field and meso-structural investigations revealed that the Anzola shear zone overprinted basement rocks characterized by inherited lithological and structural heterogeneities (Corvò et al., 2022). Gabbroic rocks and migmatites define the hanging wall and footwall, respectively. According to a detailed petrographical and geochemical characterization (EPMA, LA-ICP-MS), (ultra-) mylonitic rocks developed at the expense of a multi-lithological sequence showing amphibolite to granulite facies metamorphic conditions and deformation features related to preshearing event. Estimated P-T conditions by geothermobarometry indicate that mylonitic deformation started at high temperature (~820 °C) with presence of melt and continued as solid-state deformation down to amphibolite facies (~650 °C). As regard the timing, we show preliminary petrochronological results from titanite of the mylonitic amphibolites that recorded recrystallization event under amphibolite facies at about 185 Ma, which is coeval to deformation occurred at different crustal levels in the IVZ (Simonetti et al., 2021). On the basis of our findings, we argue that the shear zone development was promoted by the rheological contrasts derived from the inherited compositional and structural patterns. Moreover, we emphasize evidence of syn-deformational partial melting and small amounts of free fluids localized in certain layers that enhance the viscosity contrasts within the multi-lithological complex. Melts/fluids played a key role in both weakening mechanisms controlling the strain localization, as well as the syn-tectonic growth-recrystallization processes of the titanite, resulting in a strong influence of the U-Pb petrochronology results. Finally, our results are discussed in the framework of the geodynamic evolution of IVZ.

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Simonetti, M., Langone, A., Corvò, S., Bonazzi, M. (2021). Triassic-Jurassic rift-related deformation and temperature- time evolution of the fossil Adriatic margin: A review from Ossola and Strona di Omegna valleys (Ivrea-Verbano Zone). *Ofioliti*, 46(2), 147-161.

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Migration of basin formation and contrasting deformation style in the south-western Pannonian Basin (central Europe)

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The Pannonian Basin is a continental extensional basin system with various depocentres within the Alpine–Carpathian–Dinaridic orogenic belt. Along the western basin margin, exhumation along the Rechnitz, Pohorje, Kozjak, and Baján detachments resulted in the cooling of variable units of the Alpine nappe stack. This process is constrained by thermochronological data between ~25–23 to ~15 Ma (Fodor et al., 2021). Rapid subsidence in supradetachment sub-basins indicates the onset of sedimentation in the late Early Miocene from ~19 or 17.2 Ma. In addition to extensional structures, strike-slip faults mostly accommodated differential extension; branches of the Mid-Hungarian Shear Zone (MHZ) could also play the role of transfer faults.

During this period, the distal margin of the hanging wall tilted block of the detachment system, i.e., the pre-Miocene rocks of the Transdanubian Range (TR) experienced surface exposure, karstification, and terrestrial sedimentation. After ~14.5 Ma faulting, subsidence, and basin formation shifted north-eastward and reached the TR where fault-controlled basin subsidence lasted until ~8 Ma. 3D thermo-mechanical forward models analyze this depocenter migration and predict the subsidence and heat flow evolution that fits observational data. These models consider fast lithospheric thinning, mantle melting, lower crustal viscous flow, and upper crustal brittle deformation. Models suggest ~150–200 km of shift in depocenters during ~12 Myr.

Simultaneously with depocenter migration, the southern part of the former rift system, near or within the MHZ, underwent ~N–S shortening; the early syn-rift basin fill was folded and their boundary faults were inverted. Deformation was dated to ~15–14 Ma („middle" Badenian) and continued locally to ~9.7 Ma while north of the MHZ the TR was still affected by modest extensional faulting. The particularity of this shortening is that it happened during the post-rift thermal cooling stage. The low-rate contraction and related uplift rarely exceeded this regional thermal subsidence.

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Middle-Late Jurassic ophiolite obduction and formation of sedimentary mélanges in the Western Tethys Realm

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Component analyses of ancient Neo-Tethys mélanges along the Eastern Mediterranean mountain ranges allow both, a facies reconstruction of the Middle Triassic to Middle Jurassic outer passive margin of the Neo-Tethys and conclusions on the processes and timing of the Jurassic orogenesis. This Middle-Late Jurassic mountain building process in the Western Tethyan realm was triggered by west- to northwestward-directed ophiolite obduction onto the former passive continental margin (wider Adria) of the Neo-Tethys.

Ophiolite obduction onto the former passive continental margin started in the Bajocian and trench-like deep-water basins formed in sequence within the northwest-/westward propagating nappe fronts in the footwall of the obducting ophiolites, i.e. in lower plate position. Deposition in these basins was characterized by coarsening-upward cycles, i.e. forming sedimentary mélanges as synorogenic sediments, in cases tectonically overprinted. In the Middle Jurassic, the oceanic realm and the most distal parts of the former passive margin were incorporated into the nappe stacking. Bajocian-Callovian ophiolitic and Meliata mélanges were formed as most oceanward preserved relics of trench-like basins in front of the propagating ophiolitic nappe stack, often with incorporated components from the continental slope (Meliata facies zone). In the course of ongoing ophiolite obduction, thrusting progressed to the outer shelf region (Hallstatt Limestone facies zone). In Bathonian/Callovian to Early Oxfordian times the Hallstatt nappes with the Hallstatt mélanges were established, expressed by the formation of the up to 900 m thick basin fills comprising its material mainly from the outer shelf region. In Callovian to Middle Oxfordian times the nappe stack reached the former carbonate-platform-influenced outer shelf region and the reef rim. Newly formed basins received material from this shelf region, occasionally mixed with material from the approaching ophiolite nappes. Ongoing shortening led to the formation of the proximal Hallstatt nappes with concomitant mobilisation of Hallstatt Mélanges. Persistent tectonic convergence caused the partial detachment and northwest- to west-directed transport of the older basin groups and nappes originally formed in a more oceanward position onto the foreland.

Comparison of mélanges identical in age and component spectrum in different mountain belts (Eastern Alps/Western Carpathians/Dinarides/Albanides/Pelso) suggest one Neo-Tethys Ocean in the Western Tethyan realm, instead of multi-ocean and multi-continent scenarios. The evolution of several independent Triassic-Jurassic oceans is unlikely considering the fact that re-sedimentation into newly formed trench-like basins in front of a west- to northwestward propagating nappe stack including ophiolite obduction is nearly contemporaneous along the Neotethyan Belt. The Middle to Late Jurassic basin evolutions with their sedimentary cycles and component spectra are comparable everywhere.

Upper Campanian bentonites of volcaniclastic origin in the Scaglia-type limestones of the Adria continental margin

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Upper Campanian Scaglia-type limestones in the transition zone between the Internal and External Dinarides (Placer, 2008) contain two layers of bentonitic clays. The first 110 cm thick, and the second 10 cm thick. The geochemical composition and characteristics of the bentonites, such as correlation coefficients and scatterplots of immobile trace elements, indicate a rhyolitic volcanic source within an active continental margin. According to the mineralogy of the clay, which contains smectite, calcite, quartz and muscovite/illite, the layers can be interpreted as a deposit of volcanic-ash in a marine sedimentary environment with admixture of carbonates. The encompassing carbonate succession was deposited in a deeper marine environment of the Slovenian Basin. The limestones are composed of (hemi)pelagic mudstones to wackestones and thin- to medium-grained calcarenites, originating from the adjacent Adriatic Carbonate Platform. Similar Upper Cretaceous successions containing Campanian bentonitic clay horizons have been described in the Central Apennines (Graziano and Adabbo, 1996; Bernoulli et al., 2004). The most likely source of these volcanoclastics is the bimodal rhyolitic/basaltic magmatic activity within the Sava suture zone, located in the present day Dinarides (Ustaszewski et al., 2009; Cvetković et al., 2014; Prelević et al., 2017; Schmid et al., 2020).

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First evidence of UHP in the Lago Superiore Unit (Monviso, Western Alps)

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The first occurrence of ultra-high-pressure (UHP) metamorphism in the Western Alps was documented by Chopin in 1984 (Chopin, 1984) with the discovery of coesite in the southern Dora Maira massif. Since then, just one additional UHP terrain was discovered until the end of the 90's. In recent times, new occurrences of coesite have been reported in different units of the Western Alpine belt, widening the distribution of UHP terrains, with important tectonic implications. Here, we report the first discovery of coesite in the meta-ophiolitic suite of the Monviso Massif, in the northern Lago Superiore Unit (LSU). Previous petrographic studies and thermodynamic modelling in the area suggested that these alpine units may have experienced UHP metamorphism, but no direct evidences (i.e., coesite occurrence) have been reported to date. The presence of coesite is demonstrated by µ-Raman analyses. The Raman spectra show the typical peaks of coesite, slightly shifted towards higher wavenumbers. The main peak is located at 522 cm^{-1}, and the secondary peaks at 426, 270 and 178 cm^{-1}. Coesite inclusions consist of intact single crystals (10-60 µm) hosted by garnet, without evidence for re-equilibration features. Typical coesite-related features such as radial cracks in garnet host mineral and palisade texture are present in large polycrystalline quartz inclusions (> 80 µm). Peak metamorphic conditions have been constrained through different techniques (detailed garnet inclusion analysis, elastic geobarometry and thermodynamic modelling). The occurrence of UHP terrains along the Western Alps is becoming more common than expected. Our results, alongside with the novel evidence for UHP in the Western Alps, will lead to new tectonic models for the subduction and exhumation of UHP terrains, constraining the evolution of subductionaccretionary systems.

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The prograde history of three Mn-rich garnets from the UHP Lago di Cignana Unit (Italy)

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Extensive rock recrystallization and element redistribution during retrogression often hampers our understanding of the early stages of metamorphism. Garnet is the mineral that best preserves information about its growth during the prograde history of the rock as compositional zoning. In most metamorphic rocks, garnet zoning varies between almandine, grossular, and pyrope endmembers with minor spessartine content. This variability and the diffuse presence of mineral inclusions in garnet enables the coupling of thermodynamic tools (e.g., pseudosections) with classical element exchange and elastic geothermobarometry to gather information on their pressures and temperatures of equilibration. Such studies give their best results when applied to metapelites due to their relatively large mineral variability over the typical PT range of metamorphic rocks. However, monomineralic lithotypes, such as impure quartzite or marble, consist of minerals stable over a wide PT range and therefore lack mineralogic change. Furthermore, currently available solution models are not calibrated for use on unconventional bulk rock compositions and therefore do not guarantee reliable geothermobarometric results.

In this contribution, we use elastic geobarometry to track prograde garnet growth from low- to ultrahigh-pressure conditions in three Mn-rich garnets (up to 50 % sps) from an impure marble from the Lago di Cignana Unit (Italy). The rock consists of mainly quartz and calcite with garnet porphyroblasts. The three garnets show a very large core-to-rim compositional zoning with Mn-rich cores, Fe-rich mantles, and rims with a slight increase in Mg. Mineral inclusions in garnet cores and mantles are mainly quartz, with minor titanite, calcite, and apatite. Coesite, aragonite, zircon, and rutile are instead present within garnet rims. The three investigated garnets vary in shape, zonation, inclusions type and size while having a comparable core-to-rim composition. In two garnets, quartz inclusions are tiny (20-30 µm) and spread evenly within the garnets. The third garnet has larger quartz inclusions (50-100 µm) in the core and smaller in the mantle, decreasing progressively in size from the inner to the outer mantle (50-10 µm). Elastic geobarometry on these quartz inclusions in garnet allowed the tracking of the pressures at which garnet cores and mantles formed. We can show that these garnets formed during multiple distinct growth stages along the prograde path from 1.2 GPa and 430 °C to 1.8 GPa and 500 °C and finally at UHP conditions, as testified by the coesitebearing garnet rims. This difference in pressure and temperature of garnet growth might be due to local (cm-to-mm-sized) changes in chemical composition at the scale of the thin section and/or to reaction overstepping.

Episodes of open fissure formation in the Alps

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Fluid assisted Alpine fissure-vein and cleft formation starts at prograde, peak or retrograde metamorphic conditions of 450–550 °C and 0.3–0.6 GPa and below. Early-formed fissures become overprinted by subsequent deformation, locally leading to a reorientation. Deformation that follows fissure formation initiates a cycle of dissolution, dissolution/reprecipitation or new growth of fissure minerals enclosing fluid inclusions. Although fissures in upper greenschist and amphibolite facies rocks predominantly form under retrograde metamorphic conditions, this work confirms that the carbon dioxide fluid zone correlates with regions of highest grade Alpine metamorphism, suggesting carbon dioxide production by prograde devolatilization reactions and rock-buffering of the fissure-filling fluid. For this reason, fluid composition zones systematically change in metamorphosed and exhumed nappe stacks from diagenetic to amphibolite facies metamorphic rocks from saline fluids dominated by higher hydrocarbons, methane, water and carbon dioxide. Open fissures are in most cases oriented roughly perpendicular to the foliation and lineation of the host rock. The type of fluid constrains the morphology of the very frequently crystallizing quartz crystals. Open fissures also form in association with more localized strike-slip faults and are oriented perpendicular to the faults. The combination of fissure orientation, fissure quartz fluid inclusion and fissure monazite-(Ce) (hereafter monazite) Th–Pb ages shows that fissure formation occurred episodically (1) during the Cretaceous (eo-Alpine) deformation cycle in association with exhumation of the Austroalpine Koralpe-Saualpe region (~ 90 Ma) and subsequent extensional movements in association with the formation of the Gosau basins (~ 90–70 Ma), (2) during rapid exhumation of high-pressure overprinted Briançonnais and Piemontais units (36–30 Ma), (3) during unroofing of the Tauern and Lepontine metamorphic domes, during emplacement and thrusting of the external Massifs (25–12 Ma; except Argentera) and due to local dextral strike-slip faulting in association with the opening of the Ligurian sea, and (4) during the development of a young, widespread network of ductile to brittle strike-slip faults (12–5 Ma).

Magnetic susceptibility and chemostratigraphy of the Jurassic/Cretaceous boundary interval – new data from the Slovenian Basin

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The pelagic succession from the Slovenian Basin (Petrovo Brdo section) covers the lower Tithonian to upper Berriasian interval (ca. 40 m). At 5 m of the section a sharp transition is observed between clay rich radiolarian cherts of Tolmin Fm. and calpionellid limestones of Biancone Limestone Fm. Calpionellid associations are not numerous and poorly preserved, therefore only rough biostratigraphic dating is possible. Crassicollaria Zone (upper Tithonian) was documented between 8 and 13 m of the section, while the beginning of the Calpionella alpina Subzone (present day J/K boundary) is situated at ca. 20 m. Transition between Tolmin and Maiolica Fm. falls in the UAZ 12 radiolarian Zone which is close to the lower/upper Tithonian boundary. The section supplied high-resolution magnetic susceptibility (MS), as well as chemostratigraphic data ($\delta^{13}C$, main and trace elements), acquired with portable XRF device, gamma ray spectrometer and verified with ICPMS laboratory measurements. Lithogenic elements (Al, K, Rb, Ti, Zr etc.) and MS show prominent decrease between Tolmin and Maiolica Fm., reaching minimum values in the upper Tithonian and lower Berriasian. Lithogenic input increases again at ca 30 m of the section. As in numerous Tethyan domains (e.g. Western Carpathians, Northern Calcareous Alps, Western Balkan) the increase of marly sedimentation starts in the lower part of the Calpionellopsis Zone (magnetozone M16n), this level is tentatively interpreted as being close to the lower/upper Berriasian boundary. Relative variations of K and Ti content (K/Ti, Ti/Al ratios) indicate enrichment of K and depletion in Ti in the upper Tithonian/lower Berriasian interval which accounts for decreased chemical weathering in the provenance areas. Additionally, the interval is enriched in redox sensitive trace metals (Cu, Zn, Cd) and reveals decreased $\delta^{13}C$ values, which accounts for bottom water stratification. The overall palaeoenvironmental trends might be interpreted in favor of aridification trend throughout the late Tithonian and early Berriasian and more humid episodes in the early Tithonian and late Berriasian. The trends seems to correlate throughout the Western Tethys domain and might be related with large-scale palaeoenvironmental perturbations.

Project DIVE (Drilling the Ivrea-Verbano zonE): A joint petrological, geochemical, and geophysical exploration of the lower continental crust

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Despite the structural complexity of the Alps at numerous scales, geological and geophysical investigations have respectively mapped and imaged tremendous amounts of information near the surface and at depth. However, there is an inherent gap between the two sets of approaches, leaving the middle and lower crust poorly constrained. This has been one of the main motivations to initiate the ICDP project DIVE (Drilling the Ivrea-Verbano zonE), in which three geological sites of the Ivrea-Verbano Zone will be explored through scientific drilling. In this zone, near-complete sections of the continental crust are exposed at the surface, and with careful geological preparation and geophysical site surveys we have targeted three areas with a great potential of further discoveries during DIVE. Almost all physical and chemical properties will be characterized on the recovered rock core samples, in borehole logging investigations, and additional surveys around each site. Taken together, these should cover a large range of spatial scales covering at least 6 orders of magnitude (mm to km), investigate structures and their variations in bulk properties within the lower crust, and the transition to mantle rocks in an unprecedented way. The interdisciplinary approach not only allows to correlate numerous geophysical and petrological properties, but with modelling it will also allow to investigate the causative relationships. The detailed aims, preparatory steps, as well as the current status of project DIVE, will be presented at the conference. By that time, drilling of the first hole is expected to start near Ornavasso, followed by a second hole in Megolo (both in Val d'Ossola). For the third site near Balmuccia, which is planned for later, site survey results will be presented.

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Remote sensing of active tectonics in NE Italy, eastern Southern Alps

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Due to the collision of the European and Adriatic plates, about 3 mm/yr of N-S convergence are accommodated in the Eastern and Southern Alps. This shortening is mainly taken up by c. E-W trending reverse faults along the South Alpine Front and on NW-SE-trending dextral strike-slip faults in western Slovenia. Strong historical earthquakes and instrumental seismicity, however, show that some deformation also occurs in the interior of the Southern Alps. Little is known about which faults are active here. In this study we present results from a regional-scale remote sensing analysis focusing on the Bellunese and Friulian sectors of the Southern Alps in northeastern Italy. Our aim was to identify areas with relatively increased tectonic activity based on landscape features. We made use of high-resolution digital elevation models from aerial laser scanning campaigns. We downsampled the data to 5 m resolution and calculated the most widely used geomorphic indices that might indicate active tectonics: normalised steepness index, the Chi value, terrain ruggedness index, and stream knickpoints. The results were checked with geological data, mapped faults, and seismicity. We also conducted extensive field work to verify the results on the ground. Our results show that the application of large-scale tectonic geomorphology in this particular Alpine region is complicated by numerous factors. Small-scale variations in lithologies with variable erodibility strongly influence the analysis. The same holds true for variations in dip direction and dip angles of bedding planes; occasionally, vertical strata erroneously suggest linearly trending faults. In addition, we found that glacial features and alluvial deposits have locally overprinted the traces of known faults. Despite of these challenges, we found hints for active deformation in the landscape, in particular in the epicentral area of the 1976 Friuli earthquakes. We highlight potential pitfalls of the applied methods and discuss ways to overcome some of the problems we encountered.

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Alpine-Carpathian-Pannonian Geodynamics: the McKenzie and Royden models and the limitations of their applicability

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Since the 80s' the geodynamic evolution of the Alpine-Carpathian-Pannonian (ACP) region has been clearly dominated by two geodynamic models: McKenzie (1978) and Royden (1993). The model of McKenzie was the first numerical model to explain the continental extension in terms of lithospheric stretching and following thermal subsidence. The model has envisaged, that these two processes are recorded by the intervening sedimentary processes: the initial syn-rift phase characterized by extensional growth sequences and the subsequent thermal phase best described in terms of tectonic quiescence with no, or little deformation of the sedimentary cover. The McKenzie model has been tested first in the North-Sea and brought serious breakthrough in the understanding of its geodynamic evolution, and became a strong predictive tool for the oil and gas exploration community. Further on, the model has been applied to the Pannonian Basin by Sclater et al. (1980). The results were ambiguous, and Bally and Snelson (1980) have highlighted that the syn-rift phase is not responding properly to the model prediction, as the amount of the extension of the crust was not implying the high heat-flow observed. In spite of these early concerns, the McKenzie model has been widely accepted for the Pannonian Basin for the coming decades. Evidences from reflection seismic data coupled with recent industry well-data, however were to confirm that the style and timing of extensional deformation is indeed out of the reach of model predictions. Shortly afterwards, Royden has proposed (1988, 1993) that the extension of the Pannonian Basin System would be coupled with the compressional tectonics of the Carpathians. Royden et al. have implied that the driving force behind the two concurrent processes (e.g. basinal extension and orogenic growth) would be the subduction roll-back, which they thought to be represented by the Vrancea Seismic Zone (VSZ) high-velocity subducted slab. This model was simple and elegant, to such extent, that has been widely adopted by the majority of the geoscientific community. While it is clear, that the VSZ is a well documented geodynamic entity (e.g refraction tomography, focal mechanism solution), remains unclear how far the implied subduction roll-back can be applied to the geodynamic evolution of the whole Intra-Carpathian Region (ICR). There is a number of growing evidences coming from distinct regions of the ICR, such as the Transylvanian Basin, Apuseni Mountains and ultimately the Pannonian Basin suggesting that the subduction roll-back model has certain limitations and cannot be retained as the sole viable solution to explain the Miocene-Pannonian geodynamics of the ACP area. Moreover, possible alternative interpretation(s) of the VSZ is calling for a revision of the mechanisms of basin and orogenic evolution of the whole region.

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How AlpArray is guiding us to a new model of Alpine orogenesis

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AlpArray has challenged notions of lithospheric subduction along the Alps and its effects on the asthenosphere and orogenic lithosphere. Teleseismic Vp tomography reveals a slab of European lithosphere that is largely detached at and below 150 km in the Western and Eastern Alps. Only in the Central Alps is the slab still attached, possibly reaching down to the MTZ, where it may be connected to subducted remains of Alpine Tethys. Downgoing European lithosphere appears thicker and more heterogeneous than the Adriatic upper plate. Arcuate SKS directions beneath the Alps suggest that asthenosphere not only flowed passively around the sinking slab, but may have induced the anomalous northward dip of the detached slab segment beneath the Eastern Alps. The structure of the orogenic lithosphere differs profoundly along strike of the Alps, as revealed by local earthquake tomography, ambient-noise studies, as well as S-to-P receiver-functions and gravity studies: In the Central Alps west of the Giudicarie Fault where the slab is still attached, the exhumed retro-wedge of the orogen overrides a wedge of Adriatic lower crust. East of this fault where the slab has detached, exhumation is focused in the orogenic core (Tauern Window) north of and above a bulge of thickened lower crust of presumed Adriatic origin. The Moho is not offset by the Giudicarie Fault and shallows eastward, from 50-60 km beneath the western Tauern Window to 20-30 km beneath the Pannonian Basin. This necessitates massive decoupling at and above the Moho to accommodate coeval Miocene N-S shortening, orogen-parallel thinning and eastward extrusion of Eastern Alpine orogenic lithosphere.

We propose a new model for Alpine orogenesis that invokes changing wedge stability and migrating subduction singularities above the delaminating and detaching Alpine slab in the east to explain eastwest differences in Oligo-Miocene structure, magmatism, erosion and sedimentation in peripheral Alpine basins. A decrease in Adria-Europe convergence rate to < 1 cm/yr after collision at ~35 Ma led to slab steepening and northward motion of the singularity, combined with increased shortening and taper of the Central Alpine wedge. There, rapid exhumation and denudation during this stage were initially focused in the retro-wedge just north of the Periadriatic Fault. In the Eastern Alps, slab pull during northward delamination drove subsidence and marine sedimentation in the eastern Molasse basin from 29-19 Ma, while the western Molasse basin filled with terrigeneous sediments. The dramatic switch at 23-21 Ma from northward advance and stagnation of the northern front in the Eastern Alps to southward advance of the southern front in the eastern Southern Alps, as well as rapid exhumation of Penninic units in the Tauern Window are attributed to slab detachment beneath the Eastern Alps combined with a northward and upward shift of the subduction singularity to the tip of the lower crust bulge. This is inferred to have reduced the wedge taper in the Eastern Alps. Rapid west-to-east filling of the eastern Molasse basin between 19-16 Ma is interpreted to reflect eastward propagation of the slab tear and the onset of Carpathian rollback subduction.

Members of 4D-MB and the AlpArray Working Group: The complete member list of the AlpArray Working Group can be found at http://www.alparray.ethz.ch. A list of active members of the 4D-MB is available at http://www.spp-mountainbuilding.de/research/projects/index.html.

A buried fold and thrust belt: the structural geometry of the central part of the Tisza Unit, East Hungary

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The basement of the south-eastern part of the Miocene Pannonian back-arc basin is represented by the Tisza Unit. The deep structure of the Tisza unit is poorly studied, despite its significant geothermal and CH potential. This work is a first step in our structural mapping project, which investigates the structures within the basement of the Pannonian Basin.

The Tisza unit is composed of Proterozoic to Early Paleozoic poly-metamorphic basement rocks, and Late Paleozoic to Mesozoic sedimentary cover. The Tisza Unit is built up by three main nappes, the Mecsek, the Villány-Bihar and the Codru subunits. The Tisza Unit is exposed in inselbergs (Mecsek, Villány, Apuseni Mts.), however, most of it is covered by several km thick Miocene succession. The pore space containing energy source materials is located in the Miocene Pannonian Basin cover sediments, and in the fractured basement rocks near its surface and in their deeper part, especially in the Cretaceous sedimentary formation. Our research targets the better understanding of the Alpine shortening tectonics and structure of the Tisza Unit, with special attention to the structures of these tectonically buried sedimentary basement patches.

In this study we use modern 3D seismic data sets and well data to investigate the central part of the Tisza Unit. Based on that, the Tisza Unit is a Late Cretaceous fold and thrust belt, which can be characterized by major thick-skinned nappes, and second-ordered thin-skinned structures. Such second-ordered structures are the active and passive roof-duplexes below the Villány nappe (Derecske), and out-of-the-syncline thrusts in the front of the Codru nappe (Vésztő). The basal thrust of the Villány nappe cuts across pre-existing normal faults and associated half-grabens, demonstrating the presence of the early Alpine rift-related structures. Major nappes are unconformably overlain by Santonian to Maastrichtian beds, nevertheless, the presence of growth synclines in this succession indicates ongoing shortening after major nappe emplacement during the latest Cretaceous. The Cretaceous fold and thrust belt of the Tisza Unit is strongly overprinted by Miocene extensional and transtensional structures, which are related to the rifting of the Pannonian back-arc basin.

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New knowledge about U-Cu mineralization in the Kozie Chrbty Mts. and its relationship to the late (Neotectonic) structures (Hronic Unit, Western Carpathians, Slovakia)

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Stratiform U-Cu mineralization (0.02-1.13 % U) in the eastern part of the Kozie Chrbty Mts. Is bound to the Permian volcano-sedimentary complex of the Ipoltica Group, Hronic Unit (Western Carpathians). The wide surroundings of the deposits are formed by other, Triassic sediments of Hronic Unit (limestones, dolomites, quartzites, shales) also by Paleogene sedimentary complexes of the Podtatranská Group (sandstones, conglomerates, claystones). The ore deposits (Vikartovce, Kravany, Švábovce, Spišský Štiavnik) are situated in the arcosic sandstones of the Upper Permian part of the Kravany Beds with carbonized fragments of higher plants. The deposits were exploited during the survey (60s – 70s of the 20th century).

Relatively late tectonic events affected the volume and the quality (and also minig-technical conditions) of considered ore deposits. This tectonics resulted in iregular distribution of mineral ore in this region. In the western part of the Dúbrava Mts. (Vikartovce, Kravany deposits), the distribution of the ore is relatively regular, limited to 1 – 2 ore bearing horizons. In this case the structure of the deposits is limited mainly by Vikartovce Fault with subvertical sence of movement. Concerning the tectonic condition, Kravany and Vikartovce deposits are situated to the north (in the bedrock block) and in close proximity (200 – 300 m) of Vikartovce Fault of east-to-west direction. On the contrary, the Švábovce and Spišský Štiavnik deposits are located on a neotectonic structure that limits Dúbrava Mts. from the north (W-E direction). The Kravany and Vikartovce deposits are disrupted by disjunctive tectonics in two directions: faults east-to-west causing 5 – 10 m declines of southern blocks faults, and faults with northeast-to-southwest direction causing 10 m declines of southwestern blocks. The deposit conditions on the eastern part of the Dúbrava Mts. are limited by the combination of the neotectonic fault systems: Vikartovce, Gánovce and Muráň-Divín.

At the Kravany deposit, local tectonic caused the formation of so-called „zone ore mineralization“, when U-Cu mineralization occurs in the tectonic zone (reprocessed carbonized plant residues, uraninite, pyrite, chalcopyrite and carbonates).

Stratiform, infiltration U-Cu-Pb mineralization in the eastern part of the Kozie Chrbty Mts. is bound to the Upper Permian clastic sediments (Kravany Beds, member of Malužiná Formation, Hronic Unit). Their lithological composition is represented by green to dark gray fine to medium-grain arcosic sandstones, arcoses, gray-black sandstones and siltstones with a significant content of carbonized plant debris. Uranium mineralization together with Cu and Pb mineralization are concentrated mainly in the cracks and pores of corbonized organic matter. Stratiform U-Cu-Pb mineralization is represented by minerals: uraninite, coffinite, U-Ti oxides accompanied by arsenopyrite, chalcopyrite, pyrite, marcasite, tetrahedrite, tennantite, galena, sphalerite, quartz, calcite and dolomite. The age of stratiform mineralization was set at 263 – 274 Ma, based on U-Pb dating. Secondary minerals described in the supergene zone of U ore deposits are uranophane, autunite, torbernite, metatorbernite, azurite, malachite, arsenopyrite, goethite, limonite, covellite, chrysocolla, gypsum and zálesíite.

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Palaeoenvironmental and drainage network reconstitution of the Oligocene Western Alpine Foreland Basin

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The Western Alpine Foreland Basin ("French Molasse Basin") is located along the western Alps and is composed of Oligo-Miocene formations resulting from the erosion of the alpine range. Although the Miocene molasse basin have been widely described since the last decades, Oligocene basins lack documentation in terms of palaeoenvironmental evolution and source to sink approach. Most of these basins formed under both the Alpine influence and the European Cenozoic Rift System influence and developed in lacustrine environment with local sedimentation next to active normal faults. Several fluvial formations with exotic materials have been briefly described and could correspond to a transport from the internal parts of the Alps, where collision started at the Eocene/Oligocene boundary. Here, we propose a new tectono-sedimentary study of these fluvial deposits based on extensive fieldwork (facies analysis, sequence stratigraphy, palynological analysis) and reinterpretation of available subsurface data (seismic profile, well data). The goal is to provide a new palaeoenvironmental reconstitution of the Oligocene molasse basin(s) with regional correlations and to determine the evolution of early alpine drainage network. We focus on the entire Western Alpine Foreland Basin from the Rhone Valley (Bas-Dauphiné, Valréas, Mormoiron) to the Digne Thrust where Oligocene molasse is called « Red Molasse » (Dévoluy, Faucon-du-Caire, St-Geniez, Esclangon, Barrême). First results show that Red Molasse is composed of massive meandering deposits, which evolve to braided river and alluvial fan in a regressive continental sequence following the flysch formation. Transition from marine distal turbidites is often missing except in Dévoluy syncline where tidal and shoreface deposits precede fluvial molasse. Exotic material from the internal alps is very common and indicates high landforms nearby. In the Rhone Valley, a massive fluvial system has been identified on seismic and well log data in the Bas-Dauphiné and we documented a 900 m field section with two meandering formations with exotic minerals in the Mormoiron basin. Paleocurrents and channels direction indicate a major divide located east of Diois-Baronnies range with Dévoluy fluvial systems flowing to the north and other Red Molasse sites located south of the divide converging to St-Geniez system. On a regional scale, it may be possible that early salt tectonic which has been widely described caused this particular drainage network. South of the divide, converging fluvial formations may have flowed in an Est-West valley between Diois-Baronnies range and Ventoux-Lure Montain where tectonic and Eocene landforms link to the Pyreneo-Provençal orogen have been documented. These deposits where probably connected with Mormoiron and Bas-Dauphiné fluvial formations and formed a major drainage system located in the Rhone Valley.

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Recording of cyclicity in the sediments of the Bajocian and Lower Bathonian on the basis of magnetic susceptibility (Carpathians, Poland)

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Investigated section is located on the eastern slope of the Ždiarska Vidla, Tatra Mts. (Slovakia), along the old tourist path. The section belongs to the Križna nappe and to the Havran and the Bujačí unit. Pelagic and hemipelagic sedimentation of the spotted limestones and marls prevailed on the margin of the Zliechov (Križna) during the Early and Middle Jurassic. The spotted limestones of the Tatra Mts. depending on the authors, are included in the Janovky Formation or in the Sołtysia Marlstone Formation. The investigated Ždiarska Vidla section is 200-m thick. This unit is dated to the Bajocian based on lithological similarity to the Kopy Sołtysie area, where rare ammonite fauna was described. The lithology is composed of spiculite limestones and marly spiculite limestones (with marly spiculite wackestone–packstone, and marly bioclastic filament wackestone microfacies). Field magnetic susceptibility (MS) and gamma–ray spectrometric measurements (indicating content of potassium, K (%); uranium, U (ppm,); thorium, Th (ppm)) have been carried out. The Ždiarska Vidla section has also been sampled for carbon isotopes with resolution of ca. 0.5-1 m. The bulk carbonate obtained carbon isotope curve is characterized by positive shift. It is assigned to the Lower Bajocian. The section is subdivided into three parts (IIA, IIB, III) on the basis of the MS, K, Th, U and δ^{13}C curves. The oldest IIA interval is characterized by a weak positive linear correlation between MS to Th, Th/U and CGR, which suggests an association of MS with the supply of terrigenous elements to basin. The p-values associated with received Pearson R are much above the assumed significance level (0.05), indicating that received results are statistically insignificant. In the IIB and III interval, MS correlates inversely to Th, CGR, Th/U, what it might show that increase MS is related to oxygen deficiency. Within the level IIB, values of Pearson r-value for correlation between MS and Th, CGR, U and K varies between -0.2 and -0.43 with p-values in the range from 0.03 to 0.3 meaning, that only part of the results is statistically significant. The III interval is characterized by a moderate negative linear correlation between MS and Th, K and CGR, where Pearson R reaches values from -0.42 to -0.56 with p-values much below the assumed level of 0.05, meaning that received results are statistically significant. Spectral analyses done on the MS signal in Intervals II and III reveal cycles of 18 m, 4-5 m and 1.3-1.8 m, respectively related to the 405-kyr, 100-kyr and 40-kyr cycles. The duration of Intervals II and III are thus assessed at 4.4 to 4.5 Myr, with a mean sedimentation rate of 4.4 cm/kyr.

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On the way to building the Norian conodont biozonation of the Circum-Pannonian Region

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Conodont biozonation of the Norian (Upper Triassic) of the Western Tethys realm is in development from the 1970's, however, a satisfactory scheme has not yet been established. The problem originates in the over-simplified taxonomy of Norian conodonts, since biostratigraphic investigations have never coupled with thorough and detailed systematic studies. Even the zonal schemes proposed after the millennium were based mainly on the species described in the second half of the 20th century. Consequently, conodont zones of the existing schemes cover longer time intervals, although a finer subdivision would be possible. An ongoing research attempts to refine the Norian conodont biozonation of the Circum-Pannonian Region based on abundant conodont faunas of various localities.

The old trench at Mátyás Hill of the Buda Hills (Transdanubian Range, Hungary) exposes a ca. 20 m thick sequence of hemipelagic cherty dolostones of Lower to Middle Norian age. Dense sampling of the section yielded well-preserved conodont elements in high numbers. The lower half of the succession can be dated as Lower Norian (Lacian-3) based on the presence of *Norigondolella navicula*, *Norigondolella hallstattensis* and *Ancyrogondolella* ex gr. *triangularis*. In the upper half of the section, bedding is often disturbed, intervals of fractured blocks are common. Conodonts with morphological characters transitional to those of typical Middle Norian species first occur at the lower level of this interval, though Lacian forms remain dominant. This part represents the Lower-Middle Norian transition, which is often characterized by sedimentary breccias and/or fissure fills (e.g., Dovško section – Karádi et al., 2021; Kälberstein quarry section – Gawlick and Böhm, 2000). Species indicating inevitably Middle Norian age (Alaunian-1) were found 1.5 m below the top of the section where Lacian species are absent. This fauna is composed of *Ancyrogondolella equalis*, *Ancyrogondolella* ex gr. *transformis* and *Mockina* ex gr. *matthewi*.

Due to the large morphological variety and the very low number of figured specimens, the taxonomic revision of these Norian assemblages is yet to be done. Anyhow, the establishment of a high-resolution Norian conodont biozonation of the Circum-Pannonian Region seems feasible, which will allow a better correlation potential within the Western Tethys realm.

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Crustal structure in the eastern Alps from ambient-noise Tomography

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Since the onset of continental collision in the eastern Alps, several large-scale reorganizations have affected the crustal structure, such as Adriatic indentation, eastward extrusion or the Tauern window exhumation. This work aims to improve the understanding of the tectonic history of the region, by providing a new shear-velocity model of the eastern Alpine crust. It makes use of data from the AlpArray and the dense SwathD networks from which phase velocities are measured. These are inverted in a two-step approach based on a Markov-Chain Monte Carlo sampler to obtain the model structure and its uncertainties. The shallow structure is well correlated with the major faults in the area. Additional information from the anisotropy at mid to lower crustal levels is interpreted in terms of the strain direction. Eastward orientated fast axis are observed at a large depth range in the central part of the mapped region. This may indicate that the eastward extrusion affects all crustal levels down to Moho depths. The mapped features are compared to previous works from local earthquake tomography and receiver functions to provide a joint interpretation of the crustal structure.

AlpArray Working Group: http://www.alparray.ethz.ch

Seismic activity along the Periadriatic and Sava Faults in the past two millennia – an archaeoseismological assessment

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Most faults of the Periadriatic Fault System have been active during Oligocene and Miocene times. Its western part seems to be inactive ever since, while the Lavanttal and Sava faults in the east show limited seismic activity. We conducted a systematic archaeoseismological survey along the Periadriatic-Sava fault system, assessing buildings and archaeological sites for earthquake damage. Eight sites, four Roman and four Medieval, display evidence for destructive earthquakes during the past 2000 years. These are San Candido (Medieval) and Lienz (Medieval) on the Pustertal fault, Teurnia (Roman) and Millstatt (Medieval) on the Mölltal fault, Arnoldstein (Medieval) and Magdalensberg (Roman) just north of the Karavanke fault, Roman Celeia (Celje) at the Savinja / Sava faults, and Roman Siscia (Sisak) nearby the Croatian Sava fault. Damaged upright walls of Medieval buildings and deformed floors of Roman settlements testify to local intensity up to IX. Ongoing studies of archaeological stratigraphy and construction history allow dating of one or more seismic events at each site, ranging from the 1st century AD to the 17th century. We would be cautious about pointing out epicentres at this moment. However, it is remarkable that sites, 70 km apart in average, along a a 380 km long segment of an 'inactive' fault zone carry evidence for so many high-intensity destructive events.

Facies analysis of Ladinian and Carnian beds in the area of Rute Plateau (External Dinarides, Central Slovenia)

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The Rute Plateau is a region located 25 km south of Ljubljana. Structurally, it belongs to the External Dinarides, which form an extensive fold and thrust belt. The study area is located in the eastern part of the Hrušica Nappe in a very complex tectonic area between two major NW-SE fault zones.

The peculiarity of the Rute Plateau consists in a varied succession of sedimentary and volcanoclastic rocks of Ladinian and Carnian age, while the whole area is divided into different tectonic blocks with local differences in stratigraphic evolution. The reason for these deformations and the variability of the paleotopography lies in the Middle Triassic extensional phase, which completely disintegrated the uniform Slovenian carbonate platform at the end of the Anisian (for details see Rožič et al., this volume). Subsequently, the Ladinian strata of the External Dinarides reveal that deep marine sediments in this area were deposited in small basins or tectonic depressions, while carbonate deposition continued on higher or relatively less subsided tectonic blocks (isolated platforms). During the Ladinian, tectonic movements were also accompanied by volcanic activity.

Six sedimentological sections were logged in the studied area, and the Ladinian strata were divided into four different facies: F1 - deep marine (volcano)clastic rocks, F2 - hemipelagic limestones, F3 - resedimented limestones and F4 - shallow marine carbonates. Each of these Ladinian facies is characteristic of a particular sedimentary environment and is indicated from the most distal sedimentary environment (F1) to the most proximal carbonate platform environment (F4). Facies F1 consists of greenish to light ochre bentonitic clays, tuffitic sandstones, pelitic tuffs, and subordinate felsic extrusive rocks. Facies F2 consists of laminated black micritic limestones (mudstones to wackestones) with horizons of bioclastic packstones rich in filaments, limestones rich in organic residue and interbedded with dark chert laminas and marlstones. In facies F3 we find up to 30 cm thick beds of calcarenites, limestone breccias often with large olistoliths, graded and laminated calciturbidites - mostly packstone, grainstone and rudstone beds with rare chert laminas and nodules. Finally, facies F4 consists largely of massive, light grey calcimicrobial and dasycladacean limestones with horizons or lenses of white bioclasts and intraclasts derived from coral reefs. The last two facies are commonly dolomitized.

At the end of the early Carnian, the entire region was subjected to the regional emersion phase when deposition of clastic sediments began. It is characterized by facies F5 - red clastic sediments consisting mainly of sandstone with quartz grains and carbonate lithoclasts and conglomerates. Within all these facies, we were able to determine 28 different microfacies, which, based on their composition, further elucidate sedimentation in different paleoenvironments.

Origin of submarine swell (Czorsztyn Ridge of the Pieniny Klippen Belt, Polish/Ukrainian Carpathians) and it's geotectonic consequences by biostratigraphy/volcano-sedimentary record

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The most important geotectonic element within Polish/Slovakian/Ukrainian Western Carpathians basins has been the Czorsztyn Ridge (Swell), which originated during Early Bajocian time. Then, palaeogeographicaly during Middle Jurassic–Late Cretaceous span it has been the main object which separated two large Carpathians basins – the Magura Basin on NW side and the Pieniny Basin on SE side – and therefore the detail dating of its origin is crucial for recognition of its geodynamic significance. This first uplift is correlated with stratigraphical hiatus between sedimentation of dark/black shales of oxygen-poor environments (latest Pliensbachian–earliest Bajocian) and white/light grey crinoidal limestones of well oxygenated regimes (late Early Bajocian), which documented drastic change of sedimentation/palaeoenvironments which took place in meantime as effect of uplift. This stratigraphical gap was perfectly dated biostratigraphicaly by ammonites collected from the basal part of crinoidal limestones in several outcrops of the Polish part of the Pieniny Klippen Belt (PKB). The evidences of condensation event at the beginning of crinoidal limestones sedimentation are marked by: phosphatic concretions concentration, pyrite concretions, large clasts of green micritic limestones, fossils (ammonites, belemnites, brachiopods). On the other hand, high variable thickness of these limestones (from ca. 10 m up to 100 m) suggests origin of synsedimentary tectonic blocks and troughs during syn-rift episode. This Bajocian tectonic activity within Pieniny Klippen Basin corresponds very well with others Middle Jurassic Western Tethyan geodynamic reorganizations. Estimation of duration of aforementioned hiatus – based on a cyclostratigraphic analysis of the carbonate content from the Subalpine Basin in France, which indicates that the Early Bajocian only lasted c. 4.082 Ma – time necessary for origin/uplift of the Czorsztyn Ridge is about 2 Ma.

Tectonic rejuvenation of Middle Jurassic structures took place during the earliest Cretaceous (Berriasian) times and have been connected with active volcanogenic events which occur now within several tectonostratigraphic units of the Ukrainian Carpathians, including PKB. In the Veliky Kamenets active quarry (PKB) a continuous section occurs with a Lower Jurassic (since Hettangian?) to the lowermost Cretaceous (Berriasian) sedimentary succession. The biostratigraphy of the Toarcian-Berriasian part of this section is very precisely based on ammonites, dinoflagellates and calpionellids. Basaltic rocks occur in the uppermost part and overlie creamy-white *Calpionella*-bearing limestones. They are directly covered by biodetritic limestones and synsedimentary breccias. The latter are the so-called Walentowa Breccia Member of the Łysa Limestone Formation, according to the Polish and Slovakian parts of the PKB, which are dated by calpionellids as middle and/or upper Berriasian and upper Berriasian, respectively. Importantly, in this breccia some clasts of basaltic rocks occur (sometimes developed as pillow lavas and/or peperites) which implies they are middle and/or upper Berriasian in age as well. New investigations are concentrating on radiometric dating of these basaltic rocks, which geochemically have previously been determined to be caused by intra-plate volcanism. Integrated litho-, bio-, chemo- and magnetostratigraphic studies carried out in this section can be here supplemented by absolute age determination of a submarine volcanic event. Additionally, this is a unique chance to calibrate the absolute age of the J/K boundary.

Variation in style of Adriatic lower crust indentation west and east of the Giudicarie Fault

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Neogene tectonics of the Alps is marked by the indentation of the Adriatic Plate into the Alpine Orogen and onset of escape tectonics in the Eastern Alps. This resulted in the formation of a system of strike-slip faults, mainly the Periadriatic Fault (PF), separating the Eastern and Southern Alps, and the sinistral Giudicarie Fault (GF), which offsets the PF. The GF is kinematically related to Neogene shortening in the Southern Alps but questions remain on its geometry at depth, in particular its relation to the crust/mantle boundary (Moho).

In this study, we compare geological cross-sections and pre-existing geophysical datasets (controlled-source seismology, local earthquake tomography) with a new high-resolution 3-D local earthquake tomographic model from the AlpArray and SWATH-D experiment along two N-S profiles west and east of the GF, as well as a NW-SE oriented section across the GF. These sections reveal differences in the style of indentation tectonics, specifically in the behavior of the Adriatic lower crust, between the Central and Eastern Alps. West of the GF, the lower crust of the Adriatic plate detached from its mantle lithosphere and wedged within the Alpine orogenic crust, whereas to the east of the GF, the Adriatic lower crust forms a bulge just to the south of the PF. The Adriatic upper crust responded by shortening and formation of a fold-and-thrust belt, while the Europe-derived orogenic crust underwent upright, post-nappe folding and exhumation in the Tauern Window. We discuss the possible causes for such along-strike variations in terms of changes in crustal rheology and structural inheritance within the Adriatic Plate, contrasting metamorphic histories within the Alpine orogenic crust west and east of the GF, and potential Neogene slab break-off beneath the Eastern Alps.

Exhumation of metamorphic core complexes of the internal Dinarides was triggered by the opening of the Pannonian Basin

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The Sava suture zone of the internal Dinarides contains Maastrichtian trench-fill sediments, termed “Sava flysch” that record the closure of the northern branch of the Neotethys. Subsequent collision between Adria-derived thrust sheets and blocks of European affinity in Latest Cretaceous to Paleogene times culminated in the formation of the Dinarides fold-and-thrust belt. The suture zone hosts numerous Oligocene plutons of I-type granitic composition. Many of these intrusions are located in the center of metamorphic core complexes (MCCs) that were exhumed in early Miocene times. This phase of post-collisional extension was concomitant with the opening of the northerly adjacent Pannonian Basin and associated with granitic S-type magmatism. Both the processes responsible for extensional deformation and magmatic activity in the internal Dinarides are still a matter of debate.

Our Study contributes spatio-temporal constraints to better understand the tectono-magmatic processes of this area. We present field-kinematic, geochronological, and thermobarometric data from two MCCs at the transition between the internal Dinarides and the Pannonian Basin. Both MCCs are characterized by plutonic rocks in the center, surrounded by up to amphibolite-grade mylonites of exhuming shear zones. Heterogeneous extensional reactivation of formerly contractional structures that gave rise to these core complexes as low-angle detachments in the early Miocene is indicated by a variation in deformation ages of 3 Ma, obtained by Ar-Ar in-situ dating of white mica from deformed rocks of the respective shear zones. While Motajica MCC was exhumed from within the Sava zone during E-W extension at approximately 20 Ma, Cer MCC was exhumed as part of the underlying Adriatic basement during N-S extension between 17-16 Ma. For the Cer MCC, a concordia age of 17.6±0.1 Ma (2σ) obtained by U-Pb LA-ICP-MS on zircons from an S-type granite in combination with an Ar-Ar inverse isochron age of 16.6±0.2 Ma (2σ) obtained on white mica from the same sample, indicate a cooling rate of approximately 400 °C/Ma.

Our results contribute to the idea of rapid exhumation of mid-crustal material in the form of MCCs in response to the opening of the Pannonian Basin. This is further corroborated by results of Raman spectroscopy on carbonaceous material, as the temperature profile across the shear zone implies extremely condensed isotherms of 250 °C/km. Additionally, U-Pb analyses show that zircons of the I-type intrusion contain inherited cores with age maxima at 270 Ma and 516 Ma and newly formed rims with an age maximum at 31.7 Ma, indicating the timing of intrusion. The S-type granite of Cer in parts reworks the I-type intrusion, as inherited cores include ages of 31-32 Ma, while the rims show an age of 17-18 Ma, suggesting a syn-extensional emplacement. Our data further shows that zircons of the I-type intrusion contain a significant amount of inherited cores with an age spectrum that resembles the detrital age spectrum from sediments of the Sava zone. This challenges the idea that these I-type melts were solely generated from igneous protoliths, and rather suggests a formation from melting of Paleozoic to Mesozoic successions constituting tectonically buried nappes of the internal Dinarides.

Challenges in the interpretation of the structural and metamorphic record in the Adula and Cima Lunga units (Central Alps)

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The Adula and Cima Lunga units show the best preserved record of the deformation and metamorphic history of the Central Alps. Alpine studies lasting more than a hundred years documented a complex tectono-metamorphic evolution, including the presence of relicts of ultrahigh pressure and high temperature metamorphism. Throughout this long history of researches, a few key questions stand out, still challenging the geological community. Major questions regard how to reconcile the structural pattern with the metamorphic path, as well as the timing relationships. The occurrence of ultrahigh-pressure and/or high-temperature rocks embedded within significantly lower grade metamorphic rocks rises a major challenge for developing a consistent geodynamic model for exhumation of such deep-seated rocks. Subduction zones are, in fact, efficient players driving material from the surface down into the Earth's mantle. However, the mechanisms to exhume part of this material (and particularly the denser oceanic rocks) back to the shallow crust are still highly debated. Scientists generally invoke either mechanical decoupling within a tectonic mélange or variable metamorphic re-equilibration during the retrograde path. These interpretations are based on the common assumption that the mineral assemblages form under lithostatic pressure and near-equilibrium regional geothermal gradients. Hence, the resulting metamorphic histories based on the estimation of the pressure and temperature conditions represent the major tool for tectonic reconstruction as proxies of the burial and exhumation history of the rocks during subduction-exhumation phases.

Alternative explanations highlight the role of deformation in promoting the coexistence of multiple local equilibria, which cease to correlate with lithostatic conditions and thus burial depths. In this view, the non-hydrostatic stress and the local temperature deviations are accounted as important components potentially modifying the metamorphic system.

In this contribution, we show new structural, petrological and thermochronometric data from the Adula and Cima Lunga units. The wide dataset comprises new field mapping covering the entire areas (several hundred square kilometres) and structural-petrochronological analyses at the meso- to micro-scale. Our results show the highly variable pressure-temperature-time-deformation paths experienced by the compositionally heterogeneous rocks of the Cima Lunga and Adula nappes. We present evidence of contrasting metamorphic records among the rocks of these nappes, providing arguments to discuss pros and cons of the tectonic models proposed to explain these contrasting metamorphic records.

A journey towards the forbidden zone: a new, cold, UHP unit in the Dora-Maira Massif (Western Alps)

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The distribution of ultrahigh-pressure metamorphism (*UHP*) at the scale of a mountain belt is of prime importance for deciphering its past subduction history. In the Western Alps, coesite has been recognized in the southern Dora-Maira massif, in the lens-shaped Brossasco-Isasca Unit, but has not been found up to now in the other parts of the massif. We report the discovery of a new *UHP* unit in the northern Dora-Maira Massif (Western Alps), named Chasteiran Unit (Manzotti et al., 2022). It is only a few tens of metres thick and consists of garnet-chloritoid micaschists. Garnet inclusions (chloritoid, rutile) and its growth zoning allow to precisely model the *P*–*T* evolution. Coesite crystals, which are pristine or partially transformed to palisade quartz occur as inclusions in the garnet outer cores. According to thermodynamic modelling, garnet displays a continuous record of growth during the prograde increase in *P* and *T* (25–27 kbar 470–500 °C) (stage 1), up to the coesite stability field (27–28 kbar 520–530 °C) (stage 2), as well as sub-isothermal decompression of about 10 kbar (down to 15 kbar 500–515 °C) (stage 3). The main regional, composite, foliation, marked by chloritoid and rutile, began to develop during this stage, and was then overprinted by chloriteilmenite (stage 4). The Chasteiran Unit is discontinuously exposed in the immediate hangingwall of the Pinerolo Unit, and it is located far away from, and without physical links to the classic *UHP* Brossasco-Isasca Unit. Moreover, it records a different, much colder, *P*–*T* evolution, showing that different slices were detached from the downgoing subduction slab. The Chasteiran Unit is the fourth and the coldest Alpine *UHP* unit known so far in the entire Alpine belt. Its *P*–*T* conditions are comparable to the ones of the Tian Shan coesite-chloritoid-bearing rocks.

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Tectonic implications of paleomagnetic results from the Northern Adriatic area: an overview

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The systematic paleomagnetic investigations concentrating on the northern part of stable Adria and the External Dinarides provided tectonically applicable results for nearly 200 localities from Italy, Slovenia and Croatia. The ages of the studied localities were tightly controlled by a bed by bed checking of the fossil content. The age of the acquisition of the magnetization was constrained by between-locality fold/tilt test, which often proved the pre-deformation “primary” age of the magnetization. It is important to emphasize that most of the sampled sediments were shallow water carbonates with weak natural remanent magnetizations (about 30 % of the sampled localities failed to yield paleomagnetic signal). However, those providing results are extremely valuable, for inclination flattening is practically absent in platform carbonates, therefore the estimation of the paleolatitudes are reliable.

The majority of the tectonic models published for the area are in agreement about the existence of two Mesozoic carbonate platforms, an Adriatic and a Dinaric, which came into contact during the Late Eocene-Oligocene thrusting of the latter over the former. They are in the External Dinarides, but the exact boundary between them is a matter of discussion. The tectonostratigraphic complexity of the External Dinarides is the main reason for the large number of models published for the Northern Adriatic area.

The paleomagnetic results, which permit to conclude to potential large-scale relative movement between areas, suggest that stable Adria and the whole chain of the Adriatic islands moved in a co-ordinated manner, *i.e.* the islands represent the imbricated margin of stable Adria, at least from the Aptian onward. During the Late Cretaceous, the area was close (38 °N) to the northernmost limit (40 °N) of the intensive carbonate production (carbonate factory). Stable Adria with its imbricated margin exhibits about 30° larger CCW rotation than the High Karst belonging to the Dinaric platform, thus giving further support to considering the chain of the Adriatic island as belonging to Adria. The practically parallel “primary” paleomagnetic declinations characterizing the Northern Adriatic area are at variance with the oroclinal origin of the arcuated shape of the chain of the Adriatic islands and of the thrust front between them and stable Adria. We attribute this shape to the dominance of the Late Cretaceous E-W compression in the northern segment, the Late Eocene-Oligocene NE-SW compression in the central segment, and the N-S oriented Neotectonic compression in the Central Adriatic area.

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Pressure-temperature-time evolution of Austroalpine metamorphic rocks from the southeastern Pohorje Mountains

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We have studied eclogite, garnet clinopyroxenite, and garnet-bearing micaschist and gneiss from the southeastern flank of the Pohorje Mountains (Mts.) in order to better understand the pressuretemperature (P-T)-time evolution of these rocks. Geochronology was performed by in-situ analyses of monazite in different textural positions with an electron microprobe and a laser-ablation inductively coupled plasma mass-spectrometer. P-T trajectories were obtained by thermodynamic modelling considering strongly the chemical zoning of garnet and mica and the mineral inclusions in these phases. In addition, we calculated the influence on intracrystalline cation diffusion on garnet zoning also to gain time constraints.

Two high-pressure (HP) events were proved for metamorphic rocks of the Pohorje Mts. These events occurred at temperatures between 570-650 °C for micaschist and 670-740 °C for eclogite + garnet clinopyroxenite in Late Cretaceous and Eocene times. In addition, we found that a micaschist sample taken close to the Pohorje pluton was partially overprinted in the Miocene (18.9±0.2 Ma) by this intrusion at depths of 30-32 km. Thus, the subsequent uplift of the Pohorje pluton and its surrounding occurred at a mean rate of 1.6-1.7 mm/a. The studied metamorphic rocks were also significantly exhumed probably soon after the Eo-Alpine event that had led to peak pressures up to about 2.3 GPa. This exhumation was accompanied by cooling. Another burial process followed during which Eo-Alpine rocks were significantly overprinted at peak pressures up to 2.4 GPa in the Eocene. For example, two generations of potassic white mica (phengite) formed in micaschist. The Eo-Alpine one was relatively coarse grained, whereas the Eocene generation replaced this coarse-grained phengite by newly grown small flakes. No indications for ultrahigh-pressure metamorphism were found.

We interpret our findings, including previous results on rocks of our study area in the Pohorje Mts., in a geodynamic context as follows: A first collision of continental (micro)plates occurred in the Late Cretaceous after a branch of the Neotethys Ocean was closed. The subduction of the corresponding oceanic plate including sediments on top led to eclogite (+ HP garnet clinopyroxenite) and HP micaschist which were exhumed during the continent-continent collision in an exhumation channel. About 45 Ma after this Eo-Alpine collisional event, another part of the Neotethys Ocean was closed followed by a second collision of continental (micro)plates. This process led to clearly overthickened crust and deep burial of rocks residing in the Eo-Alpine exhumation channel. Exhumation of the studied metamorphic rock units, probably mainly caused by surface erosion, followed this Eocene collisional event. A particular event in the Miocene is characterized by intrusions of large volumes of acidic magma. These intrusions formed the Pohorje pluton, which produced discernable contact metamorphism, for instance in micaschist, close to its margin.

Anagolay: the shape of the Philippines and the Luzon Syntaxis

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The India-Asia collision can have only a limited role as an actualistic model for the closure of Western Tethys and the subsequent Alpine orogenies because the impacting margins appear to have been sub-parallel and rather regular and the intervening ocean seems to have contained few volcanic edifices or continental fragments. A better guide to possible pre-collision processes is provided by the incipient Australia – Southeast Asia collision, which has already proved its worth as a key area for the study of small extensional zones within overall compressional environments. Insights into the possible roles of ridge-related features during oceanic closure are now being obtained from studies in the northern part of the Philippines Archipelago, which was largely formed by post-Middle Cretaceous volcanic activity associated with subduction of oceanic crust from both east and west. Double-sided subduction inevitably produces geomorphological complexity, but not all the anomalous features of the Philippines can be attributed to this cause. A sharp bend in topographic trends involving most of the southern part of the island of Luzon is here interpreted as a consequence of the impact on the east-facing subduction zone of the Anagolay volcanic massif formed by hot-spot volcanism associated with the spreading ridge in the West Philippine Basin. This bend can be considered a small-scale analogue of the syntaxes that define the limits of the India-Asia collision and demonstrates the way in which the presence of even a relatively small region of thickened crust can influence the morphology of an entire collision zone. Similar processes must have operated in other Alpino-type orogenic belts but may be hard to recognise because the generative units are no longer observable and their effects may be partly concealed by later tectonic over-printing.

Quartz and zircon in garnet elastic geobarometry of HP rocks from the Sesia Zone

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The Sesia zone is a rifted portion of the Adriatic Margin that subducted to high-pressure conditions during the Alpine Orogeny. It consists of two main complexes: the Internal Complex (IC) and the External Complex (EC). The IC is made up of polymetamorphic micaschists, eclogites, and orthogneisses equilibrated at eclogite facies conditions; the EC consists of alpine monometamorphic orthogneiss with minor paragneiss and quartzites metamorphosed at epidote blueschist facies conditions and intensely retrogressed at greenschist facies conditions. The question is therefore to understand if we can trace the Alpine metamorphic history through methods that do not rely only on chemical equilibration.

To tackle this objective, we used elastic geobarometry to derive pressure and temperature (P-T) conditions reached by three micaschists from the IC and one garnet-orthogneiss from the EC. Entrapment P obtained for the quartz inclusions in garnet in the IC range from 1.5-2 GPa at 600-650 °C, in agreement with the P-T estimates determined through thermodynamic modelling. Coupled quartz and zircon in garnet geobarometry in the garnet-orthogneiss from the EC also display P-T conditions of 1.8 GPa and 650 °C. These estimates disagree with the greenschist facies mineral assemblage of the rock (Ttn + Grt + Phg + Chl) and with the results of thermodynamic modelling for the garnet-bearing assemblage (0.6-0.8 GPa and 500 °C). The misfit in P-T estimates between elastic geobarometry and thermodynamic modelling might be due to an elastic reset of the quartz and zircon host-inclusion pairs at HP conditions. The use of coupled elastic geobarometry and thermodynamic modelling can help to unravel complex tectonometamorphic histories.

How active is recent tectonics in the central Balkans: Evidence from the Serbian Carpatho-Balkanides

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Since the Late Cretaceous, after closure of the Neotethys ocean, tectonic processes in the central Balkan Peninsula were mainly controlled by the mutual interaction of the Adriatic and the Eurasian plates, and tectonic units in-between. Most of the tectonic structures that have been active during Cenozoic times were inherited from previous tectonic stages under different tectonic regimes.

Tectonic activity within the Carpatho-Balkan orogen in eastern Serbia since Miocene is conditioned by the existence of the rigid Moesian promontory east of the research area, which limited thrusting of the Carpatho-Balkan units. Rather than that, further compression and complex rotations around the Moesian promontory have been accommodated by the formation of the large strike-slip fault systems (e.g. Cerna-Jiu fault, Timok fault), that accommodated up to 100 km of cumulative displacement. According to earthquake focal mechanisms, faults belonging to these fault systems are still active.

In this contribution we present new data about the youngest and recently active faults in the area of the Carpatho-Balkanides in eastern Serbia, based on the studies of fault kinematics, seismicity and earthquake focal mechanisms, as well as tectonic geomorphological studies in karst caves. Results show that the research area is primarily characterized by strike-slip tectonics, which most likely results from far-field stress generated by the Adria-push mechanism. However, the stress field is highly heterogeneous, with local areas of transtension and transpression that have also been important in controlling the recent fault kinematics in this part of the Carpatho-Balkanides.

Partial drowning or backstepping of the Early Norian Dachstein Carbonate Platform in the Dinarides (Poros, Montenegro)

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In the Dinarides the reef rim to the open marine deep-water depositional realm (outer shelf) of the Late Triassic Dachstein Carbonate Platform is not known. On the road from Gradac to Šula near to the village Poros a more than 120 m thick far travelled and overturned Late Triassic succession of reefal to bedded siliceous limestones was studied (biostratigraphy, microfacies). The section is slightly tectonic overprinted, with slump deposits in the central and upper part.

The section starts with a roughly 20 m thick reefal to fore-reefal limestone succession with deep-water matrix in the upper part (Lacian 2 in age with following conodonts: *Epigondolella. rigoi*, *E. abneptis*). Near the base the reefal limestones is think-bedded to massive (rudstones), higher up in the section various bedded. We attribute these fore-reefal limestones as part of the Late Triassic Dachstein Limestone, interestingly with a deepening upward sequence from the middle Lower Norian onwards. Around the Lacian 2-3 boundary the depositional characteristics changed relatively abrupt from reefal- rudstones to bedded siliceous limestones intercalated by few and turbidite layers containing shallow-water debris. The next, 30 m thick part of the succession consists of dm-bedded limestones with chert nodules and layers, grey limestones and reddish limestones (radiolarian-filament wackestones), in parts with slump intercalations or medium-grained microbreccias. Conodont dating show that the age of this part of the section is Lacian 3 to Alaunian 1-2 in the upper part (dated by *E. spatulata* to *E. slovakensis*) probably reaching the Alaunian 3. The Alaunian 3 to Sevatian (with *E. bidentata*) is characterized by a thick series of slump deposits with carbonate turbidite intercalations. Upsection follow polymictic breccias (debris flows) and carbonate turbiditic microbreccias with older open-marine hemipelagic components, as proven by conodonts. The overlying dm-bedded grey-reddish siliceous limestones with red chert nodules are Rhaetian in age dated by the appearance of *M. hernsteini*. Upsection 5-10 cm-bedded grey siliceous and slightly marly limestones (in a thickness of less than 20 m) follow, overlain by roughly 10 m thick dm-bedded red-grey siliceous limestones with red marl to claystone intercalations, in the lower part with slump deposits, again overlain by 5-10 cm-bedded grey siliceous and slightly marly limestones. An exact age of this part of the series could not be determined, only conodont multielements could be isolated from this part of the succession. The age is most likely Rhaetian 2-3, but earliest Jurassic for highest parts of the sequence cannot be excluded.

The higher Lacian to Late Norian part of the succession corresponds to the reef-near facies belt in open shelf position, known in the type-area in the Northern Calcareous Alps as Gosausee Limestone facies. However, the section Poros shows during the Norian a general deepening trend during the time span Lacian 3 to the end of the Rhaetian opposite of the well-known platform margin in the Northern or Southern Alps. In the Dinarides a backstepping of the reef belt in the late Early Norian result in a drowning unconformity of the Early Norian part of the long-living Dachstein Carbonate Platform.

New data on the Late Pleistocene evolution of the Klagenfurt Basin, Austria

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The Klagenfurt Basin in the southern Austrian region of Carinthia was glaciated during the Last Glacial Maximum (LGM). Next to numerous lakes, the present-day landscape predominantly exhibits landforms such as moraines and large river terraces systems. These landforms can be seen as markers for post-LGM tectonics: If they are deformed, the basin has taken up a share of the ~N-S shortening prevailing due to the ongoing collision of Adria and Europe. If the landforms are undeformed, this deformation is accommodated elsewhere, most likely further south along the Periadriatic and Sava Fault system or by a NW-SE-trending strike-slip fault system at the junction between Southern Alps and Dinarides in Slovenia. Our study is motivated by the recent discovery of earthquake-triggered mass movements in Carinthian lakes and new data on Late Pleistocene-Holocene speleothem damage in the Karawanken mountains, illustrating that the area is seismically active. We used newly available high-resolution digital elevation models to scan the area for postglacial deformation but found no conclusive evidence for tectonic activity since the Würm glaciation. We then analysed several outcrops of Late Pleistocene sediments throughout the Klagenfurt Basin to check for soft-sediment deformation features that could be linked to strong seismic shaking. These outcrops were documented as 3D virtual models. Deformed silty-sandy layers were encountered in several places, and one outcrop showed spectacularly folded fluvial gravels. However, we do not need to invoke tectonics as the causative mechanism. Instead, we interpret these structures as evidence for a late glacial advance. Luminescence dating is underway to put constraints on the timing of this event. Our study implies that although there are records for recent strong earthquakes around the Klagenfurt Basin, the rates of deformation are so low that they can not be detected in the post-LGM landscape.

Nappe stacking and syn-nappe folding in the northern Dora-Maira Massif (Western Alps)

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The internal structure of the Dora-Maira Massif is of key importance for understanding exhumation mechanisms of continental-derived HP-UHP rocks in the Western Alps. Numerous petrologicalgeochemical studies have been done on the world-famous UHP Brossasco-Isasca Unit in the southern Dora-Maira Massif, and recent syntheses have provided an updated view of its metamorphic (Groppo et al., 2019) and structural (Michard et al., 2022) history. By contrast, the northern Dora-Maira Massif has been much less explored. We are presently undertaking a multidisciplinary project aimed at better constraining its geometry and history. We studied in detail an area comprised between the Germanasca and the Chisone rivers. The first results are as follows:

The nappe stack comprises, from bottom to top, the Pinerolo (Carboniferous metasediments intruded by dioritic and granitic plutons), Chasteiran (UHP), Muret (polycyclic unit, made of a Variscan basement overprinted during Alpine HP metmorphism) and Serre (Permian rhyolitic to granitic rocks, and the associated epiclastic rocks; slices of Mesozoic cover) Units. The pre-Alpine history of the Muret Unit (6-7 kbar, 650 °C) dated at 324 Ma (U-Pb LA-ICP-MS on monazite inclusions in garnet) is well preserved in undeformed volumes (Nosenzo et al., 2022). A new, colder (garnet + Fe-rich chloritoid +coesite), UHP unit (the Chasteiran Unit) has been discovered (Manzotti et al., 2022 and this meeting). This Unit, located in the immediate hangingwall of the Pinerolo Unit, occupies the same structural position than the UHP Brossasco-Isasca Unit, but records temperatures 200 °C lower.

Geological mapping, structural data, and petrological investigations provide new constraints on the geometry and kinematics of this part of the Dora-Maira Massif. The main foliation D1 developed at different peak PT conditions in the different units. During their stacking, a new foliation D2 developed associated with kilometer-scale, E-W trending folds. Final doming of the Dora-Maira nappe stack (D3) is associated to the westward displacement of the Adria mantle indentor. Detailed geological maps and cross-sections will be provided for illustrating the main steps of the history.

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Exhumation response to climate and tectonic forcing in the southern Patagonian Andes (Torres del Paine and Fitz Roy plutonic complexes)

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Alpine landscapes form in mountain belts that likely experienced tectonic uplift during plate's convergence, and efficient erosion dominated by glacial carving and circle retreat. In southern Patagonia N-S oriented late Miocene plutonic complexes are exposed in deep incised valleys with summits topographically above the glacial equilibrium line altitude. Two of the most emblematic ones are the Fitz Roy (Chaltén, latitude 49 °S) and the Torres del Paine (latitude 51 °S) plutonic complexes, ~2 km higher than the mostly flat bottom valley that is partially covered by the Southern Patagonian Icefield. This continental region is located above an asthenospheric window that opens and migrates from the latitude 54 °S towards the latitude 46 °S since ~16 Ma, and experienced dynamic uplift during episodes of spreading ridge collision with the continental margin. Here we present a new dataset of combined low-temperature thermochronometers from the Chaltén and Torres del Paine plutonic complexes, and their thermal history inversion numerical modeling, to identify the geodynamic processes forcing on the exhumation of the mountain belt. These complexes are separated by 200 km along the strike of the belt, and share a pulse of rapid exhumation at ca. 6 Ma, likely showing that glaciation was regionally starting at this moment. After a period of quiescence, in Torres del Paine the exhumation rate is accelerated from ~2 Ma to the present, interpreted as a signal of the Pleistocene climatic transition creating incise valleys. Only in the Fitz Roy a pulse of rapid exhumation is present at ca. 10 Ma, approximately coincident with the time range in which the ridge was subducting beneath the continent at that latitude. This allows us to separate the climatic from the tectonic/mantle forcing to the exhumation in southern Patagonia, and represents the first in-situ observation of the passage of the asthenospheric window in the lowtemperature thermochronometric record of the region.

Discovery of sheath folds in the Adula nappe and implications for the tectonic evolution (Central Alps)

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Orogenic deformation patterns show intricate overprinting and structural relations, variations of style and orientation of folds and sense of shear, which are traditionally interpreted as due to polyphase deformation, i.e. distinct deformation phases separated by periods of tectonic quiescence. The Adula nappe in the Central Alps displays exceptional exposures of complex internal structures involving heterogeneous rocks (meta-pelitic and meta-granitic gneisses, micaschists, amphibolites, eclogites, minor quartzites and limestones). The Adula structures are distinguished through the style and the orientation of folds, schistosity and the observation of refolded folds. Structural features show a great variability within the unit, making the structures along the nappe difficult to correlate. However, the Adula deformation patterns are classically interpreted as generated by multiple, distinct deformation phases (five deformation phases; D1-5), despite only one schistosity and lineation may be clearly recognized in the field. Kinematic indicators indicate dominant top-to-N sense of shear, although local top-to-S shear is interpreted as developed during the D3 backfolding phase (e.g. Löw, 1987; Nagel, 2008). In this contribution, we show a recognition of sheath folds from the central part of the Adula nappe, the largest high-pressure nappe of the Central Alps. We performed detailed geological mapping (scale 1:10000) and structural characterization of the spectacular outcrops of the *Piz de Cressim* glacial cirque. Here a large antiform is described as the main structure classically associated with the D3 backfolding phase. We show that the meso/leucocratic heterogeneous rocks (orthogneisses, micaschists, migmatitic gneisses, amphibolitic lenses) form highly non-cylindrical folds. Sheath folds are highlighted by several cm to km scale omega and elliptical eye-structures in cross sections perpendicular to the shear direction (yz plane). Local variations of style and orientation of folds and sense of shear are easily explained by the three-dimensional structure of the sheath folds. All lithological units show one penetrative foliation and a related stretching lineation with variations in orientation. We suggest that the Cressim antiform formed during a progressive, highly non-cylindrical folding under top-to-N deformation accomplished within rheological heterogeneous rocks.

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Lower to Middle Jurassic clastic formations of the Western Carpathian Klippen Belt: testimony to the rifting-breakup-drifting Processes

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The Lower to early Middle Jurassic terrigenous clastic deposits witness the early breakup processes of Pangaea. Rifting and subsequent ocean-floor spreading of the Central Atlantic branch that propagated eastward into the Alpine–Carpathian realm split several continental blocks (Adria, Tisia, Dacia, Moesia), and smaller intervening fragments (such as Cervinia and Oravic), off the southern European plate margin. Alongside the ocean-facing margins of Europe and drifting blocks, the initial rifting phases are recorded by terrigenous terrestrial fluvial-limnic, deltaic to open marine clastic formations. Although showing some regional variations in composition and age, they share many common developmental characteristics.

In the Carpathian Pieniny Klippen Belt (PKB), the Lower – early Middle Jurassic clastics are partly preserved in the Šariš (Grajcarek) Unit that was derived from the outer (northern) margin of the continental ribbon surrounded by the Pennine oceanic branches. Palaeogeographically, this continental splinter is known as the Czorsztyn Ridge and its detached Jurassic–Eocene sedimentary nappes are designated as the Oravic tectonic units (Šariš, Subpieniny and Pieniny).

The Šariš sedimentary succession related to the incipient rifting stage begins with massive quartzitic sandstones of probably Hettangian age deposited in continental to shallow-marine environs. The mature rifting stage is represented by quartz-calcareous, partly turbiditic sandstones rich in imprints of Sinemurian ammonites intercalated by thin layers of grey shales. Overlying spotted marlstones of the Fleckenmergel facies of the Pliensbachian–Toarcian Allgäu Fm. are locally passing into black shales representing the Toarcian oceanic anoxic event. Deposition of oxygen-depleted black shales continued into the Aalenian and early Bajocian as the Szlachtowa Fm., which is characteristic of the Šariš Unit. In addition to micaceous black shales with common imprints of pelagic bivalves of *Bositra buchi*, it comprises also beds of black turbiditic siliciclastic sandstones rich in white mica flakes and few allochthonous coal seams. Black shales with pelocarbonate nodules out of the reach of turbiditic currents are identical with the concomitant Skrzypny Fm. recognized also in the successions of the Subpieniny Nappe. Beds of calciturbiditic crinoidal limestones occurring in the upper part of the formation indicate input of shallow-marine bioclastic material derived from the adjacent Czorsztyn Ridge uplifted during the middle–late Bajocian. Subsequent latest Bajocian hiatus and drowning of the Czorsztyn Ridge, along with a sudden decline of clastic input in the Šariš Basin, are interpreted as the breakup phase of a nearby oceanic zone.

The post-breakup pelagic succession represents the drifting stage and consists of the late Middle–Upper Jurassic dark, calcite-poor siliceous shales, red ribbon radiolarites, red marlstones and cherty limestones, followed by the Lower Cretaceous spotted micritic limestones with cherts, mid-Cretaceous Fleckenmergel and dark silicitic shales and Upper Cretaceous red calcite-free claystones. Finally, the synorogenic phase is recorded by the Maastrichtian–Paleocene calcareous flysch with olistostrome bodies and limestone megaolistoliths derived from the overriding Subpieniny Nappe.

The thermotectonic evolution in front of the Dolomites Indenter

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The Adriatic Indenter is subdivided into a western and an eastern domain termed Canavese-Insubric Indenter and Dolomites Indenter, respectively, and offset for ~75 km from late Oligocene onwards by the NNE-SSW-trending sinistral-transpressive Giudicarie fault system (GFS). The N(NW)-directed movement of the Dolomites Indenter (DI) modifies the early Cenozoic nappe structure of the Alpine orogen as the accommodated shortening changes substantially, depending on the oblique shape of the indenter and its counter-clockwise rotation. The Austroalpine basement units northwest of the GFS experienced open folding of the Cretaceous nappe stack and preserved Cretaceous metamorphic ages. In contrast, the previously deep-seated Neoalpine metamorphic Subpenninic and Penninic units of the Tauern Window in front of the DI's tip are exhumed and the Austroalpine units adjacent to the DI are brought into a subvertical or even overturned position.

The combination of several thermochronological methods and structural field work allows for constraining time on this tectonic evolution: The Austroalpine units directly adjacent to the DI belong to the uppermost nappe system of the Eoalpine orogeny (Drauzug-Gurktal Nappe System) and experienced an anchizonal to lowermost greenschist-facies metamorphic overprint during the Alpine orogeny resulting in an only partial reset of Variscan Rb/Sr Biotite ages (Pomella et al., 2022). Fission track data from the western Tauern Window and the Austroalpine units adjacent to the north-western corner of the DI, indicate cooling below 180-200 °C (Zircon Fission track data) in the Early Miocene and below the 100-120 °C (Apatite Fission track data) in the Late Miocene (Klotz et al., 2019). (U-Th)/He on Apatite data, derived from a horizontal section of the Brenner Base Tunnel and reaching from the DI into the Austroalpine nappe stack, indicate continuous differential uplifting of the northern block along the, in this area, approximately E-W striking Periadriatic fault system until the Pliocene (Klotz et al., 2019).

Earthquake focal solutions and satellite-based geodetic studies show, that indentation is ongoing today. The significant present-day seismotectonic activity concentrates in the Friuli area in the southeast, whereas there is currently no significant seismicity along the western and northern boundaries of the DI or in the northerly adjacent Austroalpine basement and the Tauern Window. Increased seismic activity can only be detected north of the Tauern Window, along, and north of the Inn Valley (Reiter et al., 2018). Based on field evidence and the thermochronological record, the recent seismic distribution indicates an important change in style and localisation of deformation compared to what is documented from the past.

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Calcite microstructures recording polyphase deformation history of the Meliata Unit

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The geological structure of the Western Carpathians is very complicated and is result of several deformation phases. The Meliata Unit (Meliaticum) as a significant part of the Western Carpathians proves existence of substantial tectonic movements. The Meliata Unit incorporates the Permian to Jurassic blueschists-facies Bôrka Nappe and the Jurassic low-grade mélange complexes with huge Triassic olistostrome bodies – the Meliata Unit s.s. Based on microstructural characteristics, the calcite is one of the most suitable minerals for study of deformation history. Calcitic metacarbonates are common elements of subduction-accretionary complexes and thus also a considerable element in rock composition of the Meliata Unit. Samples were taken from various Meliatic complexes either within the Bôrka Nappe, or as olistoliths embedded in the Jurassic mélange. Variations in deformation microstructures are clearly visible in sampled metacarbonates, what was main aspect to separate them into groups reflecting different P/T conditions. The distinguished groups more-or-less correspond to their regional occurrences and grade of metamorphosis of surrounding rocks. The first group (GI) contains relatively large calcite grains and microstructure pointing to the Grain Boundary Migration deformation mechanism, which suggests the higher temperature during dynamic recrystallization. The higher temperature is also proven by character of twin lamellas. The GI microstructures are related to the subduction processes after closure of the Meliata Ocean and exhumation of the high-pressure complexes. The second group (GII) is characterised by a significant grain size reduction and strong shape preferred orientation and thus with development of calcitic mylonite zones. They are related to forming of the Meliatic accretionary wedge. The third group (GIII) shows completely recrystallized microstructure of relatively uniform calcite grain size with sharp edges of grains. They were recrystallized in an annealing regime due to higher temperature gradient generated by a shallow granitic intrusion associated with the exhumation of the underlying Veporic metamorphic dome. The last deformation phase is marked by the bulging deformation mechanism, thus to a partial replacement of primary grains by newly formed fine-grained calcites and represent final stages of nappe emplacement.

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Finding Quaternary Seismogenic Activity Along the Eastern Periadriatic Fault System: Dating of Fault Gouges via Electron Spin Resonance

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The Periadriatic Fault System (PAF) is among the most important post-collisional structures of the Alps; it accommodated between 150-300 km of right-lateral strike-slip motion between the European and Adriatic plates from about 35 until 15 Ma. The scarcity of instrumental and historical seismicity on the easternmost segment of the PAF is intriguing, especially when compared to nearby structures in the adjacent Southern Alps. Through this project, we aim to show which segments of the PAF accommodated seismotectonic deformation during the Quaternary by applying Electron spin resonance (ESR) dating to fault gouges produced by this fault system. The method is especially useful for dating shear heating during earthquake activity at near-surface conditions due to its dating range (~104 - ~106 years) and low closing temperature (< 100 °C). During our field campaigns, we acquired structural data and collected 19 fault gouge samples from 15 localities along the PAF, the Labot/Lavanttal Fault, and the Šoštanj Fault. We measured the ESR signals from the Ti and Al centers following the additive and regenerative protocols on 60 mg aliquots of quartz, and compared the measurements between different grain size fractions. Here, we present our preliminary results from selected localities, suggesting Quaternary earthquake activity along the studied part of the PAF.

Formation of esseneite and kushiroite in calc-silicate skarnoid xenoliths from Southern Slovakia

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Skarnoid calc-silicate xenoliths composed of anorthite, clinopyroxene and Mg-Al spinel were discovered in an alkali basalt quarry located in the Belinsky vrch lava flow, near Fiľakovo (Southern Slovakia). Randomly oriented tschermakite pseudomorphs are replaced by olivine, spinel, and plagioclase. The relict amphibole within the pseudomorphs is characterized by high ^{VI}Al (1.95 to 2.1 apfu), and very low occupancy of the A-site (< 0.1 apfu), which are a diagnostic feature of highpressure metamorphic rocks. Pyroxene compositions plot along continuous mixing line extending from nearly pure diopside-augite towards a Ca(Fe^{3+}Al)AlSiO$_6$ endmember with an equal proportion of ^{VI}Al^{3+} and Fe^{3+}. Forsterite (Fo72–83) and Fe^{3+}-rich ilmenite crystallized from the melt, leaving behind the residual calcic carbonate with minor MgO (1–3 wt%). Euhedral aragonite and apatite embedded in the fine-grained calcite or aragonite groundmass indicate slow crystallization of residual carbonatite around the calcite-aragonite stability boundary. Olivine-ilmenite thermometry (Andersen and Lindsley, 1981) yielded temperatures between 770 and 860 °C. Pressures of 1.8–2.1 GPa were estimated by intersection of the olivine-ilmenite thermometer with the calcite-aragonite stability boundary calculated for a CO$_2$ saturated environment using Perple_X (Connolly, 1990). Tschermakite touching interstitial plagioclase was suitable for the application of the barometer of (Molina et al., 2021), which yielded 781±13 °C and 2.05±0.03 GPa consistent with the olivineilmenite-calcite-aragonite thermobarometry. The estimated PT conditions fall well inside the garnet stability field, although no garnet has been observed in the mineral assemblage. However, the presence of esseneite and kushiroite with melilite inclusions suggest high CO$_2$ partial pressure, low SiO$_2$ activity and strongly oxidizing conditions, in which the high Al, Fe pyroxenes are formed at the expense of the garnet (Ohashi and Hariya, 1975). The protolith is still ambiguous, and two options have been considered. The relict tschermakite in spinel-plagioclase-forsterite pseudomorphs suggests a metamorphosed calc-silicate marble originating from a sedimentary protolith. High Cr contents in spinel and pyroxene, abundant Cu-sulfides, and high CaO contents, 0.3–1.0 wt% CaO, in forsterite, suggest a magmatic protolith, similar to layered gabbro-anorthosite complexes modified by interaction with calcic carbonatite melt.

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Age and structure of the Stubai Alps (Ötztal-Nappe, Tyrol/Austria)

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The Ötztal-Nappe in the central Eastern Alps represents a classical area of polyphase deformation and metamorphism. The pre-Mesozoic basement (Ötztal-Stubai Complex; OSC) comprises metasediments (paragneiss and mica schist), metaigneous rocks and metabasites that experienced a polymetamorphic overprint during Ordovician, Variscan (Devonian to Carboniferous) and Eo-Alpine (Early/Late Cretaceous) events. In the Stubai Alps, basement rocks are unconformably overlain by a monometamorphic Permo-Triassic cover sequence (i.e. “Brenner-Mesozoic”), which truncates pre-Mesozoic structures and allows discriminating pre-Alpine and (Eo-)Alpine structures.

Ordovician metagranites (analysed using LA-ICP-MS U-Pb dating of zircon), deformed together with their metasedimentary host rock, highlight the large-scale structure of the OSC. During the Variscan event, metabasitic rocks of the central OSC underwent eclogite-facies metamorphism followed by an amphibolite-facies overprint. Two pre-Alpine fold generations can be distinguished: i) NE-dipping fold axes of isoclinal folds overprinted by ii) subhorizontal NW-SE trending fold axes that are associated with a pervasive axial plane foliation. Shearbands dissecting the foliation indicate a top-NE directed shear sense, which probably correlates with post-Variscan exhumation. Locally, the shearbands show a SE-directed overprint, which is attributed to Late Cretaceous extension in the course of the Eo-Alpine event.

(Eo-)Alpine metamorphism of the Ötztal-Nappe, represented by a southward increasing gradient from greenschist-facies conditions in the northwest to epidote-amphibolite-facies conditions in the southeast, led to a differential structural overprint. Ar-Ar white mica ages from the Stubai Alps yielding Middle to Upper Pennsylvanian ages (post-Variscan cooling) and “mixed” Variscan-to-Alpine ages reflect the metamorphic gradient. Late Cretaceous ages from Rb-Sr analyses on biotite and (UTh)/He) zircon thermochronology provide time constraints on large detachment faults that created several tectonic klippen of Mesozoic rocks in the study area. These detachments formed in a general SE-directed extensional regime, which is widely reported from Upper Austroalpine units.

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Architecture and sedimentary evolution of the Ladinian Kobilji curek Basin of the External Dinarids (Rute Plateau, central Slovenia)

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The largest Mesozoic paleogeographic perturbation of the present-day Alpine-Dinaric transition zone occurred in the Ladinian. The entire area was subjected to intense tectonic extension related to the rifting of the Neotethys Ocean. The most intense subsidence occurred in the central part of this segment of the continental margin, and the area remained deep-marine (called the Slovenian Basin) until the end of the Mesozoic. To the south, extension also resulted in differentiation, but the predominant paleoenvironments were either continental (often emerged areas) or shallow-marine. Locally, however, small-scale, short-lasting, deep-marine environment also developed. Herein we present the study of the Kobilji curek Basin in the Rute Plateau (central Slovenia, 25 km south of Ljubljana), where the Ladinian platform to basin transition has recently been studied in detail.

The study includes sedimentological analysis, biostratigraphy, mineralogical analysis, and detailed mapping. In the studied area, following Ladinian facies were outlined: F1 - deep marine (volcano)clastic rocks (bentonitic clays, tuffitic sandstone, tuffs), F2 - hemipelagic limestone (micritic and filament limestone), F3 - resedimented limestone (breccia and calcarenite), and F4 - shallow marine carbonates (bioclastic limestone and dolomite) (for details see Kocjančič et al., this volume). The base is Anisian dolomite and the top Carnian clastites. In contrast, the highly variable Ladinian facies merge both laterally and vertically. Detailed geological mapping revealed that the area can be divided into four tectonic blocks with characteristic sequences, separated by roughly N-S and E-W trending paleofaults. In the NW tectonic block (B1), the most basinal succession is outcropping with two intervals of platform carbonates, while the sequence in the SE block (B4) is entirely characterized by platform carbonates. In the transition blocks (B2 and B3), platform carbonates predominate with minor basinal intervals. The entire Ladinian succession shows five major subsidence pulses followed by partial or twice also complete platform progradation. The first subsidence is documented exclusively in B2 and B3 (F1 and F2), followed by platform progradation (F4). During the second subsidence, the major paleofault between B1 and B2 is activated. This pulse is evident in B1 as a fairly thick basinal succession (F1) containing carbonate resediments (F3) in the upper part, indicating distant platform progradation. This pulse is also seen in B2 as thin deep marine limestones (F2 and F3), again followed by platform carbonates (F4). The third pulse is seen in B1 as coarse resediments (F3) followed by general platform progradation (F4), and in B2 as thin deep marine carbonates (F2 and F3) followed by platform carbonates (F4). This platform progradation seals the paleofault between B1 and B2. The fourth pulse is uniform in blocks B1 and B2 and consists of a continuous basinal interval (F1 and F2) followed by a final rapid platform progradation (F4). The fifth subsidence is uniform in B1, B2, and B3 and begins with hemipelagic limestone (F2) followed by (volcano)clastic rocks (F1) with some felsic extrusive rocks. In B4, this pulse either did not occur or the rocks were eroded during regional emersion in the early Carnian.

From Permian to rift-inception: new insight from the Western Southern Alps (Varese Area)

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The Permian-Triassic tectonic evolution of Western Adria has been variously interpreted either as the first rifting phase that led to the opening of the Alpine Tethys or as the result of continental-scale strike-slip movements. Additionally, a common view on the age of inception of the rifting of the Alpine Tethys, its duration and its relationship with the antecedent Variscan tectonic phases, is still lacking. The European Western Southern Alps expose the basement and cover rocks of Western Adria and therefore represent a key area for understanding and testing the post-Variscan to prerifting evolution of this plate. We focus, in particular, on a relatively poorly deformed sector of Northern Italy (Varese Area), where the outcropping Permo-Carboniferous sequence and the overlying Triassic to Early Jurassic units allow to investigate the crosscut relationships between structures that were active during pre-rift and syn-rift tectonic phases. By means of a 3D geological model of the Varese Area, built on a brand-new geological map, firstly we restored Alpine tectonics and then performed a progressive geological restoration of faults, aided by new preliminary thermochronological data. We unveiled a polyphasic strike-slip Permian tectonic phase that switch to an unexpectedly early inception of the rifting.

Platform to basin transitions: mapping observations at the Krvavica Mountain, and Čemšeniška Planina, in the Sava Folds Region

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The Krvavica Mountain and Čemšeniška Planina are situated on the northern limb of the Trojane anticline, a part of the Sava Folds region in central Slovenia. This Cenozoic fold belt is situated in the transition zone of the Pannonian basin, the Alps and the Dinarides. This area was a part of the Adriatic rifted margin of the Neotethys during the Middle-Late Triassic. Repeated rifting phases continued into the Jurassic. This tectonic conditions created the Slovenian Basin, which subsided until the Late Cretaceous. The extensional phasees were followed by contraction in the Paleogene and Neogene during the Dinaric and Alpine phases (Placer, 1998a; Schmid et al., 2020). The interplay of two-phase thrusting led to specific young-on-older tectonic contact between the Dinaridic Carboniferous-Permian clastics ("softbed" of Placer, 1998b) and Mesozoic formations of uncertain origin (Placer, 1998b). The study area SW from Celje, near the Krvavica Mt., provides good outcrops. According to previous studies the Krvavica Mt. is composed of the platform Schlern Formation while the Čemšeniška Planina is partly composed of Bača dolomite, a characteristic Slovenian Basin formation. Our observations show that through the Krvavica Mt. three formations can be traced from S to N: 1) the Pseudozylian Formation of latest Ladinian to Carnian age, composed of siliciclastic basin sediments (shales, sandstones, siltstones, micritic cherty limestones, breccia, and pyroclastics), 2) the Schlern Fm. composed of Triassic platform carbonates and 3) formation composed of latest Jurassic to Early Cretaceous carbonates and mixed carbonate-siliciclastic rocks. These formations are repeated at least twice by a major thrust. On the other hand, a platform progradation into the clastics basin can also be supposed; this feature is typical in central Slovenia (Gale el al., 2020). However, 500 m west of the Krvavica Mt. in the eastern side of Čemšeniška Planina and on the Flinskovo ridge, recent mapping showed a lithologically typical but condensed Slovenian Basin-type sequence. Here, the succession starts with the pelagic Norian Bača dolomite, followed by the Hettangian–Pliensbachian calciturbiditic Krikov Formation. After a potential gap in Toarcian, the latter is followed by the recently described Bajocian-Bathonian Ponikve Breccia as a part of the Tolmin Formation (Rožič et al., 2018). After a possible gap in the early late Jurassic, the Late Jurassic-Early Cretaceous Biancone Formation represents the youngest exposed lithostratigraphic unit in studied area. The proximity of fundamentally different lithological sequences can shed new light on the platform to basin transition at the border of Slovenian Basin with the Dinaridic carbonate platform. However, the structural geometry is complex, and could be also explained by normal faulting to achieve young-on-older contacts. Alternatively, post-folding, gently dipping thrusts could dismember the pre-existing northern limb of the Trojane anticline. The displacement of the tilted (folded) Mesozoic Slovenian basin succession can also be explained by a post-folding thrust, which led to the contact of the pelagic formations with the underlying folded Carboniferous-Permian rocks of the Dinarides.

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Geological history of the Troiseck-Floning Nappe (Austroalpine unit, Styria/Austria)

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This contribution reports LA-ICP-MS zircon ages and Rb-Sr biotite ages from the Troiseck-Floning Nappe, forming the northeasternmost extension of the Silvretta-Seckau Nappe System in the Eastern Alps. The Troiseck-Floning Nappe comprises a basement formed by the Troiseck Complex and a Permo-Triassic cover sequence. The basement consists of paragneiss with intercalations of micaschist, amphibolite and different types of orthogneiss, which was affected by a Variscan (Late Devonian) amphibolite facies metamorphic overprint. The cover sequence includes Permian clastic metasediments and metavolcanics, as well as Triassic quartzite, rauhwacke, calcitic marble and dolomite. During the Eoalpine (Cretaceous) tectonothermal event the nappe experienced deformation at lower greenschist facies conditions.

Detrital zircon grains from paragneiss are in the range of 530-590 Ma, indicating an Ediacarian to earliest Cambrian source and a Cambrian to Ordovizian deposition age of the protolith. Late Cambrian to Ordovician crystallization ages from leucogranitic intrusions represent the earliest magmatic event of the Troiseck Complex. The amphibolite bodies derived from basalt with a calcalkaline to island arc tholeiitic signature.

Leucocratic orthogneiss with K-feldspar porphyroclasts and a calc-alkaline granitic composition plots in the field of volcanic arc granite. The youngest zircon grains indicate a Late Devonian crystallization. Two pegmatite gneisses with a calc-alkaline composition are early Mississippian in age.

Mylonitic orthogneiss with a pronounced stretching lineation appears as irregularly shaped layers. It is leucocratic, very fine grained and contains scattered feldspar porphyroclasts with a round shape and a diameter of about 1 mm. Its chemical composition is granitic/rhyolitic with an alkali-calcic signature. In classification diagrams it plots in the field of syn-collision granite. Zircon ages of about 270 Ma indicate a Permian crystallization. Similar rocks interpreted as Permian rhyolitic metavolcanics appear in the cover sequence. They share a similar chemical composition and crystallization age of 270 Ma. Associated intermediate metavolcanics developed from calc-alkaline basaltic andesite.

According to Rb-Sr biotite ages cooling of the Troiseck-Floning Nappe below c. 300 °C occurred at about 85 Ma in the west and 75 Ma in the east.

In summary, the Troiseck Complex developed from Cambrian to Ordovizian clastic metasediments and granitic and basaltic magmatic rocks emplaced in the same time range. During the Late Devonian, it was affected by the Variscan collisional event, causing deformation at amphibolite facies conditions and intrusion of calc-alkaline granites. In early Mississippian time pegmatite dikes intruded, maybe induced by decompression and exhumation. The deposition of clastic sediments and (sub)volcanic rocks (rhyolite and basaltic andesite) constrains a surface position of the Troiseck Complex during the Permian. Based on regional considerations an extensional environment is assumed. In Triassic times carbonate platform sediments were deposited. During the Eo-Alpine collision in the Cretaceous the unit was part of the tectonic lower plate and subducted to shallow crustal levels, indicated by a lower greenschist facies metamorphic overprint. The Troiseck-Floning Nappe was formed and exhumed since about 85 Ma. Rb-Sr as well as apatite fission track data from the literature indicate tilting with more pronounced exhumation and erosion in the eastern part during Miocene lateral extrusion of the Eastern Alps.

Internal deformation and tectonic evolution of the Dolomites Indenter, eastern Southern Alps: A combined field and analogue modelling study

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In the evolution of the Alps, the Adriatic plate is traditionally considered as rigid indenter and research on collision and extrusion tectonics mainly focused on the areas north of it. However, the structure of the northernmost part of the Adriatic microplate in the eastern Southern Alps of Italy and Slovenia, referred to as Dolomites Indenter (DI), demonstrates significant internal deformation of a continental indenter that contains the structural memory of Jurassic extension leading to the formation of the Alpine Tethys. Here we argue that these pre-existing NNE-SSW trending normal faults are of paramount importance for understanding and explaining Paleogene to Neogene crustal deformation of the DI. In particular, we demonstrate through physical analogue modelling that lateral changes of thrust fault orientations are controlled by the inherited fault bound basin and platform configuration (e.g., in the Cadore area, where the Trento platform merges into the Belluno basin).

In our brittle and brittle-ductile analogue experiments, shortening is orthogonal or oblique to platform and basin configuration, which is represented by either (i) pre-scribed strength contrasts between platforms/basins or (ii) graben structures modelled by an initial extensional phase. This approach allows us to test various deformational wavelengths as well as timing and localisation of uplift of the DI's upper to middle crust. Modelling results indicate that the localisation of deformation is controlled by lateral strength contrasts, as transitions from platforms to basins represent. Analyses of surface displacement vectors show that these areas are associated with changes in shortening directions, resulting in, curved faults. All models emphasise that the overall style of deformation is less dependent on the material of the basal décollement, but is ruled by the inherited platform and basin configuration, independent of orthogonal or oblique inversion.

To compare analogue modelling results with deformation in the DI, structural fieldwork accompanied by thermochronological sampling was carried out. Examined cross-cutting criteria covering the entire DI comprise evidence for four distinguishable deformation phases during Paleogene (Dinaric) shortening and subsequent Neogene (Alpine) continental indentation: Top SW, Top (S)SE, Top S and Top E(SE). However, shortening directions along several of the studied faults, e.g. the overall SSE-vergent Belluno thrust (Valsugana fault system), change locally from top SSW to top SSE along strike.
Based on our modelling results, we infer that the variability of shortening directions along these thrust faults may depend on inherited structures and do not necessarily reflect different deformation phases. As such the number of deformation phases in the Southern Alps may have been overestimated so far.

Differentiation and genesis of the Middle Triassic mafic volcanic and volcaniclastic facies in NW Croatia - case study from Vudelja quarry

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The Middle Triassic period represents a very dynamic time in a broader Tethyan region. Tectonic movements related to disintegration of Pangea and opening of the Neotethys gave rise to the formation of volcanic and volcaniclastic deposits. In the NW Croatia, these rocks outcrop in approximately 60 km long intra-Pannonian Mountain chain (Mts. Kalnik, Ivanščica, Strahinjščica, Kuna Gora, Desinić Gora and Ravna Gora), representing the junction between the Southern Alps and Internal Dinarides. Among these mountains, Mt. Ivanščica represents a complex structure built of shallow-marine to pelagic successions originating off the passive continental margin of Adria microplate. These deposits are found in a tectonic contact with ophiolitic mélange containing remnants of Neotethys. Middle Triassic volcanic and volcaniclastic rocks from this area include basic/intermediate to acidic effusive and pyroclastic lithologies and are interfingered with marine sediments.

The specific area of Vudelja quarry, situated in the central part of the northern Ivanščica slopes, is composed mainly of mafic lithologies and their volcaniclastic derivates. Volcanic and volcaniclastic rocks of basaltic composition were studied in detail to distinguish different facies and their spatial distribution. Three different facies were recognized: 1)autoclastic effusive facies; 2) pyroclastic flow facies, and 3) resedimented autoclastic facies. Autolcastic effusive facies is composed of hyaline to intersertal basalts, with incorporated clasts of the same lithotype. This facies was formed by effusion of basaltic magma. Basaltic clasts were likely incorporated by the primary effusive flow during magma ascent, or following effusion while flowing over the fragmented basaltic material. Quenching fragmentation of a basaltic effusion in the marine environment is another possible process explaining the formation of basalt clasts. Pyroclastic flow facies is composed of plagioclase crystalloclasts, basaltic lithoclasts and scoria fragments, with the flow texture indicated by clast arrangement and glassy matrix with flow features. This facies occurs only locally and its geographical extent is limited thus indicating a small volume of the flow, characteristic for basaltic pyroclastic flows of scoria and ash type. Resedimented autoclastic facies is dominant at the outcropping quarry front and is composed of several lithotypes with various grain sizes and types of matrix. Clast dimensions vary from block to ash size. Some samples exhibit common sedimentary features such as horizontal lamination. The facies was formed by the autofragmention processes of hot basaltic magma in contact with sea water, and subsequent resedimentation of newly formed volcaniclastic particles. Due to an intense tectonic disruption, spatial organization of determined facies is not clear, though the alienation from the primary source can generally be followed from south to north.

Studied locality presents a portion of Middle Triassic volcanic and volcano-sedimentary formations well known from the Southern Alps, Transdanubian Range and the Dinarides. Intense volcanic activity, related to the rifting between the future Adria microplate and southern edge of Laurasia, fed the material to a complicated pattern of sedimentary environments formed along the future Adria passive margin. Extensional tectonics created deep faults within the continental crust which might have served as conduits for submarine basaltic extrusions.

Tectonic Transfer from the Western Alpine Front to the French Rhône Valley in its 3D-Structural Context

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The Western Alps current tectonics is characterized by seismically active radial extension in the core of the belt, combined with transcurrent to transpressive tectonics in its external zone and foreland associated with a moderate seismicity. We focus on the tectonic transfer from the W-Alps to their foreland, namely the French Rhône Valley, a region with high societal challenges, including demography, nuclear powerplants, and chemical industries. We combine seismotectonic and geodetic (GNSS) approaches to constrain the stress and strain fields of the area extended from the alpine External Crystalline Massifs to the eastern edge of the French Massif Central, which encompasses the Rhône Valley. Seismic strain rates for a set of subareas defined on tectonic arguments (seismotectonic zoning) have been evaluated. They are processed by combining the total seismic energy obtained with statistical integrations of Gutenberg-Richter distributions with representative focal-mechanisms obtained from stress inversions. Seismic strain rates are then compared to the geodetic strain field obtained from an updated GNSS solution focused on the study area. Seismic strain rates of subareas in the Rhone Valley and surroundings range between a few nanostrains/yr and 10E-2 nanostrains/yr. In terms of amplitude, geodesy seems to provide deformation rates one order of magnitude higher than seismicity. However, our seismic strain tensors are globally consistent with the geodetic ones, specifically in the front of the Alps (Belledonne region), where seismic and geodetic networks are denser. In a last step, we replace these strain and stress fields in a new 3D-structural model, which has been developed on purpose. It integrates the main crustal units and the main faults of the area, allowing to better constrain the relationship between the current deformation and stress patterns of the Rhône Valley under the Alpine influence, and the inherited fault system carving the entire domain.

Petrography of ultrabasic and basic rocks from the Ozren ophiolite complex (Bosnia and Herzegovina)

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The Ozren ophiolite complex (OOC) in Bosnia and Herzegovina is a part of large Dinaride ophiolite belt (Babajić, 2019, and reference therein). This contribution comprises mineralogical-petrographical descriptions of representative rocks of the OOC, which we sampled during the field investigation: lherzolites, harzburgites, dunites, gabbros, dolerites, and troctolites. The mineral composition was determined by polarized transmitted light microscopy and introductory EPMA. The purpose of this and the next study is the determination of magmatic and metamorphic evolution, and geochronology of the OOC. Lherzolites contain Ol (55 vol. %), Opx (25 %) and Cpx (15 %). Anhedral Opx porphyroclasts have Cpx exsolution lamellae. Similarly, porphyroclastic Cpx contains Opx exsolution lamellae. Late magmatic Cpx and Opx aggregates ingrow the Ol matrix and porphyroclastic Px1 boundaries. Spinel is immersed in the Ol matrix. Harzburgites are composed of Ol (55 vol. %), Opx with Cpx exsolution lamellae (35 %), and Cpx with Opx exsolution lamellae (5 %) the latter following Ol-Opx boundaries. Spinel occurs in the form of anhedral grains. Dunites are rare. A remnant of the inferred gabbroic layer was identified from a borehole core and a few km-size gabbro-doleritic blocks within peridotites. These gabbros have ophitic texture and contains primary magmatic porphyric Pl, Cpx and green Amp1. Clinopyroxene and Amp1 are partially replaced by blue-green Amp2 aggregates and Chl. Plagioclase is weakly altered. Moreover, we found cross-cutting gabbroic (microgabbros, called dolerites, to gabbro-pegmatites) dykes, and dunite-associated troctolites in peridotite. These dykes have randomly oriented minerals, only locally showing mylonitization signatures. A basaltic dyke cross-cuts gabbro collected from a borehole core. Dolerites are composed of Cpx, Amp and Pl but we also found an Ol-bearing dolerite dyke cross-cutting peridotite. It has well preserved magmatic ophitic texture composed of Ol, Opx, Cpx, Amp, Pl, Ilm and Ap. Pyroxenes and amphiboles are weakly chloritized and Ol is serpentinized. Dolerites and basalts have an ophitic texture, defined by fine-grained prismatic Pl, Px and Amp. Secondary Amp2 and Chl follow the grain boundaries of magmatic minerals. Ophiolitic breccias cover some peridotite parts. These breccias contain 1 cm – 10 m size fragments of all lithological members of the OOC, including radiolarites. Gabbros from ophiolitic breccia have coarse grained Pl and Px. Exsolution lamellae in Px and their kink-banding are characteristic features from the subsolidus late-magmatic conditions. A rare plagiogranite intrusion in peridotite is composed of Qz, Pl and needle-like Amp aggregates after Bt. Such an association of ultrabasic and basic rocks have formed by a contribution of percolating gabbroic magmas through the peridotites at a higher lithosphere level, crystallizing Pl and Cpx. Amphibolites were found only at one locality so far, most likely indicating metamorphic sole of an ophiolitic thrust sheet. The preliminary results suggest at least two magmatic evolutional stages of the OOC, in the Spl and Pl stability field, respectively. Metamorphic overprinting is indicated by the newly formed Amp generations and an amphibolitic sole.

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Jurassic pelagic succession of NW Croatia – a key to better understanding tectonic setting of the Southern Alps – Dinarides transition zone

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Ivanščica Mt. is an inselberg in the transitional area where S-verging Southern Alpine structures overprint NNW-verging Dinaric structures (van Gelder et al., 2015, and references therein). It is composed of Triassic to Cretaceous shallow to deep-marine sedimentary succession of the Adriatic continental passive margin (Šimunić et al., 1976), overthrust by ophiolitic mélange (Babić et al., 2002). Early Cretaceous siliciclastic flysch-type deposits continuously overlaying pelagic limestones clearly indicates distal position of these successions on the continental margin. However, so far complete Jurassic succession on Mt. Ivanščica was never found, causing different interpretations of its Mesozoic history. Babić (1974) assumed the existence of Jurassic pelagic succession on top of the Late Triassic shallow-water carbonates, describing up to few meters of Early to Middle Jurassic condensed pelagic limestone overlain by Late Jurassic radiolarian cherts and pelagic limestones. Contrary, Šimunić et al. (1976) assumed shallow-marine conditions throughout the Early Jurassic followed by emersion until latest Jurassic. Our study revealed for the first time complete shallowwater to pelagic Jurassic succession on Mt. Ivanščica.

Southern slopes of Ivanščica Mt. are mostly built of ophiolitic mélange, except for prominent hills built of the Late Triassic Dachstein limestone, which were so far interpreted as klippes (Šimunić et al., 1976), or olistoliths (Babić and Zupanič, 1978). Our new data indicate continuous succession on top of Dachstein limestones composed of shallow-marine carbonates, represented by intraclasticpeloidal packstones to grainstones, gradually transitioning to wackestones with pelagic influence. The onset of pelagic sedimentation took place around the end of the Early Jurassic when thin bedded marls, shales, marly limestones with intercalated fine-grained calciturbidites were deposited. Higher in the succession Callovian to possibly early Tithonian radiolarian cherts are overlaid by calcarenites, late Tithonian to Early Cretaceous pelagic limestones and Early Cretaceous flysch-type deposits.

Discovery of the Jurassic pelagic sediments allows for a new interpretation of structural relations on the Ivanščica Mt. In our opinion occurrence of Dachstein limestone, previously interpreted as klippes or olistoliths represent an imbricate fan. Because the Southern Alps thrust front in this area was interpreted according to these mapped klippes and nappe contact, our findings may also have an impact on the redefining of the easternmost Southern Alps thrust front.

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The Albian/Cenomanian Boundary Event (OAE1d) reflected in ammonite-rich layers in central Serbia (Topola area)

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Occurrences of the Albian/Cenomanian Boundary Event (OAE1d, namely Breistroffer Level), reflected in a series of four distinct positive δ^{13}C excursions (peak in the latest Albian) are until now not described in Serbia even various associations of late Early Cretaceous ammonite faunas are known from several locations in central Serbia. These ammonite-bearing sedimentary rocks are exposed in the narrow belt of the Belgrade-Kosmaj-Topola-Gledić Mts. above shallow-water orbitolinid foraminifera-bearing limestones (carbonate ramp deposits).

Near village Kotraža (22 km SE of Topola) a roughly 20 m thick sedimentary succession of sand- and siltstones, marls and claystones with intercalated volcanic rocks and two distinct ammonite bearing horizons is preserved ("Stragari facies" in the Serbian literature). In the lower (roughly 11 m thick) and more coarse-grained part of the succession, beside belemnites, gastropods, and plant remains, a rich, but poor to moderately preserved ammonite fauna occur in slump deposits together with coarse eruptive volcanic material: *Kossmatella agassiziana*, *Puzosia (Puzosia) mayoriana*, *Mortoniceras (Subschloenbachia) perinflatum*, *Anisoceras perarmatum*, *Anisoceras* sp., *Idiohamites elegantulus*, *Mariella* sp., *Ostlingoceras cf. puzosianum*, and *Scaphites (Scaphites)* sp. The occurrence of *Praeschloenbachia perinflatum* indicates the Upper Albian *Mortoniceras perinflatum* Zone. Upsection a fining-upward trend indicates ongoing deeping of the depositional realm due to the stepwise sea-level rise from the late Albian onwards and the decease of the orbitolinid-bearing carbonate ramp. In the more fine-grained and slightly organic-rich silt to fine-sand layers approx. eight meters above the first ammonite-bearing level following ammonite fauna indicate the uppermost Albian to lowermost Cenomanian (*Arrhaphoceras briacensis* Zone or *Stoliczkaia dispar* Zone): *Phylloceras (Hypophylloceras) velledae*, *Kossmatella agassiziana*, *Puzosia (Puzosia) mayoriana*, *Beudanticeras* sp., *Mortoniceras* sp., *Stoliczkaia (Stoliczkaia) dispar*, *Mariella* sp., and *Scaphites (Scaphites)* sp.

Whereas in the Western Tethys Realm the latest Albian OEA1d is mainly characterized by the deposition of organic-rich fine-grained sediments, in central Serbia west of the Drina-Ivanjica continental realm more coarse-grained sediments were deposited. However, the occurrence of the younger ammonite-rich interval in slightly organic-rich sedimentary rocks mirror the global late Albian OAE1d, whereas the older ammonite-rich intervall is a precursor event associated with intense volcanic activity near to the study area. This intense volcanic activity led to the regional drowning of the shallow-water orbitolinid foraminifera-bearing carbonate ramp and creates relief as indicated by the slump deposits. It is proposed that in central Serbia regional and global events work in concert to form in the late Albian deeper-water environment ammonite-rich horizons, which have the potential for a correlation of late Albian events in the Dinarides and adjacent areas.

Acknowledgements: In the frame of the IGCP 710 „Western Tethys meets Eastern Tethys“.

Peak pressure estimates of Koralpe-Saualpe-Pohorje Complex based on Raman Spectroscopy

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The Koralpe-Saualpe-Pohorje Complex in the Eastern Alps represents a lithologically heterogenous (U)HP nappe with eclogite lenses embedded in gneissic and metasedimentary rocks. The aim of this project is to determine whether or not tectonic pressure occurred due to differences in viscosity of different lithologies. In this study we investigate in detail the P and T conditions during the formation of the Koralpe–Saualpe–Pohorje Complex along a NW-SE transect. In order to determine the P conditions, quartz inclusions in garnet are investigated with Raman spectroscopy (RSQI barometry). With Zr-in-rutile thermometry, the temperature conditions will be determined. Preliminary results show an overall residual P increase of the quartz inclusions from the northern Saualpe towards Pohorje in the South. The quartz inclusions inside garnet in eclogite show higher residual P with ≤ 0.72 GPa with respect to the ones in the metasedimentary or gneissic lithologies with ≤ 0.43 GPa. Elemental maps of garnets in eclogite from three locations show rather variable results with a significant variation of Ca and Mg content in the core, whereas the Mn content is general very low. The metasedimentary and gneissic garnets are predominantly much richer in Fe and show higher Mn with respect to the eclogites.

Tectonic and metamorphic record in the Badstub Formation, Carboniferous of Nötsch, Austroalpine

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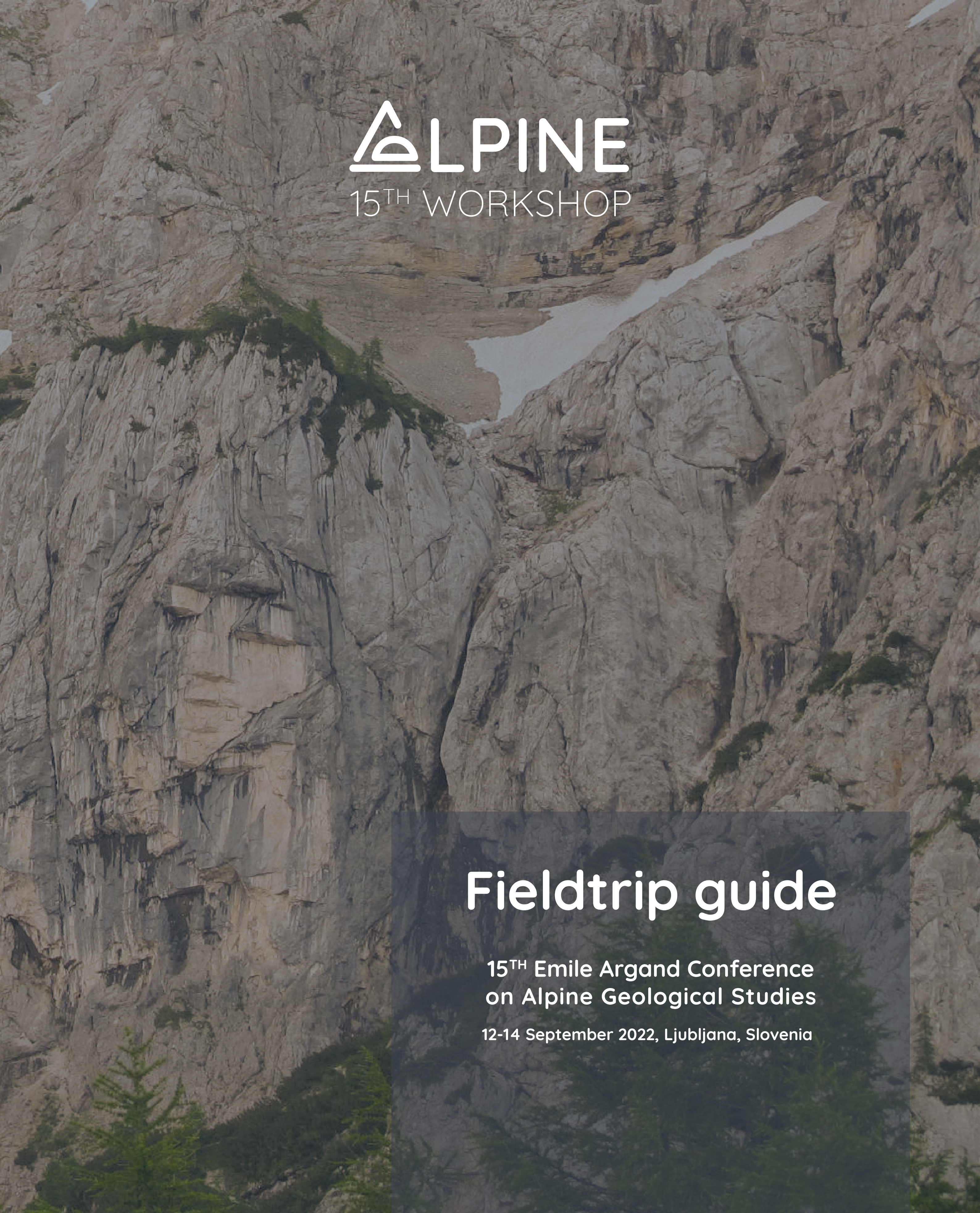
The Badstub Formation is part of the Carboniferous of Nötsch sedimentary sequence, of the Upper Austroalpine domain. This formation outcrops in Carinthia (Austria), a few kilometres north of the Periadriatic line (Gailtal line), where a sequence of various conglomerates and breccias with interbedded sandstones, siltstones, and fossiliferous carbonatic schists is exposed. These rocks preserve pristine sedimentary features and even an outstanding fossil record, but multi-scale structural analysis revealed a tectonitic foliation localized in fine-grained rocks, different sets of mineralized faults and veins, and corona textures. Vein fillings and coronas are characterized by equilibrium mineral assemblages that include prehnite, pumpellyite, chlorite, phengite, winchite, and riebeckite. Chlorite-thermometry and thermodynamic modelling on mineralized veins and coronas revealed PT conditions of 260-310 °C and 0.25-0.50 GPa and testify that the Badstub Formation recorded a metamorphic imprint characterized by a low temperature/depth ratio (≈15 °C km^{-1}). The comparison between a 2D thermo-mechanical numerical model and the metamorphic conditions inferred with thermodynamic models suggest that the Badstub Formation underwent a thermal state consistent with that of the Alpine subduction. These results provide the first quantitative pressure constraints on Alpine subduction metamorphism on the Austroalpine Carboniferous covers nearby the Periadriatic line. Thus, within the Upper Austroalpine nappe system, pre-Alpine rocks were involved into the Alpine subduction at different structural levels and under metamorphic conditions, which therefore span from eclogitic to prehnite-pumpellyite facies.

Ladinian halfgrabens above Ajdovska deklica in Mt. Prisojnik, Julian Alps
(Author: Boštjan Rožič)



ALPINE
15TH WORKSHOP

Fieldtrip guide

15TH Emile Argand Conference on Alpine Geological Studies

12-14 September 2022, Ljubljana, Slovenia

Adria margin of the Alpine-Dinaric transition area – sedimentary view and a structural glimpse

FIELDTRIP A

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Introduction

The entire region of western Slovenia is characterized by sedimentary rocks and sediments that reveal a long geologic history, stretching from the Devonian to the present, and documenting the late-Variscan and the entire Alpine orogenic cycle. Structurally, western Slovenia is marked by the Alpine-Dinaric transition zone. The Dinarides are characterized by the Late Eocene to Oligocene SW verging thrusts, while in the Southern Alps the S-verging thrusts overprint the previous. Neotectonic activity is dominated by NW-SE dextral striking strike-slip faults (Placer, 1998, 2008; Vrabec and Fodor, 2006) (Fig. 1).

In general, the oldest rocks occur in the northern part of the Southern Alps in the Karavanke (Karawanken) Mts., while the rocks become progressively younger towards the south. The Variscan cycle starts with Devonian passive margin carbonates dominated by Middle Devonian reef limestones, which pass upward and downward into the deep marine thin-bedded limestones with intercalations of fine clastics. In the Early Carboniferous, the deposition of flysch (Hochwipfel Fm) begins (Turnšek, 1970; Ramovš, 1993; Ramovš and Buser, 2009). After emergence (discontinuity), the extensive foreland basin was formed, and the Late Carboniferous to Early Permian is characterized by the deposition of a shallow-marine carbonate-siliciclastic sequence (Auernig, Schulterkofel, Dovžanova soteska, Born, Rigelj, Troghkofel fms) in the Southern Alps (STOP 1/1) (Novak, 2007; Novak and Skaberne, 2009) and by the deltaic-fluvial clastites in the Dinarides (Mlakar et al., 1993). The Middle Permian begins with carbonate breccias (Tarvis/Trbiž Breccia Fm) overlain by thick, mostly reddish/purple fluvial clastites (Val Gardena/Gröden Fm) (Skaberne, 2003; Skaberne et al., 2009). The thickness of this formation varies greatly, indicating intense normal faulting and marking the transition to the Alpine orogenic cycle.

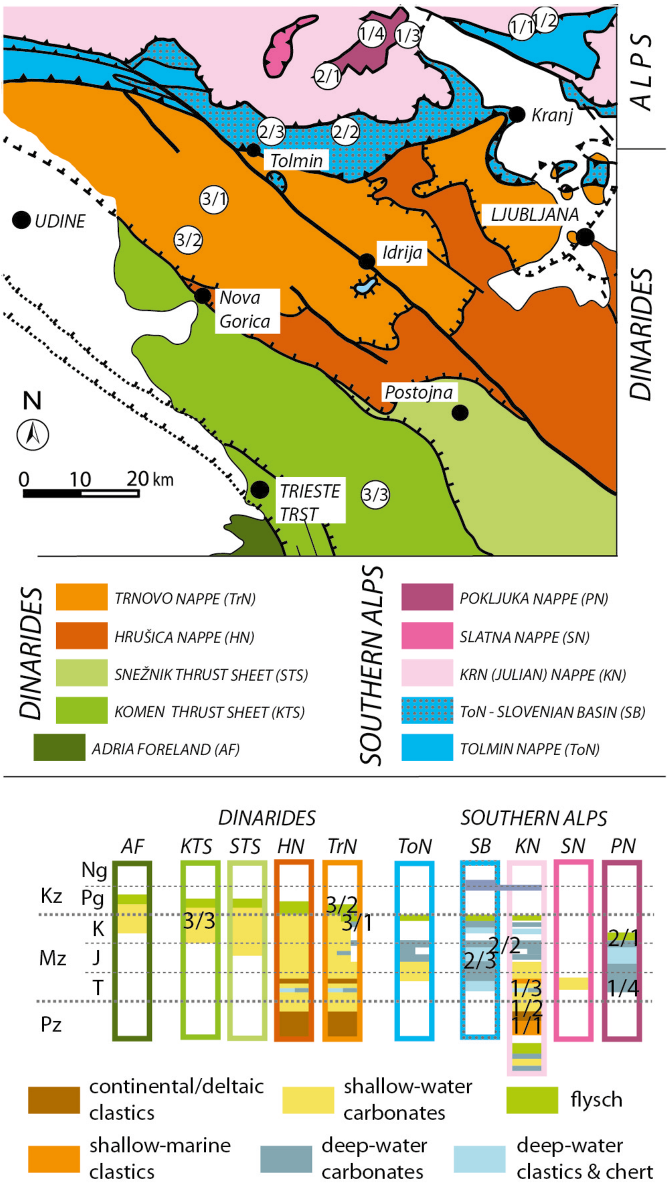

Figure 1: *Structural subdivision of western Slovenia (after Placer 1999 and Goričan et al., 2018) and generalized stratigraphic columns of the main thrust units. The structural distribution of the major Mesozoic paleogeographic units is as follows: Dinaric Carbonate Platform – AF, KTS, STS, HN, TrN and ToN, Slovenian Basin – SB, Julian Carbonate Platform – KN and SN, Bled Basin – PN.*

At the beginning of the Late Permian, the region is characterized by a marine transgression, and a long period of predominantly carbonate sedimentation begins (STOP 1/2). The Upper Permian of the Southern Alps is dolomitic (Karavanke Fm) and calcareous in the Dinarides (Žažar Fm), overlain by Lower Triassic mixed siliciclastic-carbonate marine deposits (Werfen Fm) that change to pure carbonates in the Anisian (Buser, 1989, 1996; Skaberne and Ogorelec, 2003). This broad shelf area, known locally as the Slovenian Carbonate Platform, begins to disintegrate already in the Anisian, with the formation of small-scale basins dominated by deeper marine (Ljubelj Fm), often organic-rich (Strelovec Fm), or condensed carbonates (Han Bulog-type) (Buser, 1996; Miklavc et al., 2016; Celarc et al., 2013; Gale et al., 2022). In the locally uplifted areas of the Dinarides, erosion leads to stratigraphic gaps and the development of fluvial-deltaic (Stopnik conglomerate) or marsh (lower Skonca beds) sediments (Čar and Skaberne, 2003; Čar, 2010).

The Ladinian is marked by an extensive paleogeographic reorganisation of the region, related to the opening of the Neotethys Ocean. As a result of intense normal faulting and volcanic activity, laterally highly variable rocks were formed. Deep marine clastic, volcanic, siliciclastic, and carbonate successions were deposited in the subsided areas (Pseudozilian beds) (Buser, 1996; Dozet and Buser, 2009). At the same time, a platform carbonate continued to be deposited in the less subsided areas (Schlern Fm), while calcareous-volcaniclastic sediments (Buchenstein Fm) and volcanics (e.g. Rio Fredo/Mrzla reka Riolite) developed in smaller intraplatform basins (Celarc et al., 2013), while the half-grabens were characterised by coarse carbonate clastics (STOP 1/3) (Ukve/Uggovizza Breccia Fm). In the Dinarides, a synsedimentary Idria Hg ore originated (upper Skonca beds) (Čar, 1990, 2010, 2013).

Towards the end of the Ladinian, rifting events ceased and platforms prograded over small-scale basins (Šmuc and Čar, 2002; Skaberne et al., 2003; Celarc et al., 2013). Two major carbonate platforms were formed, the Dinaric (Adriatic, Friuli) Carbonate Platform (DCP), now found in the Dinarides, and the Julian Carbonate Platform (JCP) of the Southern Alps. In contrast, the most subsided areas remained deep-marine until the end of the Mesozoic (Cousin, 1981; Buser, 1989, 1996). We divide them into two main paleogeographic units: A) the Bled Basin (BB) was on the ocean side of the JCP; and B) the Slovenian Basin (SB) was between the DCP and the JCP. Today, the SB, BB, and JKP deposits are found in different nappes of the eastern Southern Alps. BB forms the structurally highest Pokljuka Nappe, JCP the middle Slatna and Krn nappes, and the SB the lowermost Tolmin nappe (STOP 2/2) (Placer, 1998; Goričan et al., 2018). The BB succession is characterized by carbonates (STOP 1/4) (Zatrnik, Biancone fms) with the exception of Middle – Upper Jurassic radiolarites and replaced by flysch already in the Valanginian (STOP 2/1) (Studor Fm) (Kukoč et al., 2012; Goričan et al., 2018; Gale et al., 2019, 2021).

The JCP is characterized by the Upper Triassic platform, which is reef-rimmed and loferitic in the inner parts (Razor, Main Dolomite, Dachstein Limestone fms) with marl-rich Tor/Tamar Fm documenting the Carnian Pluvial Event (Turnšek and Buser, 1991; Ogorelec and Buser, 1996; Turnšek, 1997; Dozet and Buser, 2009; Ogorelec, 2011; Gale et al., 2013). The thick carbonate succession that characterizes the Julian and Kamnik – Savinja Alps intermits at the drowning unconformity near the Carnian/Norian boundary (Celarc et al., 2008, 2014). Deep-marine carbonates are thin in much of the JCP, (Martuljek Fm) and carbonate reinstallation is rapid, while in the NW part the longer lived Trbiž/Travisio basin was formed (Krnica/Carnizza, Bača Dolomite, Dovška Baba/Frauenkogel, Klek/Hahnkogel fms) (Gale et al., 2015). The JCP remained shallow marine in the Lower Jurassic when it disintegrated due to the opening of the Alpine Tethys (Buser, 1996; Šmuc, 2005; Rožič et al., 2014). On the western margin of the drowned JCP, the Bovec Basin was formed. It is characterized by Jurassic basinal marls (Skrile Fm), (hemi)pelagic and resedimented limestones (Travnik, Biancone fms). The central part of the drowned JCP turned into a submarine plateau, named the Julian High, characterized mainly by condensed carbonates with numerous long-lasting unconformities (Prehodavci, Biancone, “Scaglia” fms) (Jurkovšek et al., 1988; Šmuc, 2005; Šmuc and Goričan, 2005; Šmuc and Rožič, 2010).

The SB succession begins with Carnian sandstone, breccias, calcarenite (resedimented limestone), and marls (Amphiclina beds) (Buser, 1996; Gale et al., 2016). Upward, gravity-flow deposits are dominated by carbonates, while (hemi)pelagic interbeds vary from carbonates (STOP 2/3) (Bača Dolomite, Slatnik, Krikov, Biancone, Volče fms), marlstones (Perbla, Lower Flyschoid fms), and radiolarites (Tolmin Fm) (Cousin, 1981; Buser, 1996; Rožič, 2005, 2009; Gale, 2010; Goričan et al., 2012a,b). Resedimented limestones were shed from both platforms until the end of the Pliensbachian, whereas after the disintegration and drowning of the JCP, the northern parts of the basin became dominated by pelagites (Rožič, 2009; Rožič et al., 2009, 2017, 2018). The transition to flysch sedimentation occurred at the end of the Cretaceous (Upper Flyschoid Fm) (Buser, 1996).

The DCP documents the emersion phase at the beginning of the Carnian (Celarc, 2008). The unconformity is overlain by alternating fluvial clastic and shallow marine limestone sedimentation (“Raibl beds”) (Jelen, 1990; Čar, 2010), followed by a long, continuous deposition of carbonates (STOP 3/3) (Triassic Main Dolomite/Dachstein Limestone fms, Jurassic Podbukovje, Laze, Šentrumar, “Reef Limestone” fms, Cretaceous Brje, Povir, Repen, Sežana, Lipica fms, end-Cretaceous – Paleogene Liburnia, Trstelj, Alveolinid-Nummulitid Limestone fms) (Buser, 1996; Dozet and Strohmenger, 2000; Otoničar, 2007; Dozet and Buser, 2009; Buser and Dozet, 2009; Jurkovšek et al., 2013; Jež and Otoničar, 2018). The turn to flysch deposition occurs first in the northeastern part of the DCP at the end of the Cretaceous (STOP 3/1) and becomes progressively younger towards southwest due to a propagating thrust belt (STOP 3/2), with the youngest, i.e. Eocene (Lutetian) flysch found on the Slovenian coast (Pavšič, 1994; Pavšič and Peckmann, 1996; Buser, 1996; Drobne et al., 2009).

Post-thrusting subsidence occurred already in the Oligocene in the central and eastern parts of present-day Slovenia, including the Ljubljana field, characterised by two pulses. Oligocene subsidence begins with sedimentation of coarse fluvial deposits (Škofja Loka conglomerate), followed by a pronounced transgression (Gornji grad, "Sivica", Govce fms) accompanied by volcanic activity (Smrekovec Volcanic Complex). After the unconformity, the middle Miocene transgression is documented (Laško, Dol fms), followed by lacustrine sediments of the Upper Miocene and Pliocene (Aničić et al., 2002; Jelen et al., 2008; Pavšič and Horvat, 2009; Kralj, 2009; see also Fieldtrip guide for excursion B in this volume). The Quaternary is characterised by fluvial and glacial sedimentation (Markič, 2009; Bavec and Pohar, 2009).

Figure 2: The localities of the Dovžanova soteska section (STOP 1/1) and Košutnik potok section (STOP 1/2).

DAY 1, STOP 1/1 – DOVŽANOVA SOTESKA: Variscan marine molasse

The Dovžanova soteska (Dovžan's gorge), NE of the town of Tržič, also known as Teufelsschlucht (Devil's Gorge) in German-language literature, is a scenic north-south trending valley of the Tržiška Bistrica river, which cuts deep into the southern slopes of the Karavanke Mountains and exposes a long section of fossil-rich Late Carboniferous to Middle Permian succession. Generally, beds dip steeply toward the southwest and are therefore gradually older from the village of Čadovlje pri Tržiču through the lower entrance of the road tunnel upwards to the village of Zg. Dolina (Fig. 2). In this guide book the section is described as complete lithostratigraphic successions, which is necessary to explain the sedimentary history. However, due to difficult access on these steep slopes, only parts of the succession along the 2 km section of road can be seen (Fig. 3).

Facies association and (micro)facies characteristics indicate that Gzhelian beds were deposited over the entire Karavanke Mts. area on a platform with a gently steeping ramp configuration. A clear cyclic transgressive-regressive depositional pattern can be recognised in the siliciclastic-carbonate sedimentary succession, consistent with the idealised model of the so-called Auernig cyclothem (Kahler, 1955; Krainer, 1992) in the similarly developed stratotype sections of Gzhelian Auernig and Schulterkofel formations in the Carnic Alps (Austria/Italy). Coarse-grained fluvial, coastal and/or fan-deltaic conglomerates alternate with finer-grained sandstones and bioturbated siltstones, deposited under the strong influence of storm events in the lower shoreface setting and with limestone horizons mainly related to algal mound buildups in the offshore setting below the storm wave base (Novak, 2007).

Both high frequency and high amplitude of sea-level changes, recorded in the Late Paleozoic sedimentary successions on a global scale caused considerable shifts of the coastal line due to the flat topography and the gentle angle of ramp inclination (Massari and Venturini, 1990; Samankassou, 1997). In the Early Perm-

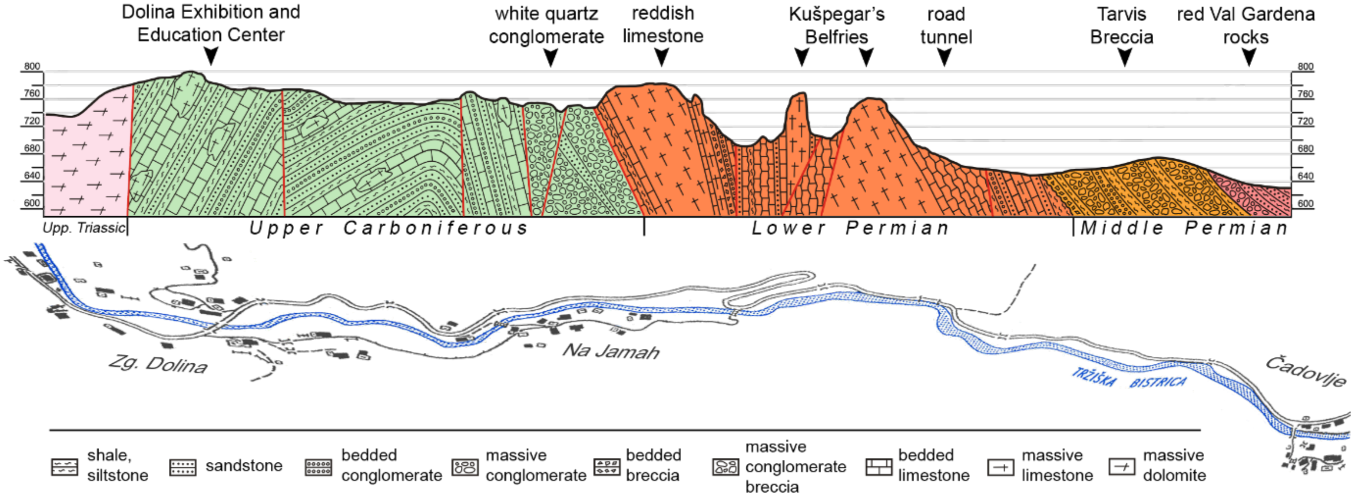

Figure 3: Dovžanova soteska section along the road from Čadovlje to Zg. Dolina exposes the most complete section of shallow-marine fossil-rich Late Paleozoic beds in the Karavanke Mts. (sketch: M. Novak)

ian, a prominent differentiation of the platform morphology is recorded in the Karavanke Mts. It is marked by the formation, drowning, reestablishment, and final subaerial exposure of a larger reef mound in the Dovžanova soteska area, while in other parts of the Karavanke Mts. predominantly siliciclastic sedimentation continued.

The lowermost part of the Permian beds of the Dovžanova Soteska Formation (Buser and Forke, 1996; Forke, 2002) reflects a rapid transgression with a progressive increase of carbonate content within the clastic sequence. It is followed by the gradual transition from dark bedded limestones to a light grey to pale red massive Dovžanova Soteska Limestone body. Since it is built of fragmented bioclasts in a micritic matrix, bounded only with *Tubiphytes*, bryozoans, algae, and small sessile foraminifers we can refer to it as a reef (or skeletal) mound. The bioclastic packstone to microbreccia, composed of fragmented allochthonous reef mound derived debris in the upper part of Dovžanova Soteska Limestone, represents the reef-flank facies deposited in the forereef facies belt and suggests a substantial topographic relief and the rigidity of the reef mound body (Stanton and Pray, 2004).

The following horizon, composed of deeper-water calcareous siltstones, marlstones, and thin-bedded marly limestones speaks for the short-term drowning of the reef complex prior to the deposition of red bedded crinoidal limestones with a rich and diverse shallow-water biotic association. Red stained silty crusts capping almost every limestone bed represent omission surfaces of the hardground type. The uppermost part of the Dovžanova Soteska Formation is marked by the reestablishment of reef growth, this time with strong marine cementation, suggesting steep slope inclination. The described development of the Dovžanova Soteska Formation with drowning event, restored reefal sedimentation, and intermediate tongue of deeper-water and upper-slope facies correlates with the description of a back-stepping reef with a landward shift of carbonate production during an episode of relative sea-level rise (Reading, 1996).

Basal quartz conglomerates of the Born Formation cut into uppermost beds of red limestone with erosional unconformity. A clear erosional surface and features like calcareous pisoids and infillings of vadose silt in the topmost limestones of the Dovžanova Soteska Formation suggest that the reef sedimentation was terminated as result of subaerial exposure (Forke, 2002). During the following transgression, the sedimentary depocentre migrated towards the open-marine inner platform. The alternation of black bedded bioclastic grain- to packstones, biocalcarenites, oolites, sandy limestones and quartz sandstones with shallow-water benthos in the Born Formation indicates deposition in an open lagoonal setting repeatedly affected by the sedimentary influx from platform-margin oolitic and sand shoals. Some of the mixed carbonate-siliciclastic rocks (e.g. paraconglomerates) display characteristics typical of the debris flow deposits (Novak, 2007). One of the rocky pyramids is built of massive light grey micritic limestone forming an isolated patch-reef with colonies of rugose corals.

The youngest Lower Permian succession of the Rigelj Formation (Novak and Krainer, 2022) indicates a gradual shift of the facies belts from high energy coast through open-marine lagoon towards the shallow-marine and shelf edge. In the transitional coastal belt, conglomerates, sandstones, and oolitic limestones were deposited. Black bedded algal limestones with clay shale intercalations were formed in the inner-shelf environment. Reef limestones and calcareous breccias mark the shelf edge setting. Black limestones with highly diverse biota and oncoids of the upper part of the Rigelj Formation suggest a shift of facies belts back into the open-marine lagoon. A substantial amount of fine-grained, well-rounded quartz pebbles in several limestone beds indicates periodical terrigenous influx from a distant hinterland. The regressive trend continues with the deposition of sandstones and calcitic siltstones in a high-energy shoreface setting.

Based on the facies relationships in the succession of Upper Paleozoic rocks in the Karavanke Mts., a change in platform morphology can be suggested. In the Dovžanova soteska area, a gently steeping ramp without both the marginal barrier and the shelf break in the basinward direction developed into a rimmed shelf with steeper slope as result of lateral and vertical accretion in response to numerous relative sea-level changes. During periods of sea-level stillstands or slow rises the reef mound on the platform margin rapidly prograded, while as a response to periods of rapid sea-level rises the initial drowning and back-stepping event gave way to vertical accretion and steeper slope angle (Reading, 1996). A similar platform evolution has been suggested in many sedimentary basins in different geologic periods.

A more detailed description of the succession with historical background, facies descriptions, and biostratigraphic data is given in Novak et al. (2019).

DAY 1, STOP 1/2 – KOŠUTNIKOV POTOK: Slovenian Carbonate Platform

In the Košutnikov potok (Košutnik Creek) section near Medvodje (Fig. 2), a continuous stratigraphic succession from the Middle Permian (Val Gardena/Gröden Fm), across the P/T boundary, to Anisian beds is exposed. The Middle Permian Val Gardena Formation of mostly fluvial origin is overlain by an Upper Permian carbonate sequence 270 m thick that was named the Karavanke Formation (Buser et al., 1988). The basal unit of this sequence is represented by an evaporitic facies up to 70 m thick composed of cellular dolomite (rauhwacke) with layers of cellular dolomitic breccia containing clasts of Val Gardena clastics. It alternates with thin black bituminous shales and grey vuggy dolomites. In the lower part of the basal unit, only in the Košutnik Creek, a 1.5 m thick sequence of well bedded black bituminous biomicritic limestone was found. According to Buser (1974, 1980) it contains tiny sulphur geodes, *Bellerophon* gastropods and numerous microfossils (*Gymnocodium bellerophontis*, *Permocalculus fragilis*, *Mizzia velebitana*, and *Glomospira* sp.) that prove the Late Permian age of the Karavanke Formation. The evaporitic sequence is overlain by a thick succession (up to 200 m) of fossiliferous biomicritic dolomites, deposited in an open lagoon and shallow shelf environment (Dolenec et al., 1981). The Late Permian age of these beds is indicated by calcareous algal assemblages (*Mizzia cornuta*, *Permocalculus* sp., *Connexia* sp.), as well as by very common small foraminifers which belong to *Glomospira* sp., *Agathammina* sp., and *Hemigordius* sp. (Ramovš, 1986).

The biostratigraphic and lithostratigraphic boundary between the Upper Permian Karavanke Formation and the Lower Triassic Werfen Formation is transitional, and no exact line can be drawn between them (Dolenec et al., 1998). The P/T boundary is placed arbitrarily at the end of the sedimentation of the well bedded grey dolomicrite. It is followed by a red coloured, more or less terrigenous sequence predominantly composed of well bedded and laminated siltstones, mudstones, and sandstones, alternating with micritic dolomites that contain no characteristic fossils. The sequence was deposited in a very shallow evaporitic restricted shelf, into which abundant terrigenous material was transported (Dolenec et al., 1981), and is about 5 m thick. These beds are overlain by mostly dark grey and brown micritic and sparitic limestones intercalated with ooid limestone, marlstones and shales. Ooid limestone contains frequent small gastropods and corresponds to the limestone of the Tesero Member of Werfen Formation. (Buser, 1974; Buser et al., 1988). In Košutnik Creek, the P/T contact is tectonic (Fig. 4). About 70 to 80 m below the P/T boundary a porphyrite dyke of Middle Triassic (Ladinian) age cuts the Upper Permian beds.

The Permian/Triassic boundary in the Southern Karavanke Mts. was the object of a stable isotope composition study in the Košutnikov potok and at Brsnina sections (Dolenec et al., 1998, 1999). In both sections, the transition from Upper Permian to Lower Triassic is characterized by a major abrupt shift in carbonate carbon δ^{13}C and δ^{18}O from heavier to lighter values (Fig. 5). The data suggests that the carbon isotope variability at the P/T boundary reflects global changes in the carbon cycle and/or climate changes, probably controlled by the Late Permian regression and further eustatic oscillations of the Tethys sea-level and by tectonics (Dolenec et al., 1998). At Brsnina, about 1.6 km to the east of the Košutnik section, the P/T boundary is exposed in an undisturbed section and represented by a sharp, not erosional, contact that consists of a clay layer (PTB clay layer) with a maximum thickness of 1 cm. It shows a characteristic magnetic susceptibility pulse and considerable enrichment in most minor and trace elements (Dolenec, 2005). The dolomite beds of the Karavanke Formation are enriched with the light carbon isotope by 4 ‰, and at the boundary the Th/U ratio also increases. The data indicates an oxic event at the P/T transition, which coincides with the terminal phase of the Late Permian marine regression (Dolenec, 2005).

Fig. 4: *Košutnikov potok section exposes the P/T fault contact between the Karavanke and the Werfen formations (photo: M. Novak).*

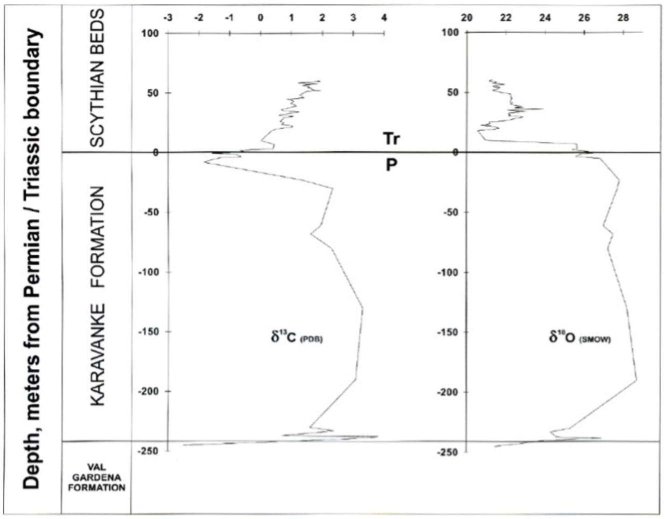

Fig. 5: *δ^{13}C and δ^{18}O data of the Košutnikov potok section (from Dolenec et al., 2005).*

DAY 1, STOP 1/3 – BLED: Ladinian rifting event

Indirect evidence of a late Anisian – early Ladinian extensional event related to the Neotethys rifting is found on the Ojstrica hill on the western edge of Lake Bled (Fig. 6). This extensional event resulted in widespread fragmentation of the entire region, creating the large Slovenian Basin and numerous short-lived basins next to it. The Ojstrica hill is made up of coarse breccias deposited in a small-scale (half)graben (Fig. 7). The base of the studied sequence consists of the shallow-marine Anisian dolomite. This dolomite-dominated formation may laterally pass into limestone (an example of which is the Bled Caste mound), characterized by calcimicrobial grains and crusts (Flügel et al., 1994; Ogorelec, 2011).

The Anisian dolomite is overlain by 6 m of Ladinian volcanic rocks (riolite and pelitic tuff), showing that the extensional event was accompanied by volcanic activity. The uppermost part of the Ojstrica hill consists of differently coloured Ukve/Uggovizza Breccia 45 m thick, in which bedding is visible in the lowest 10 m. Breccia is composed of centimetre-sized clasts and

Figure 6: Locations of the Ojstrica hill (STOP 1/3) ana Pokljuška soteska (STOP 1/4).

usually has a reddish coloured matrix. The uppermost part of the formation is more coarse-grained. The clasts can reach up to several metres in size and the matrix is usually grey. The clasts are almost invariably carbonates, mostly limestones. The composition and age of the rocks vary widely but can be assigned to underlying formations (Permian Neoschwagerina Limestone, Lower Triassic Werfen, and Anisian dolomite/limestone fms). Since all these formations outcrop in the immediate vicinity of the Ojstrica Hill, the clasts are of rather local origin.

Despite the limited outcrops of the Ukve/Uggovizza breccia on the Ojstrica hill, we assume that the sedimentary basin was a rather small (half) graben, which was quickly filled up with coarse-grained local carbonate material. Above, the carbonate platform reinstalled quickly, and shallow marine limestones of the Schlern Formation were deposited in the Late Ladinian and Early Carnian. In the Bled area these were diagenetically altered

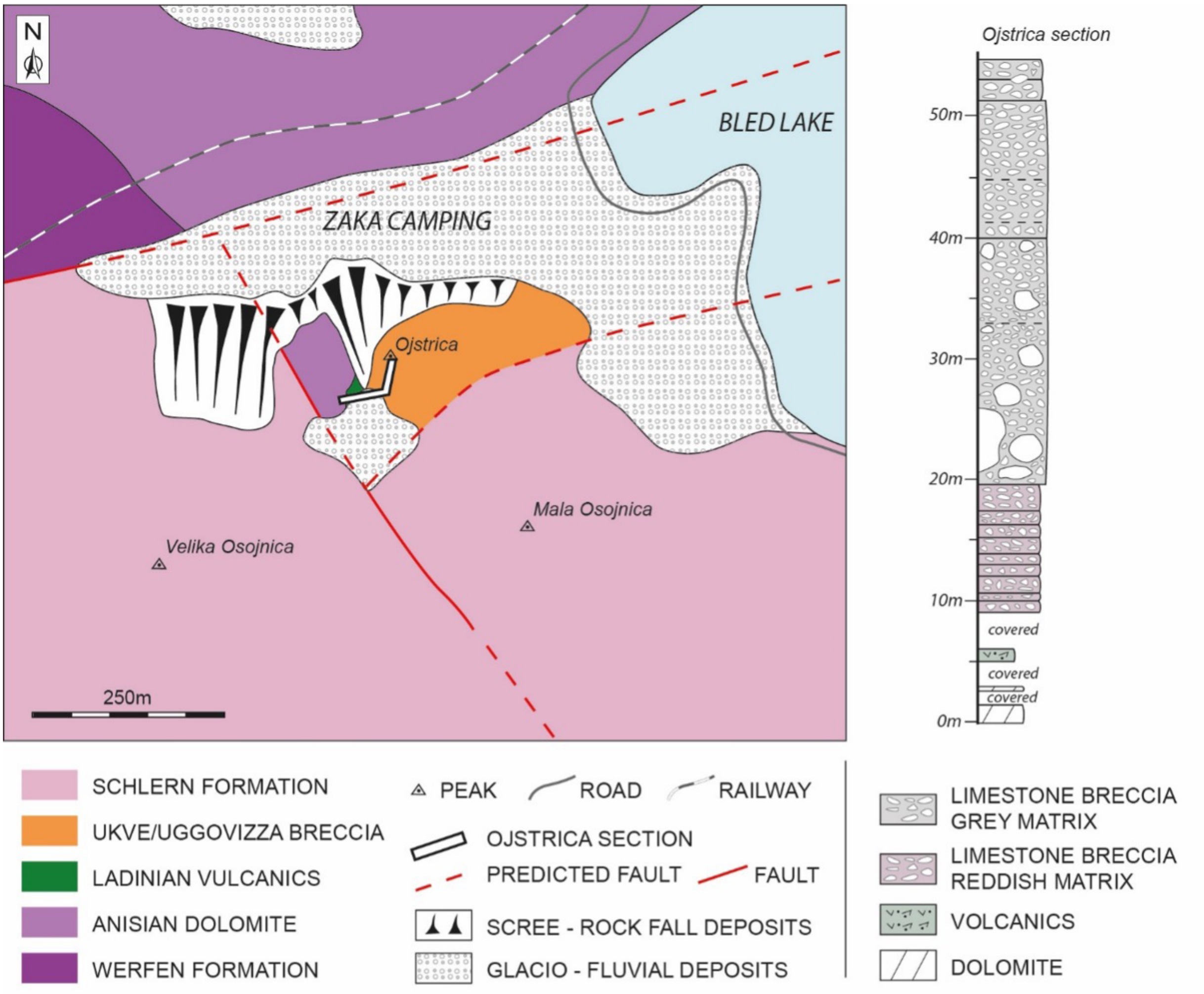

Figure 7: Detailed geologic map and stratigraphic column of the Ojstrica hill: the Ukve/Uggovizza breccia, deposited in a small (half) graben, reaches a thickness of 45 m and is in stratigraphic contact with the underlying sequence and in fault contact with the overlying sequence; however, according to regional data, probably passes upward into carbonates of the Schlern Formation, which is due to late Ladinian platform progradation.

to coarsely crystalline saharoid dolomite. Halfgrabes with a similar sedimentary record are well known from other localities in the Julian and Kamnik-Savinja Alps (Celarc et al., 2013).

DAY 1, STOP 1/4 – POKLJUŠKA SOTESKA: Upper Triassic Bled Basin

The uppermost Ladinian – Lower Cretaceous formations that make up the Pokljuka Nappe between Lakes Bled and Bohinj comprise slope and basin floor sediments. For a long time, these sediments were considered to have been deposited in a shallower side-branch (embayment) of the Slovenian Basin (Buser, 1989, 1996). However, the Pokljuka Nappe is now considered to derive from the distal part of the continental shelf, for which the name Bled Basin has been proposed (Cousin, 1981; Kukoč et al., 2012; Goričan et al., 2018). The succession of the Bled Basin starts with an interchange of Ladinian (perhaps already upper Anisian?) micritic limestone, tuff, and volcanics (Buser, 1980), equivalent to the Buchenstein Formation in the Southern Alps (Fig. 8). The same or similar formation occurs also in other parts of the Julian and Kamnik-Savinja Alps, perhaps also in the Dinarides area (e.g. Kolar-Jurkovšek et al., 1983), suggesting palaeotopography with numerous smaller basins separated by platforms. While prograding platforms sealed off most of the smaller basins (e.g. Skaberne et al., 2003), basinal sedimentation continued in the Bled Basin with the deposition of the Zatrnik (or Pokljuka) Formation. A typical lithology of this formation is bedded limestone with chert (Diener, 1884; Härtel, 1920; Budkovič, 1978; Cousin, 1981; Buser, 1986), but some considerable differences can be noted between different parts of the formation. The lowermost, upper Ladinian part is dominated by thin- to medium-bedded bioclastic wackestone and radiolarian-peloid packstone. Distal calciturbidites with peloids, micritic intraclasts, fragments of sponges, and microproblematica dominate in the Carnian part of the succession. Thicker beds of micritic limestone with chert nodules, sporadically interchanging with calciturbidites, become dominant at the transition into the Norian (Gale et al., 2019). In the upper part of the formation, dated as Lower Jurassic, pinkish calciturbidites rich in echinoderms and thin-shelled bivalves are the typical lithology of the Zatrnik Formation (Gale et al., 2022). Slumping is common in all parts of the formation, but is probably more intense in its uppermost part (Kukoč et al., 2012; Gale et al., 2019, 2021). The Zatrnik Formation is followed by Pliensbachian calcarenites and breccias of the Ribnica Breccia unit (the rest of the succession is described in STOP 2/1).

Although the aspect of the Zatrnik Formation varies, the largest part of it consists of medium-bedded micritic limestone with chert nodules. Stop 1/4 is in a natural amphitheatre of the Pokljuka Gorge (Fig. 6), a dry gorge formed at the beginning of the Holocene by the waters running from a retreating glacier. Norian age of the limestone was proven here on the basis of conodont elements.

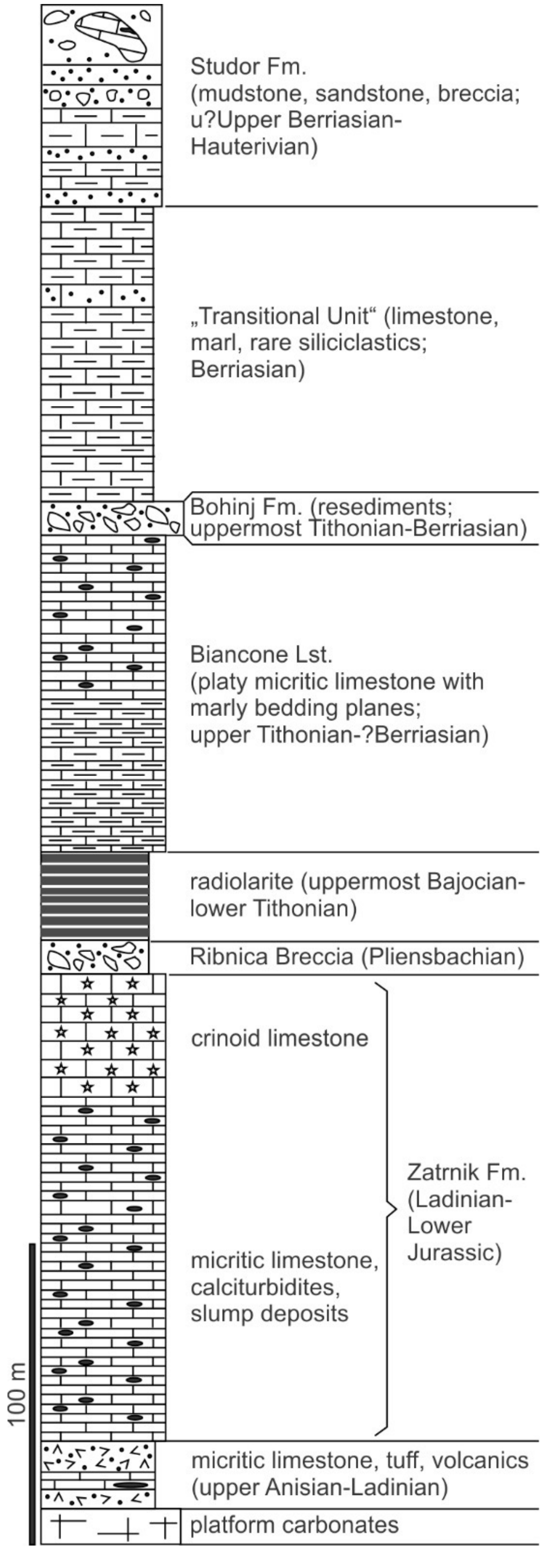

Figure 8: *Generalized succession of the Bled basin with the Pokljuška soteska section positioned in the lower part of the Zatrnik Formation (Gale et al., 2012; modified from Goričan et al., 2018).*

DAY 2, STOP 2/1 – STUDOR: Oldest Alpine Flysch

Along the road from Srednja vas to Uskovnica in the Bohinj area the topmost part of the Bled Basin succession is exposed (Fig. 9). It consists of the Biancone Limestone, Bohinj Breccia, and Studor formations, the latter representing the oldest Alpine flysch deposits in western Slovenia. Tithonian to Lower Cretaceous Biancone Limestone overlies Bajocian to Tithonian radiolarian cherts. It is represented by a succession of pelagic limestone approximately a 100 m thick, of which only the uppermost part is exposed at this locality. It is characterized by thin- to medium-bedded light grey to white limestone with discontinuous beds of dark-grey chert and irregularly shaped chert nodules. Intercalations of marl are also present. The predominant microfacies are radiolarian-rich wackestone and packstone. Parallel lamination is present in some layers. In places, normally graded calcarenites occur as several intercalations centimeters thick in micrite beds and contain intraclasts of wackestone with radiolarians and chert clasts up to 5 mm in the basal part. Radiolarians extracted from the Biancone limestone indicate a latest Tithonian to earliest Berriasian age (Kukoč et al., 2012).

Carbonate gravity flow deposits consist of 3 m of carbonate breccia and 4 m of calcarenite and are called the Bohinj Formation (Kukoč et al., 2012). Slump folds are present in the breccia. The calcarenite is massive and shows no internal folding or bedding. The breccia consists primarily of matrix-supported angular to subangular shallow-water carbonate clasts up to 2 cm in diameter. The matrix is radiolarian-rich lime mudstone with sponge spicules and scarce calpionellids. Most of the limestone clasts are bioclastic grainstones and bioclastic-peloidal packstones. Clasts of algal wackestone and oncoid packstone are present but rare. Intraclasts of pelagic calpionellid wackestone with sponge spicules and rare planktonic foraminifers are also present. Single bioclasts are common and include fragments of algae, sponges, bryozoans, echinoderms, and thick-shelled bivalves. Well-developed concentric and radial ooids and oncoids are present as isolated grains. Rare chert grains and lithic grains of igneous origin, including basalt, also occur in the breccia.

Figure 9: Locations of Studor (STOP 2/1) and Podbrdo (STOP 2/2).

Calcarenite is predominantly composed of shallow-water skeletal fragments and lithoclasts similar to those found in the breccia. Lithic grains of igneous origin, grains of chert, and opaque grains are present but less abundant than the carbonate components.

The microfacies analysis reveals that the main source area of the resedimented limestone was a penecontemporaneous carbonate platform. This platform (named the Bohinj Carbonate Platform by Kukoč et al., 2012) may have developed on top of a nappe stack, which formed during the early emplacement of the internal Dinaric units onto the continental margin. Grains of basalt indicate ophiolitic origin.

Reddish siliceous limestone similar to the Biancone limestone, from which it differs with its higher proportion of marl and red colour, is found above the Bohinj Formation at this locality. Latest Tithonian to early Valanginian age of this limestone is inferred based on radiolarians (Kukoč et al., 2012).

Mixed carbonate-siliciclastic deposits called the Studor Formation (Kukoč, 2014; Goričan et al., 2018) are exposed in the Vrčica Gorge (Fig. 10). Owing to its lithological characteristics the Studor Formation represents a unique and easily distinguishable lithostratigraphic unit in the wider area and is considered the oldest body of Alpine flysch-type deposits in Slovenia.

The formation starts with beds of light gray radiolarian wackestone/packstone 5–10 cm thick intercalated with thin-bedded sandstone, which is less frequent in the lower part of the formation. Calcarenite beds are rare. Micrite beds contain chert in places. In the upper part of the formation proportion of marl is higher and micrite and calcarenite beds become subordinate to sandstone. The sandstone beds in this part are up to 1 m thick. Horizontal and cross lamination is observed. The uppermost part of the formation is composed of two olistostrome layers composed of centimeter- to meter-sized blocks of different lithologies in a dark gray sandy matrix. Laminated micritic limestone with radiolarians (Biancone facies) prevails among these olistolithes. Carbonate breccia with limestone and chert clasts is also present, as well as smaller, decimeter-sized clasts of dark green and red chert.

Carbonate lithic grains represent approximately 40 % of all lithic grains in sandstone. For the most part, those are small micrite grains, however larger grains of peloidal and bioclastic grainstone and packstone also occur. Isolated bioclasts and echinoderm fragments are rare. Non-carbonate components predominantly include fragments of mafic rocks. Grains of basalts predominate, with grains of serpentinite, chert, amphibolite, phyllites, quartzite, granitoid rocks, and quartz sandstone are also present. Quartz grains represent approximately 10–20 % of grains and are mostly monocrystalline; however, polycrystalline quartz of metamorphic origin also occurs. Heavy minerals make up less than 10 % of all grains. Matrix of sandstone is micritic with an admixture of a clay component.

The composition of the sandstone indicates a composite source of material. Shallow-water carbonate clasts, especially isolated bioclasts, indicate the proximity of an active carbonate platform, while siliciclastic admixtures indicate the erosion of ophiolites and underlying metamorphic soles.

Radiolarians from the lower part of the Studor Formation are assigned to a relatively broad range from the latest Tithonian–earliest Berriasian to the latest Valanginian–earliest Hauterivian due to poor preservation (Kukoč, 2014). The Valanginian – Hauterivian age of the Studor Formation was previously determined using nannoplankton (Buser et al., 1979), but the exact position of the dated sample within the described section is not known.

DAY 2, STOP 2/2 – BOHINJSKA BISTRICA – PODBRDO RAILWAY TUNNEL:

Thrust structure of the Southern Alps

The eastern part of the Southern Alps is composed of four major nappes. The lowest is the Tolmin Nappe, which is in the upwards direction followed by the Krn (Julian), Slatna, and Pokljuka nappes. The Tolmin Nappe consists of Slovenian Basin successions. It is generally divided into three lower-order nappes, the lowest Podmelec, the middle Rut, and the highest Kobla nappes. The major part of the Southern Alps is composed of the next two nappes, both composed of the Julian Carbonate Platform successions. The Krn Nappe consists of rather continuous late Paleozoic to Early Jurassic shallow-marine carbonate, and a subordinate clastic succession, with two deeper marine intervals: rifting-related Ladinian and eustatic at the Carnian/Norian boundary. Within the Krn Nappe sporadic, locally occurring, post-drowning mid-Jurassic and Cretaceous deeper marine sediments (Ammonitico Rosso, Biancone, Scaglia facies) occur. Next is the Slatna Nappe, which forms the highest peaks of the Julian Alps, including Mt Triglav, and is composed solely of the Middle – Upper Triassic (Ladinian – Carnian) massive carbonates. The topmost Pokljuka Nappe is composed of the Bled Basin succession that originated out of the outer, i.e. oceanward side of the Julian Carbonate Platform. It is composed of Ladinian to Early Cretaceous deep marine sediments (STOP 1/4), including the oldest Alpine flysch in this part of the Southern Alps (STOP 2/1) (for further reading see Placer, 1998, 2008; Goričan et al., 2018).

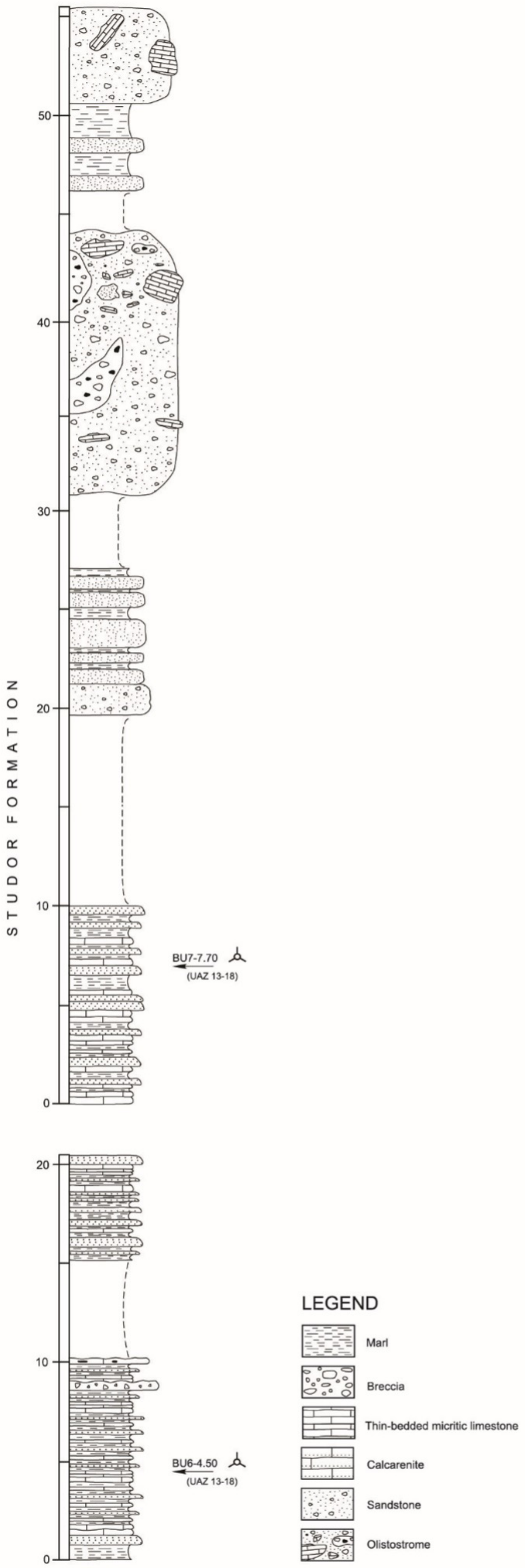

Figure 10: *Sedimentological section of the Studor Formation with positions of radiolarian datations marked (Kukoč, 2014)*

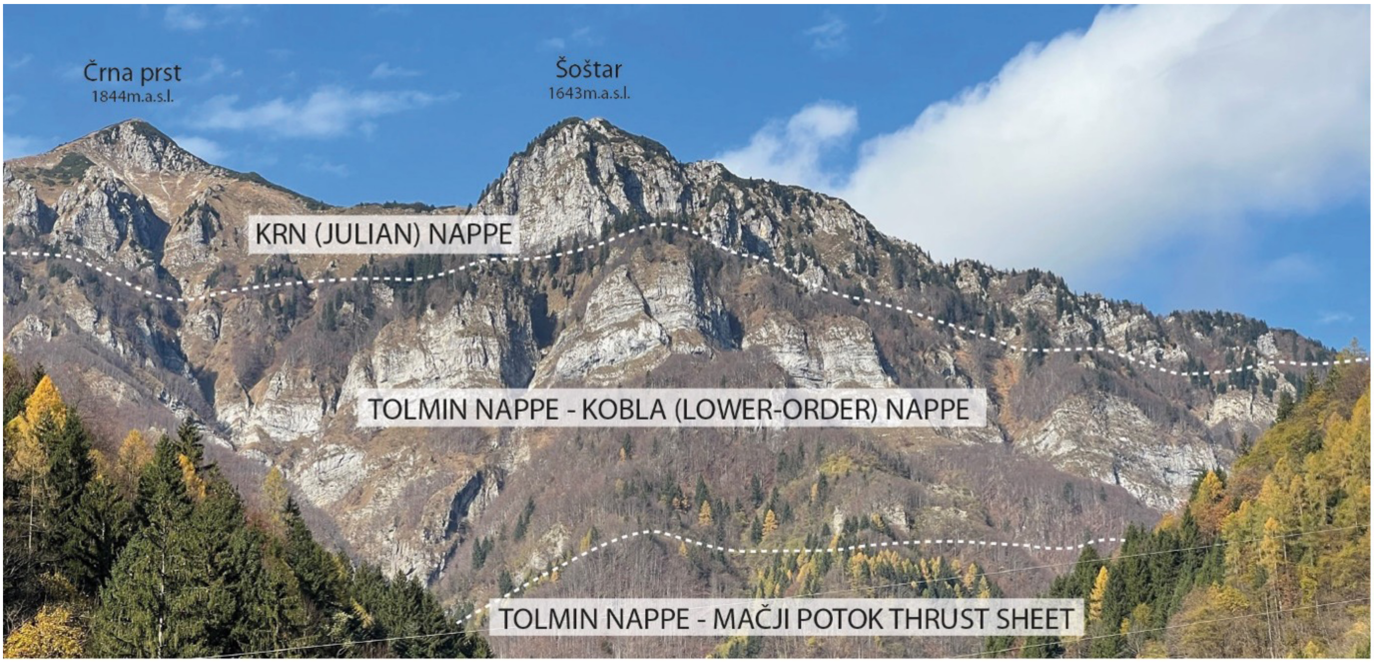

Figure 11: *Thrust structure of the eastern part of the Bohinj Range as seen from the village of Podbrdo. The highest peaks belong to the Krn (Julian) Nappe composed of Julian Carbonate Platform rocks, whereas on the southern slopes several thrust lower-order units of the Tolmin Nappe are composed of the Slovenian Basin succession.*

The nappe structure of the eastern Southern Alps is most clearly visible on the southern slopes of the Bohinj Range (Fig. 9). The top of the range is composed of the Krn Nappe, whereas the lower parts belong to the Tolmin Nappe (Figs. 11, 12).

According to Buser (1987), all three lower-order nappes of the Tolmin Nappe in the slopes between Podbrdo Village and Mt. Črna prst are visible. In general, the succession is similar to the Tolminske Ravne section (STOP 2/3), so herein only the major differences between them will be outlined. The Podmelec Nappe forms the village of Podbrdo surroundings and consists, in this area, of the Maastrichtian Upper Flyschoid Formation (see also STOP 3/1). Above the thrust-plane, the Rut Nappe starts with Upper Cenomanian – Turonian "globotruncana limestone" (described in Cousin (1981) as the upper portion of the Lower Flyschoid Formation and in Buser (1986) as a separate formation), passes through Coniacian – Campanian Volče limestone and again into the Upper Flyschoid Formation. Between the Rut and Kobla Nappes a small-scale Mačji potok thrust sheet is intercalated. This part was previously described as the Carnian Kobla Formation, but detailed study revealed that it is a thrust-sheet composed of Jurassic beds very similar to those from the Tolminske Ravne section (Svetličič, 2011). Morphologically, the Kobla Nappe is beautifully expressed. It starts with Carnian "Amphiclina beds" that are, in this nappe, composed almost exclusively of micritic limestone with chert, with sporadic resedimented limestones and some marl films between the beds. Upwards, the succession is similar to Tolminske Ravne section with some prominent variations: A) the Upper Norian – Rhaetian succession is not dolomitized (as in the major part of the basin), and above Bača Dolomite, the calcareous Slatnik Formation is preserved. It is composed of micritic limestone that in the upper section contains more abundant calciturbidites and calcidebrites. It records the latest Triassic progradation of the Julian Carbonate Platform towards the Slovenian Basin (Rožič et al., 2009, 2013; Gale, 2010). The Hettangian – Pliensbachian Krikov Formation is composed predominantly of resedimented limestones composed of ooids in the major part, and crinoids/lithoclasts in the upper part. This change documents the initial drowning of the Julian Carbonate Platform (described bellow), which was a source area for these resediments. The rest of the succession (Toarcian Perbla Fm, Aalenian – Lower Tithonian Tolmin Fm, Upper Tithonian – Berriasian Biancone Limestone Fm and Aprian – Turonian Lower Flyschoid Fm) is dominated by pelagic deposits, whereas carbonate resediments (known in other parts of the basin) are largely absent in this nappe (Rožič, 2006, 2009; Goričan et al., 2012a). This is also attributed to the paleogeographic position of the Kobla Nappe succession, which was located adjacent to the Julian Carbonate Platform, and which received large quantities of shedded carbonate until carbonate drowning, and starved from resediments afterwards (Rožič and Šmuc, 2009; Rožič et al., 2014).

The uppermost part of the Bohinj Range is composed of the Krn Nappe, which is in this area composed almost exclusively of the Norian – Rhaetian Dachstein Limestone that is developed in the loferitic facies. However, data from the 115 year-old Bohinjska Bistrica – Podbrdo railaway tunnel reveal that the contact between the Slovenian Basin and Julian Carbonate Plat-

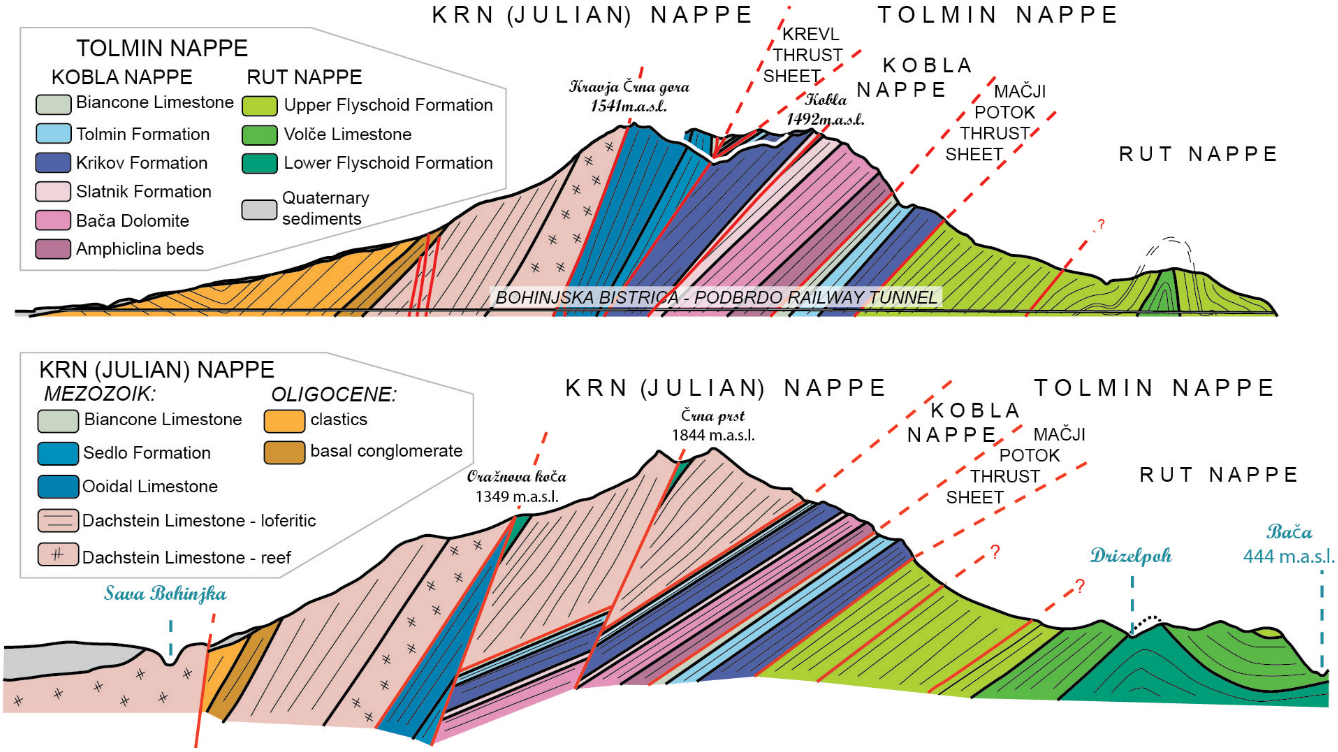

Figure 12: Two cross-sections through the eastern part of the Bohinj Range (modified from Kossmat (1907). Stratigraphy is corrected according to Buser (1987) and particularly in the central parts according to Rožič, (2006, 2009) and Rožič et al. (2009, 2013, 2014)): The upper cross-section is directly above the Bohinjska Bistrica – Podbrdo railway tunnel and shows the steeply dipping contact between the Krn and Tolmin nappes, whereas the lower cross-section is across the Mt. Črna Prst, where the contact between the nappes is a thrust fault.

form successions in the eastern part of the Bohinj Range (Kobla area) is not a thrust, but a steeply inclined, N-deeping fault (Kossmat, 1907). In the northern slopes of the Bohinj Range (between Mt. Kobla and Bohinjska Bistrica) the succession of the Julian Carbonate Platform begins with Norian – Rhaetian Dachstein Limestone in loferitic as well as reefal development (Buser, 1987; Turnšek and Buser, 1991; Turnšek, 1997). Early Jurassic is characterized by ooidal limestone overlain by bioclastic/crinoidal limestone, the latter documenting the initial (Pliensbachian) deepening of the platform (Rožič and Šmuc, 2009; Rožič et al., 2014). Above, with the stratigraphic gap, end-Jurassic – earliest Cretaceous Biancone Limestone is overlain. As described below, this progressive deepening of the platform is well manifested also in the adjacent Slovenian Basin succession. In the area around Bohinjska Bistrica, i.e. at the toe of the northern slopes of the Bohinj Range, Oligocene clastics are deposited with the stratigraphic gap above the lowest part of the Dachstein Limestone Formation. These Oligocene beds are also the westernmost outcrops of the Paratethys sediments in this part of the Alpine region (Kossmat, 1907; Buser, 1987). Such geological characteristics reveal that the internal structure of the eastern Southern Alps is surely further complicated and additional studies are needed for more comprehensive stratigraphic/structural interpretations.

DAY 2, STOP 2/3 – TOLMINSKE RAVNE: Slovenian Basin succession

Boštjan Rožič

The Slovenian Basin is probably the most prominent and longest lasting deep-marine paleogeographic unit in present-day Slovenia. Its foundation was formed during a Ladinian extensional event related to the Neotethys opening, and its margins were defined after late Ladinian progradation of surrounding platforms. This lasted until the end of the Cretaceous, when it turned into a typical foreland basin with the sedimentation of the flysch. Today, it is found in the Tolmin Nappe and can be traced in the foothills of the Alps, from the town of Tolmin in the west to the Celje on the East, where these basinal successions become covered with Paratethys sediments (Buser, 1989, 1996; Goričan et al., 2012b; Rožič, 2016; Rožič et al., 2018).

The section along the road between the villages of Perbla and Tolminske Ravne probably represents the most classical Slovenian Basin succession (Fig. 13), as three formation type-localities are found in this area (Cousin, 1981; Rožič, 2009). Along the road that climbs the northern limb of the large anticline latest Norian – Albian strata is exposed (Fig .14). The Norian – Rheatian is marked by carbonate sediments that were dolomitized to the Bača Dolomite Formation; i.e. bedded dolomite with chert nodules (1 in Fig. 14). Due to dolomitiza-

Figure 13: *Location of the Tolminske Ravne (STOP 2/3).*

tion, detailed sedimentological analysis is not possible, but the formation surely sedimented in a deep-marine environment (Gale, 2010). The overlying Hettangian – Pliensbachian Krikov Formation begins with an interval of basal limestone breccia several tens of meters thick (2A in Fig. 14), which records the earliest Jurassic rifting pulse connected to the opening of the Alpine Tethys (Rožič et al., 2017). Upwards, it passes into the alternating calciturbidites and hemipelagic limestone with chert nodules (2B in Fig. 14). Within the basin, calciturbidites start to prevail towards the north, which indicates the Julian Carbonate Platform as a main source of the resediments during this period (Rožič, 2006, 2009). In the lower part, resediments are characterised by ooids, whereas in the upper part crinoids and lithoclasts become predominant. This change in composition reflects the gradual drowning of the Julian Carbonate Platform, which is related to the late Early Jurassic rifting phase of the Alpine Tethys (Rožič and Šmuc, 2009; Rožič et al., 2014). Furthermore, the demise of shallow water sedimentation on this platform at the end of the Pliensbachian (Šmuc, 2005; Šmuc and Rožič, 2010) is directly recorded in the sharp upper boundary of the Krikov Formation (Rožič, 2009; Rožič and Šmuc, 2011).

The Toarcian is marked by the marl-dominated Perbla Formation (3 in Fig. 14), a succession typical of this stage throughout the entire Alpine Realm (Cousin, 1981; Rožič, 2009; Rožič and Šmuc 2011). In the first metre, calcareous shale is black and intensively impregnated with manganese, which is characteristic of the early Toarcian OAE (Jenkyns et al., 1991). The Middle and Upper Jurassic is characterized by pelagic siliceous limestones (4A in Fig. 14) and later, radiolarian cherts (4B in Fig. 14) (Cousin, 1981; Buser, 1989) known as the Tolmin Formation (Rožič, 2009; Goričan et al., 2012a). Only in the southern and central parts of the basin resedimented limestones occur sporadically and wedge out towards the north. In the Tolminske Ravne area, these occur as rare calcarenitic beds in the middle (Bajocian – Callovian) and uppermost (Lower Tithonian) part of the formation. The source area of these beds was the south-lying Dinaric Carbonate Platform. In recent years, it was shown that the lower interval passes southwards into limestone breccia several-tens-of meters thick, which indicates the major middle Middle Jurassic collapse and the southward retreat of the Dinaric Carbonate Platform margin (Rožič et al., 2018; submitted). This event coincides with major tectonic perturbation in the Alpine Realm, reflecting the oceanisation (or at least lithospheric breakup) (Ribes et al., 2020) of the Alpine Tethys and the initiation of the intra-oceanic subduction in the Neotethys (Gawlick et al., 2017; Schmid et al., 2020). The Jurassic ends with the upper Tithonian to Berriasian Biancone Limestone Formation (5 in Fig. 14) (Cousin, 1981). The change from radiolarian cherts to Biancone Limestone is sharp and characteristic for the entire region (Goričan, 1994; Šmuc, 2005; Clari and Masetti, 2002; Martire et al., 2006).

Early Cretaceous (Valanginian – Barremian) is marked by a prominent stratigraphic gap and the sedimentation reoccurs in the Aptian with locally thick limestone breccia (Cousin, 1981; Buser, 1989). The breccia forms a base of the Aptian – Turonian Lower Flyschoid Formation generally characterised by a rather monotonous alternation of pelagic marls and resedimented limestones, mainly calciturbidites (Cousin, 1981; Buser, 1986, 1989). In the Tolminske Ravne area this formation, however, exhibits great vertical as well as some lateral changes. Solely in the southern limb of the anticline it begins with channelized, marl-supported olistolithic breccia several tens of meters thick (6A in Fig. 14). Towards the northern limb, this bed wedges out. Upwards, the formation starts with limestone breccia (6B in Fig. 14), which passes into a marl-dominated interval (6C in Fig. 14), again into the calciturbidite-dominated interval (6D in Fig. 14), further to a marly interval with manganese (6E in Fig. 14) (probably recording Bonarelli OAE level) and then again a calciturbiditic interval (6F in Fig. 14) (the last two intervals do not outcrop along the road). An abundance of carbonate gravity-flow beds in the Tolminske Ravne section indicates their proximal position to the carbonate material source area, which was the Dinaric Carbonate Platform. This is in obvious contrast to the underlying Jurassic formations, which is explained by major tectonic perturbation of the Dinaric Carbonate Platform and Slovenian Basin transitional area that occurred between the two periods.

The rest of the Cretaceous (which will not be visited) is marked by the Coniacian to Campanian Volče Limestone Formation (7 in Fig. 14), which is dominated by light grey pelagic limestones with globotruncanids and rarer calciturbidites (Ogorelec et al., 1996; Buser, 1989). We note that all of the above-described

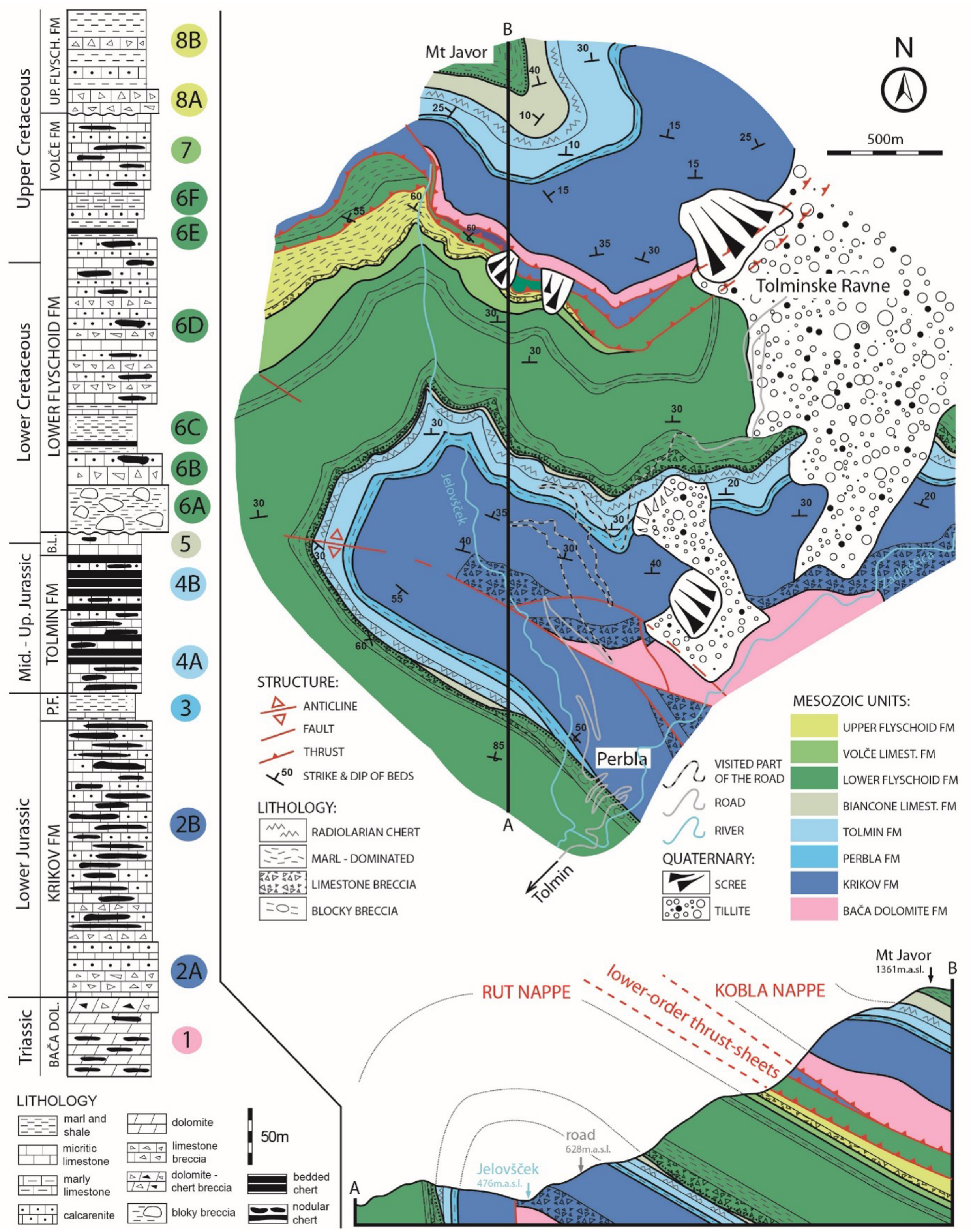

Figure 14: *Detailed geological map and stratigraphic column of the Tolminske Ravne area (after Rožič, 2006, 2009): the visited part of the succession is situated within the Rut Nappe, a middle lower-order thrust unit of the Tolmin Nappe that is entirely composed of a continuous Late Triassic to end-Cretaceous Slovenian Basin succession, which sedimented in the central part of the basin.*

cretaceous carbonates are to some degree replaced by nodular chert. The succession of the Slovenian Basin ends with latest Campanian – Maastrichtian Upper Flyschoid Formation (8A and 8B in Fig. 14) that closely resembles the Aptian to Cenomanian part of the Lower Flyschoid Formation but lacks any silification of carbonate lithologies. Upwards, it gradually turns into flysch deposits, i.e. contains progressively more abundant siliciclastic turbidites (Cousin, 1981; Buser, 1989).

DAY 3, STOP 3/1 – AVČE:
End-Cretaceous flysch on the northern margin of the Dinaric Carbonate Platform

Boštjan Rožič, Andrej Šmuc

Structurally, the Avče area belongs to the northernmost part of the Trnovo Nappe, which is the highest structural unit in the Dinaric nappe stack (Fig. 15). It is characterized by Upper Triassic and Early Jurassic shallow marine, often loferitic dolomites and limestone (Main Dolomite, Dachstein Limestone, Podbukovje fms). At the Triassic Jurassic boundary, interlayers of limestone breccia beds are common (Ogorelec and Rothe, 1992). Above the stratigraphic gap, 30 meters of poorly dated (probably end-Jurassic) crinoidal/tubiphytic calcarenites are deposited. They are overlain by olistolithic limestone breccia with muddy matrix with calpionellas (Kovač, 2016). In the northern part of the Avče area, i.e. north of the E-W trending paleofault, the Volče Formation, which is several tens of meters thick, is outcropping (for description see STOP 2/3) (Ogorelec et al., 1976). This succession records the gradual drowning of the Dinaric Carbonate Platform's northern margin, from the inner platform succession through slope sediments to the deep marine deposits.

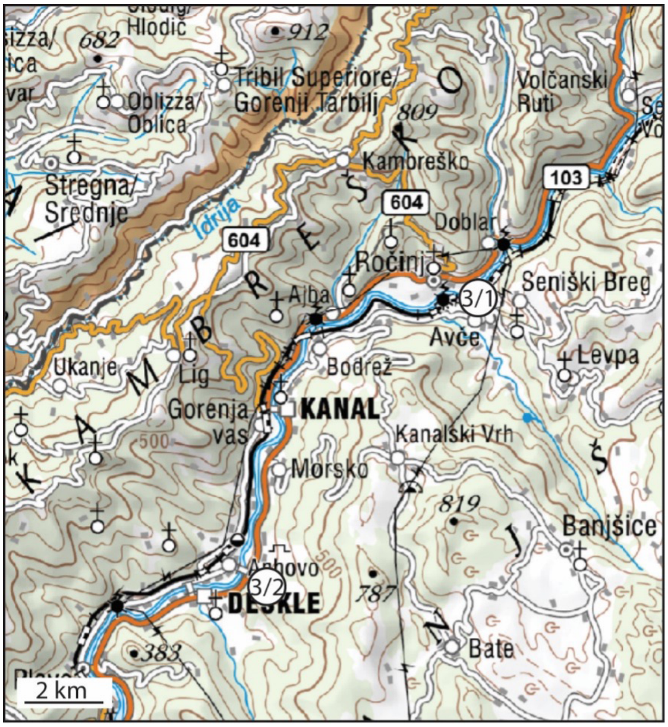

Figure 15: *Locations of Avče (STOP 3/1) and Anhovo (STOP 3/2).*

Above, with the angular unconformity, the end Cretaceous Lower Flyschoid Formation is deposited. Upper Cretaceous flysch deposits occur in both the Southern Alps and the Dinarides and chronostratigraphically belong to the Maastrichtian, and partly to the Upper Campanian (Buser, 1996)(see also STOPs 2/2 & 2/3). In the Dinarides, i.e. in the northern part of the Trnovo Nappe, the formation begins with the basal limestone breccia that is deposited with a pronounced erosional unconformity on older platform carbonate rocks (Buser, 1987, 2010; Miklavič and Rožič, 2008). As described above, basal limestone breccia locally overlies older basinal successions. The thickness of this basal package varies considerably, but often exceeds 100 m (Buser, 1986). The following flysch sequence can be divided into a lower and an upper part (Buser, 2010). In the lower part, the flysch contains thick layers (in places more than 10 m) of limestone breccia with intercalated fine-grained calciturbidite and siliciclastic layers. In the upper part, the content of limestone layers decreases, while the grain size and abundance of siliclastic turbidites increases.

In the Avče area, the basal portion of the flysch deposits outcrops along the Soča River (Fig. 16). The section begins with an internally bedded limestone breccia two meters thick that gradually changes to fine-grained parallel and cross-laminated calcarenites. Later in the section, marl packages alternate with rare beds of fine-grained siliciclastic turbidites, micritic limestones, and calciturbidites. The calciturbidites are medium bedded and show poorly defined partial Bouma sequences. An exception is a few layers of basal breccia more than one meter thick, overlain by a sharp contact with calcarenites in which partial Bouma sequence is preserved. The dominant layer in the Avče section is a package of limestone breccia 10 meters thick. It begins with a blocky limestone breccia with a marly matrix deposited on an erosional contact. The marl package, which lies directly beneath the breccia, has an unusual reddish colour, is plastically deformed, and contains large rip-up clasts that are in places still partially attached. The rip-up clasts are also present in the overlying lithologies. This breccia is overlain with erosional contact by a finer-grained breccia bed up to 7 m thick that sharply grades to calcarenite showing the Tb and Tc part of the Bouma sequence. The uppermost part of the section is marked by marls, with interbedded thick-bedded siliciclastic sandstones.

The Avče section represents a typical deep-sea foreland succession characterised by pelagic marls and limestones interbedded with various gravity-flow deposits. The composition of the calciturbidites/debrites (composed of contemporaneous bioclasts and diverse lithoclasts) indicates that they originated from the margins of the Dinaric Carbonate Platform, where rudist thickets predominated. In addition, the lithoclasts indicate a highly dissected slope between the basin and the platform, where carbonate rocks of a wide range of structural types and sedimentary environments were eroded. The formation of the thick limestone

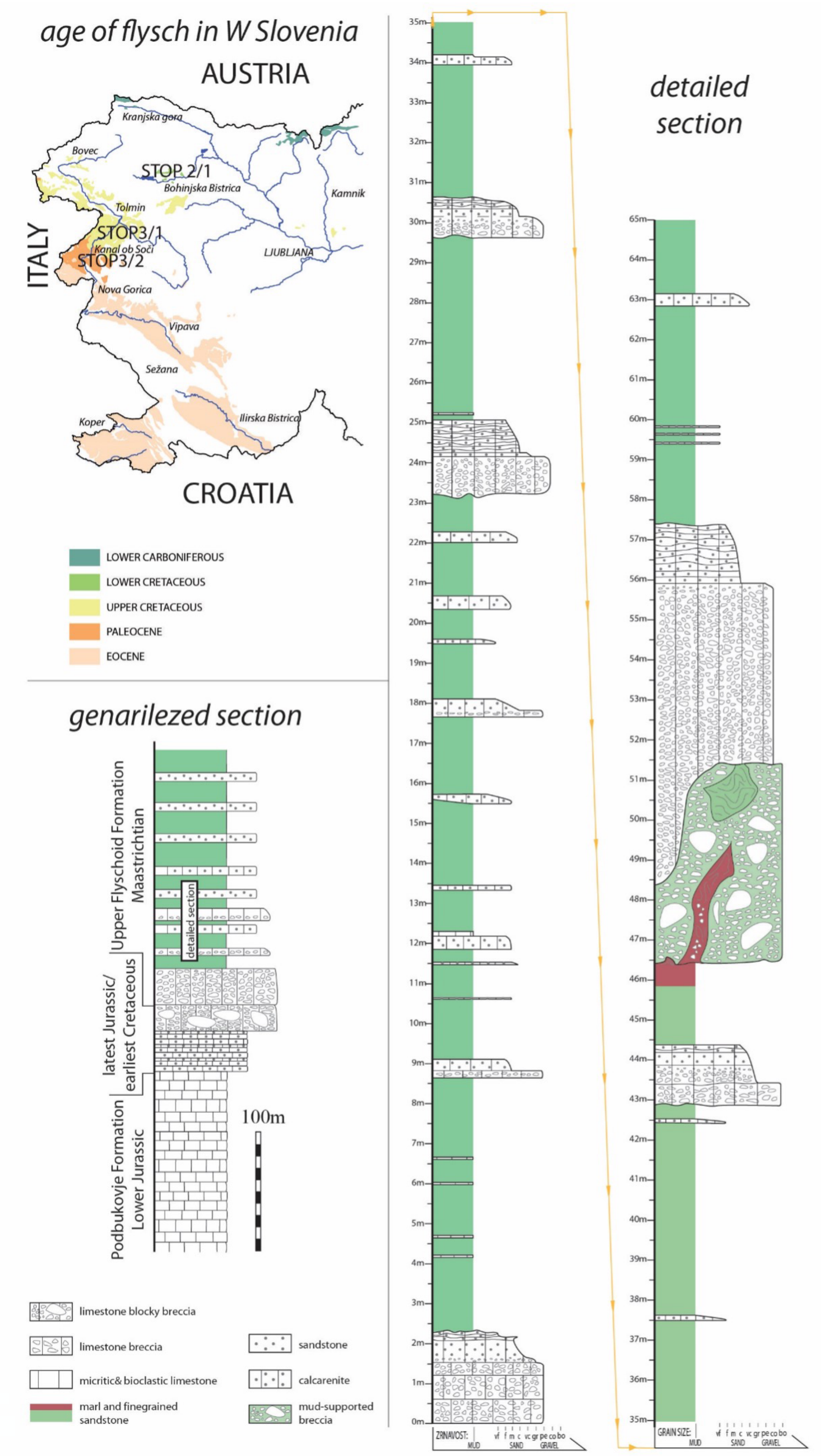

Figure 16: *Distribution of flysch in western Slovenia (upper left) with ages generally growing younger towards SW; generalized stratigraphic column of the Avče area recording the gradual deepening of the Dinaric Carbonate Platform's northern margin (lower left); and a detailed sedimentological section (right) of the Upper Flyschoid Formation logged along the banks of the Soča River.*

breccias is related to the tectonic breakup of the Dinaric Carbonate Platform. The sandstones in the Avče section were formed by distal turbidite flows. The origin of the grains was a mixed siliciclastic-carbonate shelf in the area of the internal thrust belts of the uplifting Alpine-Dinaric orogeny.

DAY 3, STOP 3/2 – ANHOVO: Mass-flow megaevents of the Paleogene flysch

Andrej Šmuc, Boštjan Rožič

Like the Avče area (STOP 3/1), the Anhovo area also belongs to the Trnovo Nape, but is located in the southern part of this structural unit (Fig. 15). In contrast to the Avče area, this area is marked by more continuous shallow marine carbonate succession, which persisted almost up to the end of the Cretaceous (Buser, 2010; Jež and Otoničar, 2018). Above, with the stratigraphic gap the Paleogene flysch is deposited. In the Anhovo area, however, the Paleocene flysch is separated from the older carbonate rocks by regional faults (Ogata et al., 2014).

The Salonit Anhovo quarry boasts spectacular outcrops of extremely large sedimentary bodies formed by various types of gravity mass flows (Fig. 17). In terms of size (up to 260 m thick), extent (100 km long), and mode of formation, these bodies extend from the Anhovo area to northeastern Italy (Ogata et al., 2014). Their internal organization is characterized by a repeating sequence of lithologic units. These large megasequences exhibit thinning and finning upward trends. They generally begin with massive blocky carbonate breccias with a marly matrix (unit 1), followed by blocks of carbonate breccias and eroded bedrock in a marly-siliciclastic matrix (unit II) (Fig. 17). These breccias are overlain with a sharp contact at the horizon of normally graded carbonate breccias – calcirudites (Skaberne, 1987; unit III) that grade into calcarenites (unit IV). The entire series is terminated by a pelagic rock stack of laminated to massive marls

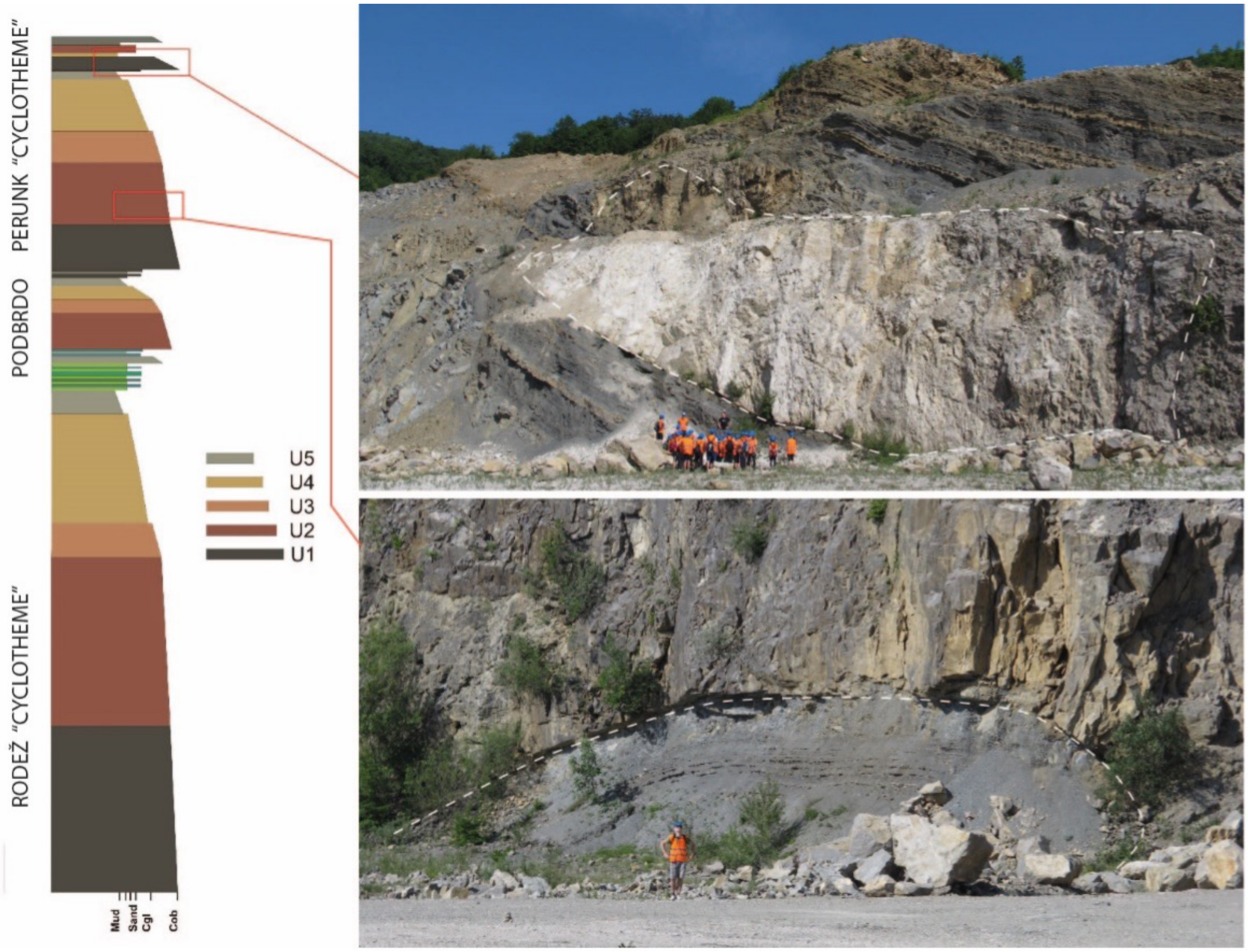

Figure 17: *Generalized stratigraphic column of the Paleocene flysch in the Salonit Anhovo quarry (left) marked by three "megacyclothemes", large olistolith of Cretaceous limestone within Perunk "cyclotheme" (upper right), and large flysch plasticlast from the U2 unit of the Perunk "cyclotheme" (lower right).*

(unit V). According to Ogata et al. (2014), these deposits formed in the proto-dinaric orogen during the process of the collapse of the submarine shelf or its sliding (with characteristic plastic deformation of the base) into the deeper part of the developing foreland-type inner basin.

Despite many years of geological research, the exact stratigraphic position of the deposits in the Anhovo quarry is still unknown. Based on the rich presedimented rudist assemblage and nanoplankton communities, the rocks of the lowermost part of the Anhovo sequence are of Upper Paleocene, or more precisely, Thanethian age (Pleničar et al., 2001; Pogačnik, 2003; Pleničar and Jurkovšek, 2009). On the other hand, the resedimented planktonic foraminifer Morozovella velascoensis found in the middle part of the sequence points to the lower Eocene.

Due to the specific chemical and lithological composition of the lithologic members of the megacyclothems, these rocks are mined in open pits and used for the production of Portland cement. To ensure safety during mining operations, various geophysical methods have been employed, from geoelectrics (Pogačnik, 2010) to shallow radar (Zajc et al., 2014).

DAY 3, STOP 3/3 – ŠKOCJAN CAVES: Inside karst of the Dinaric Carbonate Platform

Stanka Šebela

The Dinarides of western Slovenia are dominated by a thick Upper Triassic to Eocene carbonate succession of the Dinaric Carbonate Platform also known as the Friuli (in Italian literature) and Adriatic or Dinaric-Adriatic Carbonate Platform (in Croatian literature). The platform installed above the Carnian clastic deposits and continued in the SE part until its final drowning in the Eocene (Buser, 1989, 1996). The Kras (Karst) area structurally belongs to the Komen Thrust Sheet (Placer, 1999), which consists of the platform succession beginning in the Cretaceous, exhibiting prominent disconformity in the Maastrichtian and lasting until the final destruction and subsidence of the platform in the lower Eocene (Otoničar, 2007; Jurkovšek et al., 2013).

The Škocjan Caves, together with the Kačna Jama cave, belong to the first few kilometres of the Reka River underground flow that is still accessible from the surface. In this area (Figs. 18, 19), the oldest rocks belong to the Repen Formation (Cenomanian – Turonian) representing limestone with pelagic fossils (Jurkovšek et al., 1996). The karst surface and underground of the Škocjan Caves is composed of three lithological units (Jurkovšek et al., 1996, 2013). The oldest rocks belong to the Sežana Formation (Turonian – Santonian) representing bedded limestone with rare rudist biostromas (Jurkovšek et al., 1996, 2013). The Sežana Formation is some 400 to 500 m thick. Above the Sežana Formation we have the Lipica Formation (Santonian – Campanian) in the normal stratigraphic position with a thickness of 250 to 400 m (Jurkovšek et al. 1996, 2013). The Lipica Formation is represented by bedded and massive limestone with rudist biostromas and biohermas (Jurkovšek et al., 1996). The Liburnian Formation (Maastrichtian – Paleocene) represents bedded limestones (with alveolinae) with a thickness of 50 to 300 m (Jurkovšek et al. 1996, 2013). The youngest rocks in this area are composed of Slivje limestone (bedded, mainly miliolid limestone) within the Liburnian Formation (Pc).

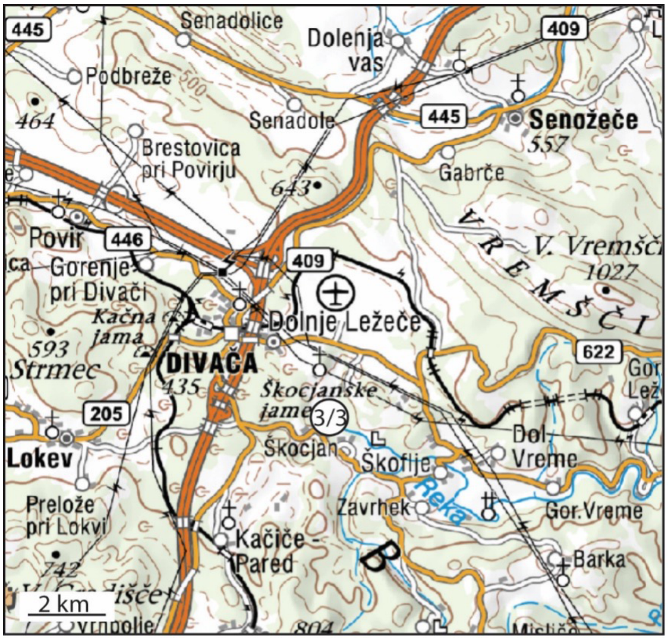

Figure 18: *Location of the Škocjanske Caves (STOP 3/3).*

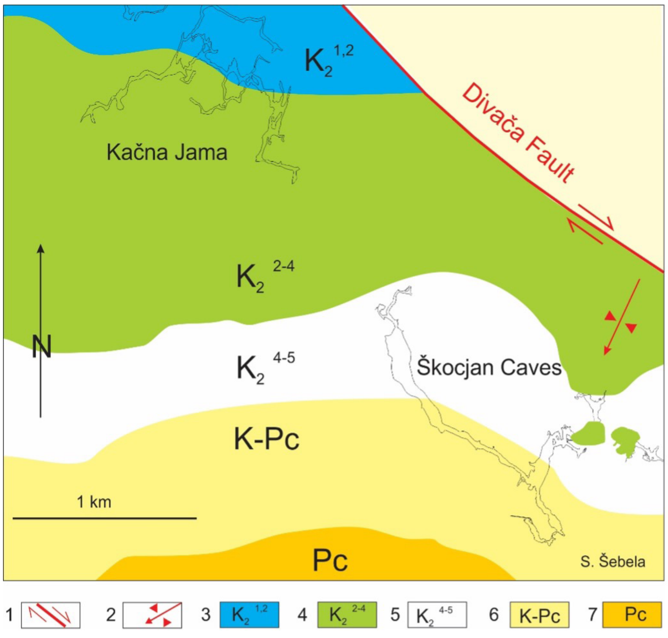

Figure 19: *Geology of the area of the Škocjan Caves and Kačna Jama, SW Slovenia. 1–fault with dextral horizontal strike-slip movement, 2–syncline, 3–Repen Formation (K21,2), 4–Sežana Formation (K22-4), 5–Lipica Formation (K24-5), 6–Liburnian Formation (K–Pc), 7–Slivje limestone within the Liburnian Formation (Pc).*

Passages of the Škocjan Caves are developed inside a lithological column 300 m thick of Cretaceous and Paleocene limestones (Šebela, 2009). Underground, the Reka River in the Šumeča Jama and the Hankejev Kanal flows largely within 130 m-thick Lipica Formation and follows in the direction of the bedding plane. The bedding planes with interbeddes slips were especially favourable for the development of the initial cave passages (Knez, 1996; Mihevc, 2001; Šebela, 2009).

The Škocjan Caves are the only karst cave in Slovenia inscribed as UNESCO natural heritage since 1986. The caves are 6474 m long and 254 m deep (Fig. 20) with the lowest point at 212 m (Mrtvo Jezero). Martelova Dvorana boasts a volume of 2.55 million m3 and is the 11th largest cave chamber in the world and the 2nd largest in Europe (Walters and Zupan Hajna, 2020).

The Reka River only flows aboveground for some 50 km. Underground, it flows through the Škocjan Caves towards the NW to Kačna Jama (20 km long and 280 m deep). However, the cave systems are not connected, as they are separated by some 870 m of air distance. The Reka River emerges after 35 km from underground as the Timavo spring in Italy. Between Kačna Jama and the Timavo springs there are other vertical cave accesses to underground water flow. The extreme flood of 1965 reached a level of 321 m above the sea and caused the waters in Martelova Dvorana to rise to a level of 107 m (Mihevc, 2017).

The remains of older cave passages take the form of roofless caves or denuded caves. The longest roofless cave is 1800 m long and is situated at an elevation of 440 to 450 m above sea level (Mihevc, 2001), and can be traced in the area north from Hankejev Kanal passage. If we presume that the roof above what is today a roofless cave was about 150 m high and that the denudation rate is 20 to 50 m per 1 million years, this cave system could be some 3 – 7.5 million years old (Mihevc, 2001, 2017; Zupan Hajna et al., 2008). The second speleological period represents passages at elevations of 340 to 300 m above sea level, as Tominčeva Jama, the upper part of Šumeča jama, and Tiha Jama. During the third period, the strong down-cutting of the water through the limestones was first active in Martelova Dvorana and later in the Hankejev Kanal and Šumeča Jama. All speleogenetic periods are linked to changes in tectonic, hydrological, and climate/meteorological conditions.

Figure 20: *Ground plan of the Škocjan Caves with schematic longitudinal section AB. Flow direction and the underground Reka River are marked in blue.*

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Fieldtrip guide. 15th Emile Argand Conference on Alpine Geological Studies, 12-14 September 2022, Ljubljana, Slovenia.

Metamorphism, deformation, exhumation, and basin formation in NE Slovenia, in the Pohorje-Kozjak Mts.

FIELDTRIP B

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Introduction

This excursion aims to present field observations and related laboratory data concerning the metamorphism, exhumation, and connected Miocene basin formation in the Pohorje and Kozjak Mts., NE Slovenia (Fig. 1).

The area is part of the Austroalpine nappe system and, at the same time, represents the western margin of the Pannonian Basin. The Pohorje occupies a specific place among metamorphic petrologists, as it contains ultra-high-pressure metamorphic rocks preserved in the Koralpe-Wölz nappe unit. The formation, physical conditions, the relationship to subduction processes, and the geodynamic interpretation of the UHP rocks all represent important subjects and points of interest on the excursion. On the other hand, the Pohorje and Kozjak Domes have recently been interpreted as Miocene core complexes (Fodor et al., 2021), and evidence of such interpretation, as well as an alternative Late Cretaceous timing, are presented and discussed during the trip. These extensional deformations were temporally linked to important magmatism, thus the structural features of the main Pohorje pluton and related dykes will be discussed. On the journey there and back the trip will cross some important tectonic features of the Eastern Alps – the Periadriatic and Labot-Lavanttal Faults – whose tectonic aspects will be briefly mentioned (Fig. 1).

1. Main structural features of NE Slovenia and surroundings

1.1. General introduction to pre-Cenozoic basement units

The crustal part of the Eastern Alps is composed of nappes derived from (bottom to top) the subducted European plate (exposed in the Tauern window, Scharf et al., 2013; Rosenberg et al., 2018), oceanic crust and related sediments of the Alpine Tethys (Penninic unit), and the Adria-derived Austroalpine nappes as the highest unit that has several subdivisions which vary according to author (Neubauer et al., 2000; Schuster et al., 2004; Schmid et al., 2004, 2020). The Penninic units, composed of a dismembered ophiolite (Koller and Pahr, 1980) and deep-marine sediments, are exposed in the Rechnitz windows (Fig. 1b), which is interpreted as a metamorphic core complex of Miocene age (Cao et al., 2013; Tari, 1996; Tari et al., 2020).

The overlying nappe stack comprises the Austroalpine nappe system, most of which was composed of pre-Permian metamorphic rocks and overlying Permian to Mesozoic successions and stacked together during the Eoalpine orogeny during the late Early to Late Cretaceous (Neubauer et al., 2000; Schmid et al., 2004). The Lower Austroalpine nappes represent the rifted margin of the Alpine Tethys (in the sense of Schmid et al., 2004, 2008; Schuster et al., 2004). The overlying thick Upper Austroalpine nappe system (UAA) is composed of various metamorphic rocks; the most extensively distributed Koralpe-Wölz (KW) unit occupies a central position within the UAA (Froitzheim and Schuster, 2008). It comprises amphibolite to eclogite facies metamorphic rocks (Schuster et al., 2004), exhibiting high to ultrahigh-pressure conditions within the study area, in the Pohorje Mts. (Hinterlechner-Ravnik et al., 1991; Janák et al., 2004, 2006, 2015; Sassi et al., 2004, Vrabec et al., 2012; Hauzenberger et al., 2016; Li et al., 2021). These (ultra-)high-pressure rocks could have formed during intra-continental subduction (Janák et al., 2004; Schuster and Stüwe, 2008; Stüwe and Schuster, 2010; Miladinova et al., 2022) and thus represent a major crustal-scale weakness zone. They were exhumed by large-scale isoclinal antiform and related shear zones (Kirst et al., 2010; Janák et al., 2015).

Above the eclogitic rocks, the metamorphic degree decreases, and frequently a sharp jump appears in the metamorphic grade. The low- to very low-grade metamorphic rocks and metasediments are part of the Drauzug-Gurktal (DG) unit (Schmid et al., 2004). The highest tectonic unit is the Transdanubian Range (TR), composed of Variscan very low-grade rocks and non-metamorphosed Permian to Mesozoic sequences; its nappe position above other Austroalpine units is confirmed by structural studies (Tari, 1994; Fodor et al., 2003; Tari and Horváth, 2010).

A great number of geochronological data constrain nappe emplacement to the Cretaceous (~100 – ~70 Ma, Frank et al., 1987; Dallmeyer et al., 1996, 1998). Late Cretaceous sediments with depositional age from ~85–70 Ma occur on top of the Drauzug-Gurktal and TR units (Fig. 2) (Willingshofer et al., 1999). Although these basins were formed in an overall contractional setting of the entire Eoalpine orogen (Ortner et al., 2015; Tari and Linzer, 2018), the Late Cretaceous basin subsidence near the study area coincided with the exhumation of the high-pressure Koralpe-Wölz unit from below low-grade units along low-angle shear zones (Neubauer et al., 1995; Kurz et al., 2002; Krenn et al., 2008; Herg and Stüwe, 2018).

1.2. Metamorphic domes

The Pohorje Mts. represent a metamorphic dome that mainly consists of the Koralpe-Wölz nappe, and is surrounded by low-grade metamorphic rocks or directly by non-metamorphosed nappes belonging to the Drauzug-Gurktal and the Transdanubian Range units, respectively (Fig. 1b, 2). The boundaries of these units were originally Cretaceous thrusts (Schmid et al., 2004), but now exhibit sharp changes in metamorphic degree (Trajanova, 2002; Herg and Stüwe, 2018). In the core of the dome, the granodioritic Pohorje pluton and subvolcanic dacite bodies intruded upon the host metamorphic rocks in the Miocene, at 18.6 Ma (Fig. 3) (Fodor et al., 2008; Trajanova et al., 2008; Poli et al., 2020). Intrusive rocks largely penetrate into the KW nappe, but in the northwest also into the rocks of the Drauzug-Gurktal unit. The northwesternmost part of the Pohor-

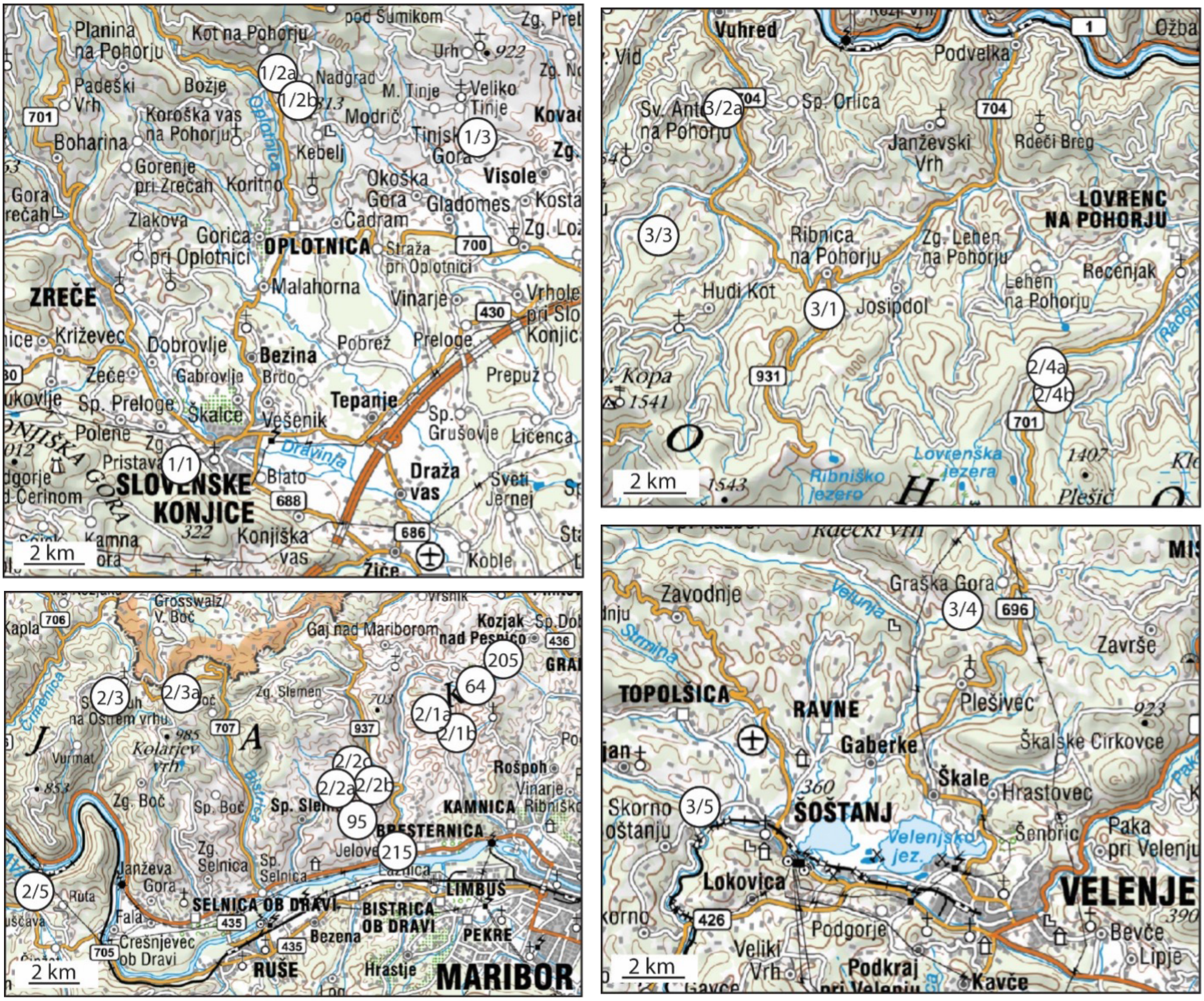

Figure 1: *Itinerary of the field trip with daily stopovers*

je Mts., situated north of the main dacite body, has a distinct structure, where only low-grade metamorphics, non-metamorphosed Permo-Mesozoic rocks, and Miocene sedimentary and dacitic volcanic formations occur (Mioč and Žnidarčič, 1976).

The Kozjak Dome and the E-W trending Remschnigg ridge (bounding the Styrian Basin) have a similar structure to the Pohorje Dome but lacks Miocene magmatic rocks (Fig. 2). Here, Miocene synrift sediments occur in small patches on top of the low-grade Paleozoic or non-metamorphic Permo-Mesozoic rocks. Slivers of Permo-Mesozoic rocks are incorporated as small lenses within the ENE-trending Kungota Fault, which merges with the NE corner of the Kozjak Dome (Fig. 3) (Žnidarčič and Mioč, 1987).

In the eastward subsurface continuation of the Pohorje Dome, the Murska Sobota (MS) Ridge is composed of the same KW medium-grade rocks as the Pohorje itself (Lelkes-Felvári et al., 2002; Fodor et al., 2013). Small slivers of low-grade Paleozoic rocks and non-metamorphosed Permo-Triassic sediments encountered by several boreholes occur sporadically on the top of the medium-grade rocks (Fig. 1b, Gosar, 1995; Fodor et al., 2013). The

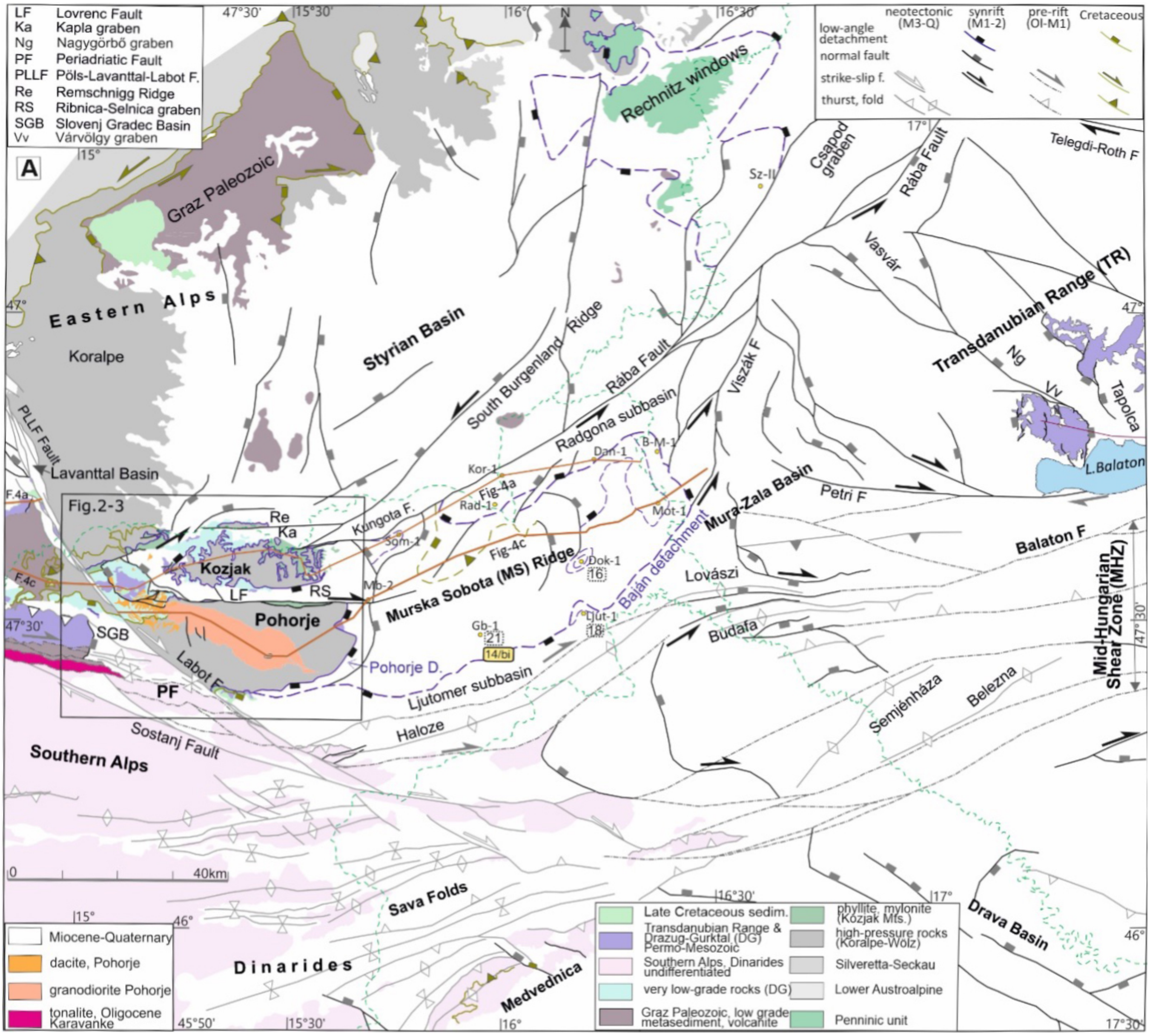

Figure 1b: *Geological setting of the Pohorje Mts. and surroundings. Pre-Miocene units and Miocene to Quaternary structures of the study area, the western Pannonian Basin (based on maps of Flügel and Neubauer, 1984; Flügel et al., 1988; Tomljenović and Csontos, 2001; Fodor et al., 2013; Schmid et al., 2020). Few thermochronological data from the Murska Sobota high is shown, see legend on Fig. 2.*

MS Ridge is surrounded in the north, east, and south by the Baján detachment, which is a low-angle shear zone imaged by seismic data and penetrated by the Baján B-M-1 borehole (Fodor et al., 2013; Lelkes-Felvári et al., 2002; Nyíri et al., 2021).

2. Extension and exhumation in the Pohorje and Kozjak Mts.

2.1. Thermochronological data

The exhumation of the Pohorje and Kozjak Domes is constrained by diverse geochronological data, including K-Ar ages on variable mineral separates, zircon and apatite fission-track ages, and zircon (U-Th)/He ages, data on which was recently summarized by Fodor et al. (2020, 2021) (Fig. 2).

Cretaceous and Lu/Hf ages on garnets, U-Pb ages on zircon and a monacite age date the timing of metamorphism of the (ultra)high-pressure rocks between 97 and 87 Ma in the southeastern Pohorje (Miller et al., 2005; Thöni et al., 2008; Janák et al., 2009; Sandmann et al., 2016; Chang et al., 2020; Li et al., 2021). Muscovite K-Ar ages from mesograde rocks of the Kozjak Dome, and from low-grade rocks of the northern Kozjak and from the southern Pohorje Domes are Cretaceous, suggesting that cooling of the structurally higher units below ca. 420–350°C already occurred during the Eoalpine orogeny (Fodor et al., 2008).

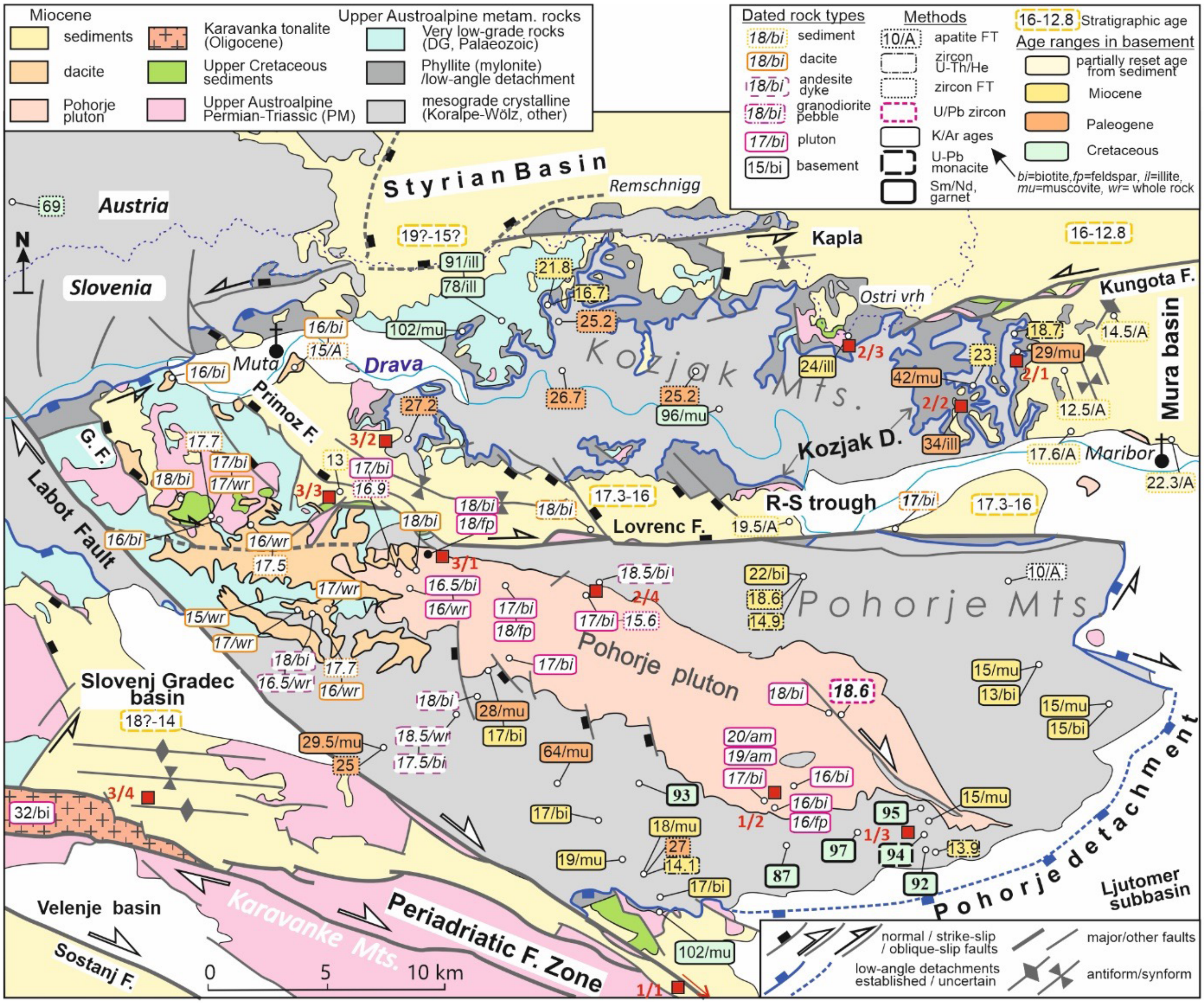

Figure 2: *Geochronological ages from the Pohorje-Kozjak Mts. (summarized in Fodor et al., 2021, after Fodor et al., 2003, 2008; Thöni et al., 2008; Trajanova et al., 2008; Sandmann et al., 2016; Li et al., 2021). Base map after Mioč and Žnidarčič, 1976; Žnidarčič and Mioč, 1988, modified. Red squares indicate excursion stops.*

Few muscovite K/Ar ages in the western Pohorje Dome and zircon FT data of the Kozjak Dome indicate Oligocene cooling (Fig. 2). This cooling could follow the thermal input derived from the Paleogene Periadriatic magmatism (Rosenberg, 2004; Schulz, 2012; Neubauer et al., 2018) or could also be connected to the earliest stage of the lateral extrusion of the Eastern Alps (Rosenberg et al., 2018).

On the other hand, the Miocene zircon FT ages are close to the possible onset of sedimentation (~19–18 Ma) and the somewhat younger zircon (U-Th)/He ages (18.7–16.7 Ma) are coeval with the earliest sediments (Fig. 2). Therefore, we prefer connecting these ages to the extensional exhumation of the Kozjak Dome, although the exact onset cannot be more precisely constrained than ~25–23 Ma.

Miocene exhumation is clearly documented by muscovite and biotite K/Ar ages from the mesograde metamorphic rocks in the eastern and southern part of the Pohorje Dome; the ages range from 22 to 13 Ma (Fig. 2) (Fodor et al., 2003, 2008). Zircon (U-Pb)/He ages of Fodor et al. (2021) constraing the late stage of cooling to around ~15–14 Ma (Fig. 2), although they are in contrast to the apatite (U-Th)/He ages ranging from 20.4 to 13.9 Ma published by Legrain et al. (2014).

The eastern part of the Kozjak detachment show a complex picture, and this is detailed in stops 2/1-2; the Palaeogene ages are interpreted as mixed ages derived from the Cretaceous deformations and the Miocene exhumation, while Miocene ages are related to activity of the Kozjak Detachment.

In the pluton, biotite, feldspar, and whole-rock K-Ar ages are scattered between 18.1 and 15.7 Ma and the FT ages lie in the same range (Dolenec, 1994; Fodor et al., 2003, 2008; Trajanova et al., 2008). Both are interpreted as cooling ages, postdating the intrusion, which is dated with a zircon U-Pb age of 18.64±0.11 Ma (Fodor et al., 2008). Fast cooling is also indicated by biotite K-Ar ages of 18-17 Ma from pebbles of the Miocene sediments of the RS trough having roughly the same depositional age as the cooling of the source granodiorite (Fig. 2). In the dacite body, and in few isolated intrusions along the Drava River, the biotite and whole-rock K-Ar age ranges is 18.2–15.8 Ma, which may be close to formation age owing to shallower emplacement depth. The andesitic and rhyolitic dykes show a K-Ar age range similar to the main dacite body (18.5–16 Ma; Fodor et al., 2008), with the exception of a single rhyodacite dyke dated as young as 14.9 Ma (Trajanova et al., 2008).

Three new zircon FT data from mesograde rocks and one published biotite K-Ar age from a micaschist (Fodor et al., 2003) from three boreholes of the MS Ridge indicate Miocene cooling (Fig. 1b; 20.8–16.1 and 14 Ma, respectively). On the other hand, mica separated from the footwall of the Baján detachment yielded a latest Cretaceous age (65 Ma, Lelkes-Felvári et al., 2002).

2.2. Structural observations

Evidence of Miocene extensional deformation comprises the following, summarized by Fodor et al. (2021): (1) the existence of sub-horizontal to low-angle detachment zones, (2) disposition and geometry of Permo-Mesozoic and low-grade rocks above and around the domes, (3) large-scale tilting of the entire Pohorje Dome, (4) eastward younging thermochronological ages, (5) anisotropy of magnetic susceptibility (AMS) data, interpreted together with (6) mesoscale ductile structures in the Miocene plutonic and host metamorphic rocks, (7) omnipresent brittle extensional structures, and the variable tilt of synrift sediments together with AMS data from sediments, (8) exposed basal contact of the exhumed metamorphic rocks and syn-rift sediments, and (9) high vitrinite reflectance values and clay mineral alteration near the Kozjak detachment.

(1 and 2) In the Kozjak Mts. a completely flat tectonic contact occurs at the top of the medium-grade rocks (Figs. 3, 4a, b). Above this contact, the very low-grade Paleozoic and tilted Permo-Mesozoic sequences are all truncated and only occur in reduced thicknesses. At Ostri vrh, strongly tilted Upper Triassic carbonate rocks are in near-direct flat-lying contact with medium-grade rocks, indicating at least 4–6 km of stratigraphic omission (Fig. 4a, b, Stop 2/3). The ~200 m thick contact zone was mapped as a separate phyllite unit (Mioč and Žnidarčič, 1976), but was later interpreted as a mylonitic shear zone (Fodor et al., 2002, 2008; Trajanova, 2002). We refer to this structure as the Kozjak Detachment. (Fig. 2, 4a, b; Fodor et al., 2003). Stretching lineations are broadly ENE-trending within the mylonite. Shear bands within the mylonites and in the underlying medium-grade rocks both exhibit top-to-NE displacement along the eastern Kozjak detachment (Stops 2/1-2 Fodor et al., 2008). Above the detachment, the strongly tilted synrift sequences corroborate large extensional deformation along this segment (Stop 2/2; Fig. 4B).

(3) Four independent datasets for pressure conditions for the Pohorje intrusion (Altherr et al., 1995; Fodor et al., 2008; Sotelšek, 2019; Poli et al., 2020) are consistent with the structural scenario that the entire massive tilted westward after pluton emplacement. Uplift of the eastern tip of the intrusion ranges from 15 to 20 km, depending on the uncertainty range of the pressure estimates (Fig. 4c). Values for the emplacement depth of the upper part of the pluton in the west range between ca. 7.5 km (2.5 kbar) to 12 km (Sotelšek, 2019; Poli et al., 2020). As the upper and lower part of the pluton are presently at the same topographic level, this means that the amount of westward tilt amounts to ~20–25°.

(4) Fodor et al. (2008) demonstrated that low-temperature thermochronological data suggests a trend of eastward younging ages (Fig. 2). K-Ar white mica ages are Oligocene (29.5–25 Ma) in the south-western and Miocene (19-15 Ma) in the eastern and southern parts of the Pohorje Dome. The available zircon FT ages and three (U-Th)/He ages (14.9–13.9 Ma) from

the basement also corroborates Miocene exhumation. Fodor et al. (2008) interpreted this data as an argument for the westward tilt of the pluton (Fig. 4c).

(5) AMS is a measure of the ductile strain of the rocks and generally indicates ~E–W ductile stretching within the Pohorje pluton (Fodor et al., 2020, Stop 1/2). Mesoscopic stretching lineations in the pluton and in some early dykes also trend in the same direction as the AMS axes (Fig. 3). Since mesoscopic lineations are associated with extensional structures (e.g. shear bands) AMS can probably be interpreted as having been related to extension rather than to pluton emplacement (Fodor et al., 2020). This deformation is clearly of Miocene age, while thermochronological ages constrain both the crystal plastic deformation and the acquisition of the AMS signal between 18.6 and ~15.5 Ma.

6) In the host metamorphic rocks, prominent stretching lineations and extensional shear bands occur both in the Pohorje and Kozjak Domes (Fig. 4). However, the age of extension is not so well constrained. Part of the ductile structures could have formed already during the Late Cretaceous, when exhumation of the mid-crustal medium-grade rocks of the Austroalpine nappe pile was a common process just north of the Kozjak Dome (Kurz et al., 2002; Neubauer et al., 1995), and a similar process has been suggested for the Pohorje (Kirst et al., 2010). We consider lineations in medium-grade rocks, which potentially formed near peak-metamorphic conditions, as being of Cretaceous age. However, K-Ar ages on muscovite and biotite seem to suggest that at least in the eastern Pohorje Dome the extensional structures could be Miocene in age (Figs. 2, 3). The same can be assumed for the extensional shear bands of the eastern Kozjak, where the formation conditions of the brittle-plastic structures were close to the retention temperature for fission tracks in zircon.

(7) Brittle extensional structures occur in map- and outcrop-scale (Fig. 3, stops 2/2, 3/2-3). West of the Ribnica-Selnica trough, map and dip data demonstrate the existence of

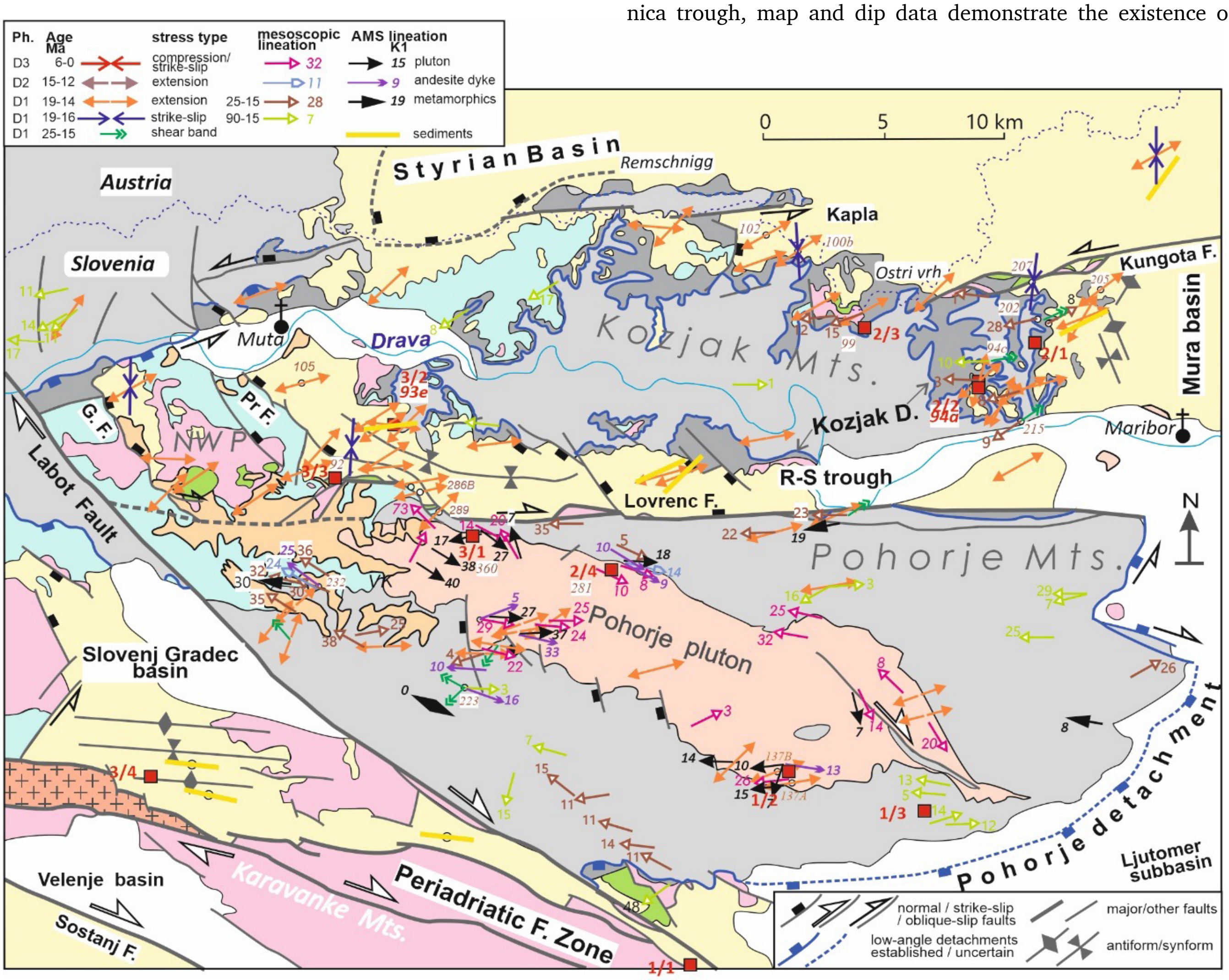

Figure 3: Structural data from the Pohorje-Kozjak Mts., after Fodor et al. (2008, 2020, 2021).

westward-tilted domino-style blocks (Primož and Golarjev Peak Faults, Fig. 3). Above the Kozjak detachment the Miocene sediments are moderately to strongly tilted to the west (Fig. 5B), while east-dipping normal faults are postulated between the west-tilted blocks.

The main brittle deformation was characterized by a NE–SW to E–W directed extensional stress field designated as D1 phase (Fodor et al., 2002, 2008, 2020) (Fig. 3). A great number of striated faults were formed when layers were still horizontal because the symmetry plane of conjugate faults are perpendicular to the now tilted beds. The directions of σ3 axes derived from brittle faults are parallel to measured K1 axes of the AMS (Fodor et al., 2020) (Fig. 3). The paucity of faults and the lack of the tectonic AMS signal in rocks younger than ~14 Ma indicate that the deformation occurred before 15 or 14 Ma. This extensional phase was overprinted by the D2 phase characterized by E–W to SE–NW extension. The extensional deformation was overprinted by strike-slip faults attributed to the Pliocene-Quaternary neotectonic D3 phase (Fodor et al., 1998, 2008). This phase was associated with large-wavelength folding of the entire dome (Sölva et al., 2005).

8) Two sites expose the contact of the mylonitic basement rocks and the deformed sediments; we visit these sites and discuss their characteristics (Fig 2,3, Stop 2/2 and 3/2).

(9) Vitrinite reflectance values are very high (up to 2.5 % Rr), and clay mineral alteration is up to thermally anchizonal conditions around the eastern termination of the Kozjak Dome and around the Remschnigg Ridge (Sachsenhofer et al., 1998a, b). These indicate significant thermal input, which was interpreted as a sign of advective heat transport from the footwall of the Kozjak detachment (Fodor et al., 2002, 2008). This is in line with partially reset apatite FT ages from the sediments overlying the shallow part of the detachment (Fig. 2).

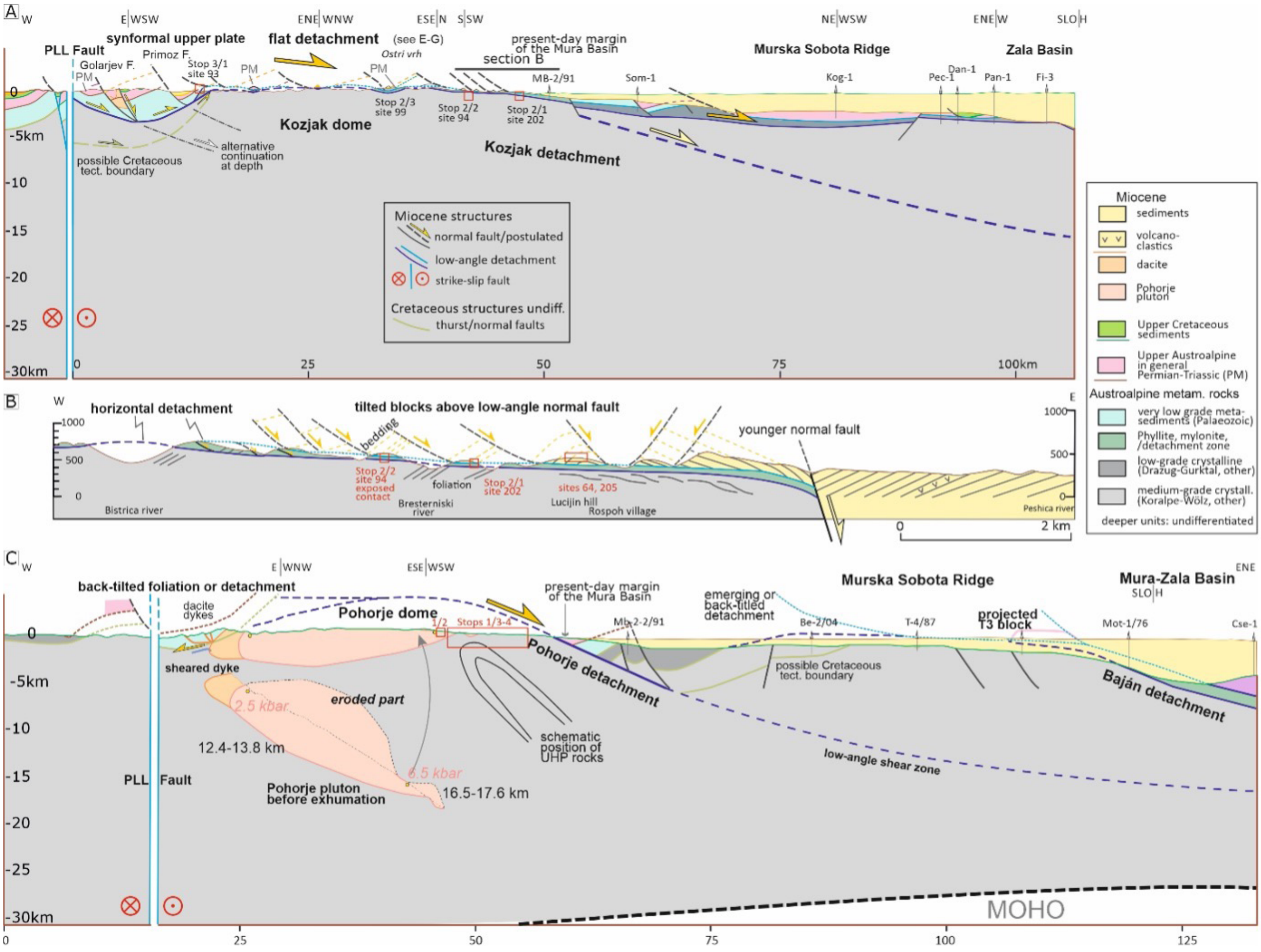

Figure 4: *Cross sections in the Pohorje, Kozjak Mts. after Fodor et al. (2021). a) Across the Kozjak Dome to the NE corner of the Murska Sobota Ridge. b) Detailed section of the gently dipping part of the Kozjak Detachment. c) Cross section from the Pohorje Dome to the MS Ridge (partly after Fodor et al., 2003, 2013). Moho depth is from Horváth et al. (2015) and Kalmár et al. (2018).*

Excursion stops

DAY 1, STOP 1/1 – CASTLE NEAR SLOVENSKE KONJICE:
View of the Pohorje Dome, and the Lavanttal-Labot fault

This stop offers a general view approximately W-E of the entire Pohorje Dome. The gently dipping eastern slope of the mountains is close to but does not correspond exactly to the Pohorje Detachment. Also, the southerly dip of the detachment near Zreče can be seen. The present view shows the denudation of the post-detachment period, and also the neotectonic gentle folding (Sölva et al., 2005) that contributed to the elevated position of the dome.

The long-lived NW-SE striking Pöls-Lavanttal-Labot Fault system (PLLF) runs along the northeastern margin of the Karavanke Mts; the castle sits on a small fault block of this brittle shear zone. As part of the Karavanke Mts., this block is mostly composed of Triassic carbonates. Between the castle and the main Karavanke block late Early Miocene (Karpatian) sediments are entrapped by the shearing (Mioč and Žnidarčič, 1976). In the Eastern Alps branches of the PLLF zone form the boundary of several small Miocene basins (Strauss et al., 2001; Kurz et al., 2011; Reischenbacher and Sachsenhofer, 2013), while it bounds the Slovenj Gradec Basin W of the Pohorje Dome (Ivančič et al., 2018), which contains late Early to middle Miocene (Ottnangian–Karpatian and early Badenian, ~18–13.8 Ma). The fault has a dextral separation of ~14 km (Ratschbacher et al., 1991; Fodor et al., 1998; Frisch et al., 2000; Wöfler et al., 2011). An important feature is that the PLLF displaces the eastern continuation of the Periadriatic Fault but merges with the active Šoštanj fault in the south; thus it is also a neotectonic feature. On the final day we cross the neotectonic folds of the Slovenj Gradec basin between the Periadriatic and PLL Faults.

DAY 1, STOP 1/2 – CEZLAK QUARRY:
Pohorje pluton and associated dykes

The excursion will visit the main quarry and perhaps a second if exploitation permits (Stop 1/2b). The granodiorite exhibits well-developed foliation, which is gently dipping foliation in most parts of the pluton. This was formed during the cooling of the pluton, from 18.65 to ~15 Ma, indicated by thermochronological ages (Fig. 2). The main quarry exposes this foliation, while shear bands were observed in another quarry nearby (Fodor et al., 2020), indicating top-to-east slip (Fig. 5c). This direction is parallel to stretching lineation and to the AMS axes (Fig. 3, 5e). Thus, we relate these deformation features to vertical flattening and an early phase of ~E–W extension during the cooling process, at temperatures of roughly 350–400 °C. This flattening also affected mafic enclaves in the granodioritic main body. On the other hand, few quartz monzodioritic lenses behaved rigidly during this deformation, as observed in the small quarry in Fig. 5c, d, Fodor et al., 2020).

The early extensional deformation could facilitate the formation of aplitic veins, which can be less overprinted by foliation than the host rock. Finally, the plutonic rocks and dykes are cut by brittle-plastic shear zones and brittle faults with variable degrees of drag folding (Fig. 5a). All these deformations show coaxial extension indicated by stretching lineation, AMS axes, shear bands, and faults (Fig. 5e).

DAY 1, STOP 1/3 – SOUTHEAST POHORJE MTS.:
UHP metamorphism

Eclogites (Fig. 6), according to Vrabec et al. (2012), contain a peak metamorphic assemblage of garnet, omphacite, kyanite, and phengite. Pyrope-rich garnet is unzoned and almost free of inclusions. The non-stoichiometric supersilicic omphacite contains up to 5 mol% of Ca-Eskola molecules. The breakdown of omphacite during decompression resulted in the exsolution of oriented rods of silica. Phengite contains up to 3.5 Si a.p.f.u. Polycrystalline quartz inclusions in peak-pressure minerals – garnet, omphacite and kyanite – are surrounded by radial fractures evidencing the former presence of coesite. Peak-pressure minerals are replaced by symplectites of diopside+plagioclase+amphibole after omphacite, plagioclase+biotite after phengite, and sapphirine+corundum+spinel+anorthite after kyanite. Sapphirine generally has a composition close to (Mg,Fe)12.4 Al38.9 Si4.5 O80, which is amongst the most aluminous yet reported. Peak metamorphic conditions were constrained from calculated phase equilibria in the NKCFMASH system with the fixed bulk-rock composition, and conventional geothermobarometry. This approach led to consistent results, the calculated peak P–T conditions of 3.0–3.7 GPa and 710–940 °C, in the stability field of coesite and in the same range as metamorphic conditions recorded by the associated garnet peridotites. This implies that eclogites and their host rocks were subducted to depths of about 100 km.

The garnet peridotites (Fig. 6) are closely associated with UHP eclogites. At least four stages of recrystallization have been identified in the garnet peridotites based on an analysis of reaction textures and mineral compositions (Janák et al., 2006). Stage I was most probably a spinel peridotite stage, as inferred from the presence of chromian spinel and aluminous pyroxenes. Stage II is a UHPM stage defined by the assemblage garnet + olivine + low-Al orthopyroxene + clinopyroxene + Cr-spinel. Garnet formed as exsolutions from clinopyroxene, coronas around Cr-spinel, and porphyroblasts. Stage III is a decompression stage, manifested by the formation of kelyphitic rims of high-Al orthopyroxene, aluminous spinel, diopside, and pargasitic hornblende replacing garnet. Stage IV is represented by the formation of tremolitic amphibole, chlorite, serpentine and talc. Geothermobarometric calculations using (i) garnet-olivine and garnet-orthopyroxene Fe-Mg exchange thermometers and (ii) the Al-inorthopyroxene barometer indicate that the peak of metamorphism (stage II) occurred at conditions of around 900 °C and 4 GPa. These results suggest that garnet peridotites in the Pohorje Mountains experienced UHPM during the Cretaceous orogeny. On the basis of petrochemical data, garnet peridotites

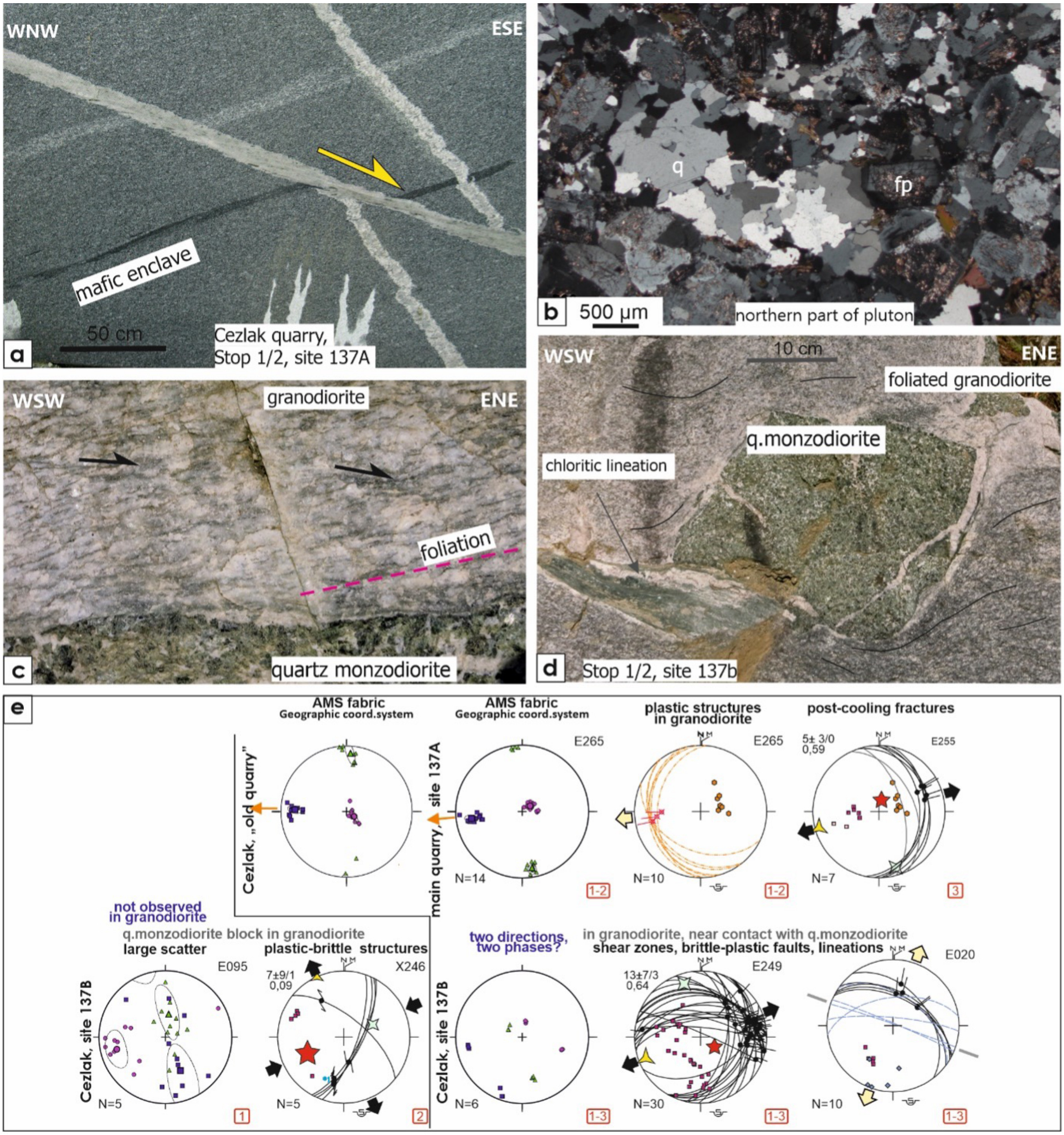

Figure 5: *Deformation features in the Pohorje granodiorite, Stop 1/2. a) Foliated granodiorite, flattened mafic enclaves cut by aplite dykes and cross-cut by east-dipping late fault. b) Dynamically recrystallized quartz and internally undeformed, zoned feldspars in granodiorite. Quartz fabrics indicate grain-boundary migration (GBM) as recrystallization mechanism. Northwestern pluton, shallow intrusion depth. c) Gently tilted foliation and top-to-E shear zones in the pluton, Stop 1/2b (site 137b). d) Map view of foliated granodiorite wrapping internally undeformed quartz monzodiorite. A larger body was sampled for AMS study. Locations of sites see Fig. 2. e) stereoplots of structures and AMS axes for different lithologies. Note dominant ~E–W extension in the main granodiorite and a separate phase in rigid quartz monzodiorite bodies. After Fodor et al. (2008, 2020, 2021) using AMS data of Márton et al. (2006). The Angelier software package (1984) was used to visualise and interpret the data*

Figure 6: *Characteristic rock samples of ultra-high pressure metamorphic rocks; eclogite (left) and garnet peridotite (right).*

could have been derived from depleted mantle rocks that were subsequently metasomatized by melts and/or fluids either in the plagioclase-peridotite or the spinel-peridotite field.

We propose that UHPM resulted from the deep subduction of continental crust, which incorporated mantle peridotites from the upper plate in an intracontinental subduction zone. Sinking of the overlying mantle and lower crustal wedge into the asthenosphere (slab extraction) caused the main stage of unroofing of the UHP rocks during the Late Cretaceous. Final exhumation was achieved by Miocene extensional core complex formation.

DAY 2, STOP 2/1 – NORTH OF BRESTERNICA, JAMŠEKOV POTOK (CREEK):

Structures of the highest blocks of basement, phyllonites

This outcrop exposes the strongly deformed "phyllite" unit that separates the mesograde metamorphics from the overlying Miocene sediments. Here, the low-grade Paleozoic units are missing. In addition to mylonitic to ultramylonitic texture (photo), the rocks exhibit nice extensional shear bands, which have top-to-NE kinematics (Fig. 7d, e). These bands are highlighted by later Fe mineralization. Few porphyroclasts also indicate the same kinematics. The parent rock could be a gneiss, which is exposed in the main valley. In other outcrops (e.g., site 215) garnet-bearing micaschist or gneiss were overprinted by mylonitisation. The K-Ar age from muscovite from this site is 29 Ma, which is interpreted as of mixed age, between Cretaceous and Miocene tectonic phases (Fig. 2, see also paragraph at the next site).

DAY 2, STOP 2/1 – NORTH OF BRESTERNICA, DAY 2, STOP 2/2 – NORTHWEST OF BRESTERNICA, SREDNJE, FARMS OF ČEPE AND VUTE:

Structures of the highest blocks of basement, phyllonites, overlying Miocene sediments

These series of outcrops expose the contact of the tilted Miocene synrift sediment and strongly deformed basement rocks near the eastern Kozjak Detachment (Fig. 4, 7, 8) The Stop 2/2a (site 94a) exposes the tilted Miocene syn-rift sediments above a 10 cm-thick fault gouge and the underlying mylonitic metamorphic rocks (Fig. 7a, b). The contact zone is marked by a dark grey fault gouge which is sub-horizontally lying. Few striae and associated faults indicate N–S extension.

The Miocene clastic beds were tilted by a different direction – to the SW – much like the same direction of nearby outcrops (Stop 2/2b). On the other hand, post-tilt fractures partly displacing the sub-horizontal contact indicate ENE–WNW extension.

Somewhat below the main tectonic contact, in a sharp road cut, mylonitic gneiss ("phyllonite") are exposed (Stop 2/2c). These rocks exhibit top-to-the-ENE shear bands (Fig. 7c). Asymmetric folds were also observed, though their age is unclear (could be related to nappe emplacement or to extension).

Nearby outcrops of the Miocene synrift sediments (site 95) also exhibit fractures having been formed before, during, and after the tilting event. In these sites the extensional directions remained the same NNE–SSW during the tectonic tilt. In a series of outcrops ~5km east of this site, a number of tilted blocks were observed in the Miocene sedimentary rocks (sites 64, 205). Faulting was associated with drag folding (Fodor et al., 2002). Considering the symmetry of conjugate fractures to tilted beds, one part of the fractures was formed before the tilt, while others have a vertical symmetry plane; this latter set is regarded as post-tilt in origin (Fig. 8).

This site has been sampled for AMS study (Sipos et al., 2018; Fodor et al., 2020). After tilt correction, the minimum K3 axes are approximately vertical, whereas the maximum K1 axes are between NE–SW and E–W directions (Fig. 8). This geometry demonstrates that AMS fabric is found in bedding planes and reflects an early deformation episode before the tectonic tilting of the sediments. In fact, AMS fabric mostly registers early deformation when beds were not cemented (and deformed). A comparison with brittle fractures that had also formed at sub-horizontal bed positions show that the early stage of fractures and stress axes indicate a good match with maximum AMS axes (Fig. 8), despite a ~30° difference in angle.

All of this data shows that early extension in the syn-rift sediments could be between NNE-SSW and ENE-WSW (N030E and N065E) (more precise values cannot be deduced from the data) (Fig. 8). Note that a clockwise change in extensional direction is systematically present in the data set of the entire Pohorje (Fodor et al., 2020), and this may have characterized the late syn-rift or early post-rift evolution of faulting.

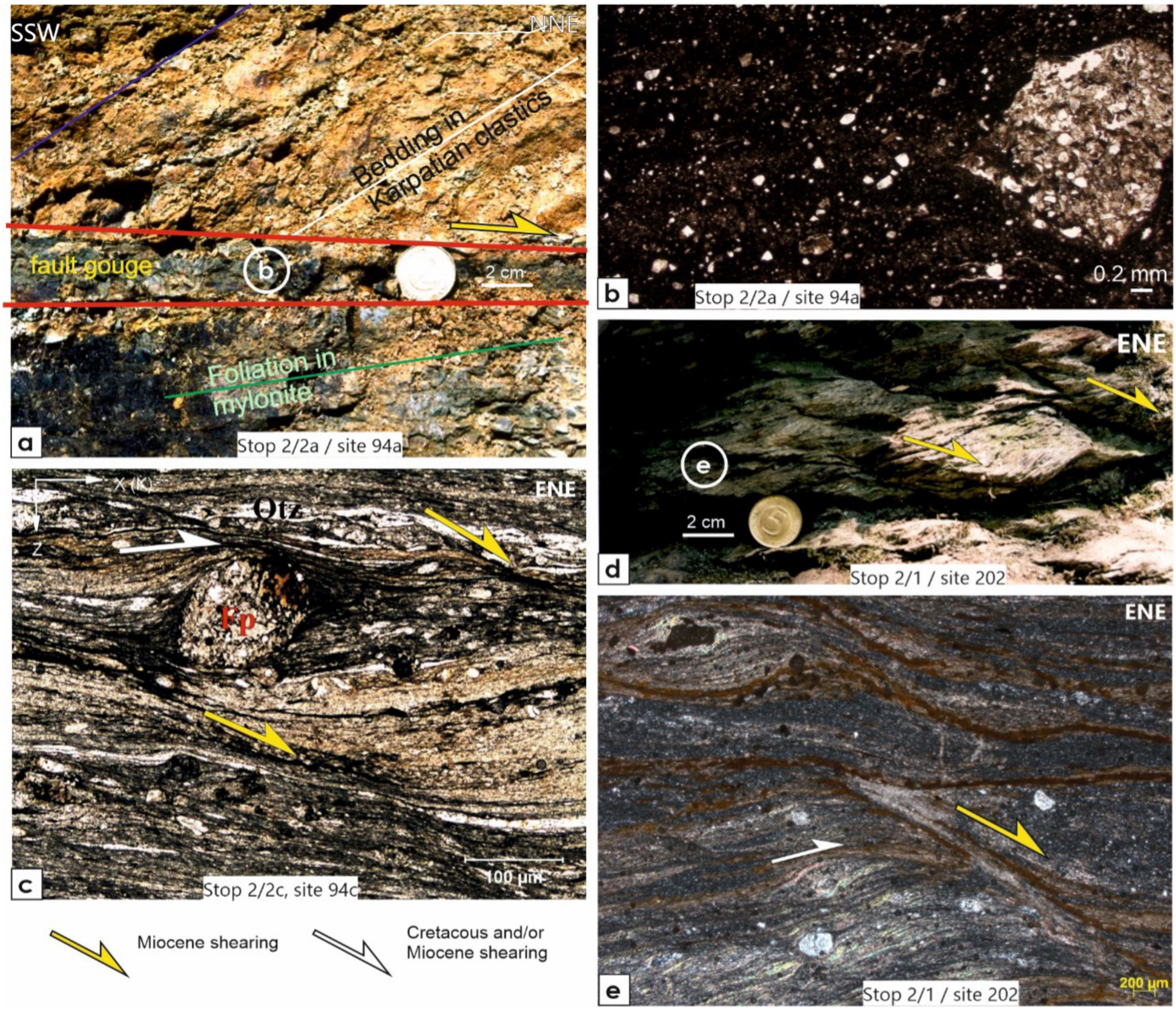

Figure 7: *Structures near the Kozjak Detachment. a) The contact of the Miocene syn-rift sediments and the mylonitic basement rocks. Stop 2/2a, site 94a. b) Photomicrograph of the fault gauge, with scattered quartz grain and one larger grain, probably derived from the Miocene. c) Extensional shear bands in mylonitic gneiss (Stop 2/2c, site 94c). Feldspar porphyroblast indicate top-to-ENE shear, the age of which would be Cretaceous and/or Miocene. d), e) Extensional shear bands in ultramylonite ("phyllonite", Stop 2/1, site 202). White shear indicators refer to an earlier (?) shearing.*

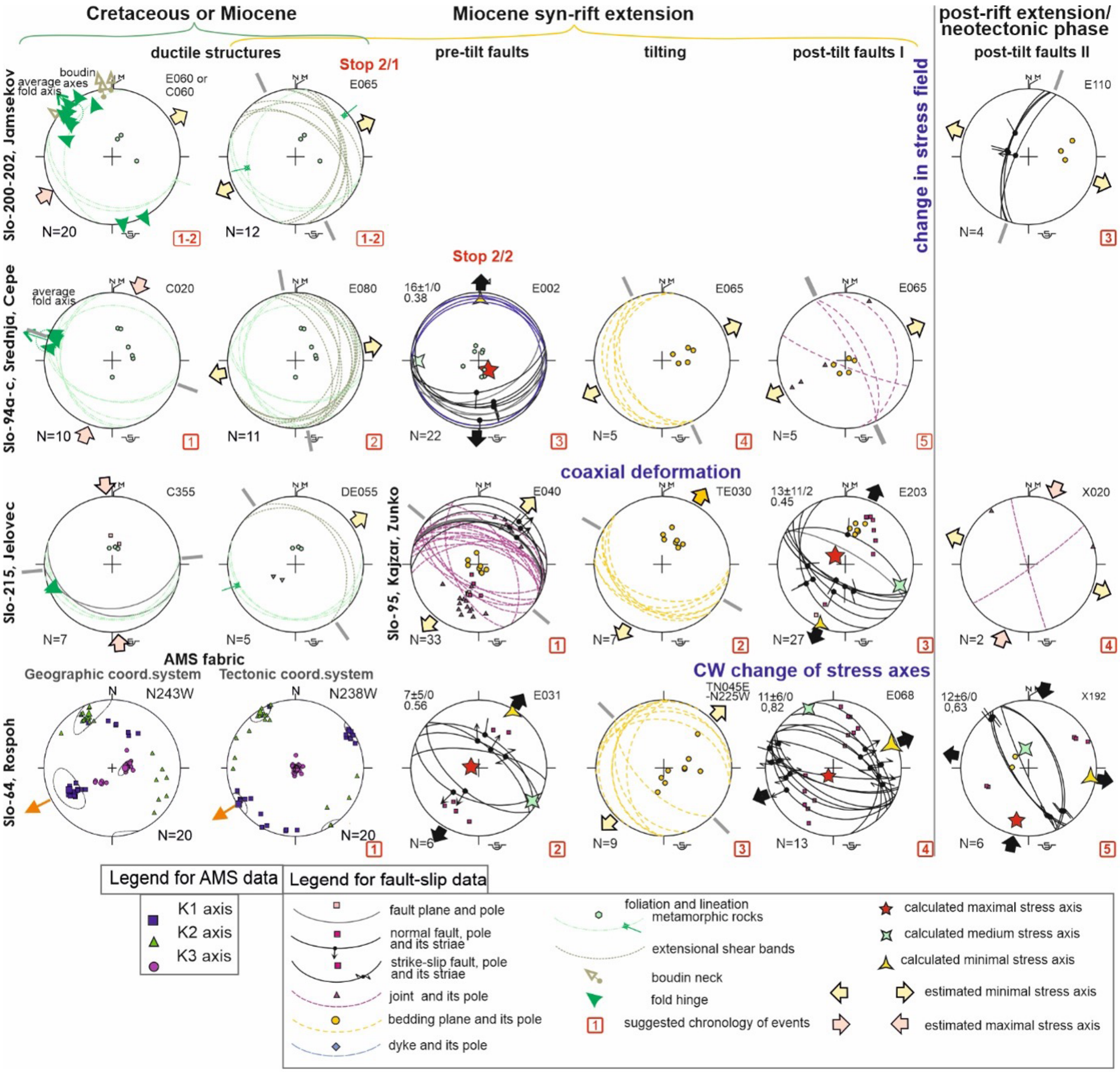

Figure 8: *Stereoplots of deformation features near the eastern Kozjak Detachment.*

Thermochronological data of stops 2/1 and 2/2

The thermochronological data from the eastern part of the Kozjak detachment presents a complex picture (Fig. 3). The mylonitic rocks just under the brittle detachment fault yielded 42 Ma and 29 Ma muscovite ages (Stop 2/2c and Stop 2/1a, respectively) (Fodor et al., 2021). In Stop 2/2a (site 94a), illite K-Ar age of 34 Ma of the fault gouge was obtained. One zircon FT (Stop 2/2c) and one zircon (U-Th)/He age (near Stop 2/1) fall in the early Miocene (23 and 18.7 Ma, respectively). In the syn-rift sediment, located just above the detachment zone, detrital apatite grains show partially reset ages (Fig. 3; Sachsenhofer et al., 1998a). As a result, we interpret the Paleogene K-Ar ages as mixed ages derived from the Cretaceous post-orogenic cooling and from the Miocene exhumation along the eastern Kozjak detachment. Exhumation of the footwall rock could have started in the early Miocene (around 23 Ma). Tilted geometry of the Miocene syn-rift rocks and their tectonic contact show that deformation was still active after 16 Ma. The thermally overprinted syn-rift sediments just above the detachment also argue for Miocene exhumation and advective heat transport to the base of the Mura Basin.

However, an onset of exhumation in the Late Cretaceous is not excluded in this region. In fact, Neubauer et al. (1995) interpreted the origin of the Late Cretaceous basins as the result of extensional exhumation of the footwall and subsidence of the hanging wall. Tilted blocks are also present near the Baján detachment, which may argue for a separate Late Cretaceous extensional phase preceding the Miocene one (Héja, 2019).

DAY 2, STOP 3 – ROAD TO SVETI DUH NA OSTREM VRHU:

Contact of Mesozoic extensional allochton with “phyllite” (mylonite)

The outcrops along the road to the village of Sveti Duh na Ostrem vrhu exposes Triassic carbonates, probably Upper Triassic formations. They are in almost direct contact with the phyllite unit. Although a little patch of Permian is present, the Mesozoic sequence is not continuous anywhere, and is in tectonic contact with the “phyllite” rather than the medium-grade rocks. The contact is not exposed, but the mylonitic “phyllite” can be seen in road cuts. The illite K/Ar method yielded an age of 24 Ma, which can be connected to exhumation along the detachment.

DAY 2, STOP 2/4 – SOUTHWEST OF LOVRENC NA POHORJU:

Variably deformed magmatic dykes at the contact of granodiorite and metamorphic host rock

The outcrop in the creek exposes foliated granodiorite cut by aplitic quartz veins and a dark andesite dyke. In the roadcut, several dacite dykes intruded into the metamorphic host rocks. All structures dip steeply to the south, thus this site represents the lateral side of the pluton, probably closer to the bottom side (Fodor et al., 2008).

The most dominant outcrop-scale ductile structure is the weakly to moderately developed foliation subparallel to the dyke–host rock contact, and its intensity generally changes within a single dyke. In closely spaced dacite dykes, the foliation drastically changes from one dyke to another, although spatially they are only 10 m apart. Dykes in the north exhibit poorly developed mineral lineation. The intensity of the foliation is stronger in the granodiorite than in the intruding andesite dykes, thus the onset of crystal-plastic deformation in the pluton preceded the dyke emplacement (Fig. 9). The granodiorote and the metamorphics show crystalplastic lineation which, however, is only weakly present in the dykes.

On a microscale, the original magmatic quartz has been internally deformed into elongated lenses, locally up to ribbon quartz (Fig. 5). Relic grains display undulose extinction and subgrains, whereas new grains with serrated grain boundaries were formed by dynamic recrystallization. Biotite and amphibole grains are often sheared and suffered pressure solution along foliation planes. Amphiboles are twinned along their long axis. Part of the feldspars phenocrysts are idiomorphic with magmatic zoning and show brittle fracturing (Fig. 9a-c). The shape-preferred orientation of quartz grains in dynamically recrystallized quartz aggregates, feldspar sigma-clasts, mica, and amphibole fishes, (Fig. 9a, c, d), and weakly developed shear bands indicate a top-to-ESE (normal-sinistral) shear sense (Fig. 3). It is the same sense as was deduced from shear bands in the host metamorphics, but this latter could also be a Cretaceous feature.

Dynamically recrystallized quartz, boudinaged biotite, and deformation features in feldspars broadly place the deformation into the higher greenschist facies. Variably deformed feldspars indicate progressively lower temperature for the initiation of deformation. This can be a sign of deformation during cooling, just after dyke emplacement, when the dyke temperature was still high enough to enhance its crystal-plastic deformation process.

Within andesite and dacite dykes, the orientation of magnetic foliations and lineations are close to that of the dyke margins and to the solid-state foliation and weak lineation. It is suggested therefore that the AMS reflects the crystal-plastic deformation of these dykes (Fig. 9e). The AMS value is highest when the foliation and shearing is strongest.

DAY 3, STOP 3/1 – SOUTH OF RIBNICA NA POHORJU:

Granodiorite dykes in host metamorphic rocks

This section exposes a similar tectonic situation as Stop 2/4. Several granodiorite dykes and one darker mafic dyke intruded into the host metamorphic rocks parallel to the boundary of the main granodiorite pluton. Dyke thickness varies from 15 cm up to 12 m. Dyke boundaries dip steeply SSW. Dyke margins are parallel

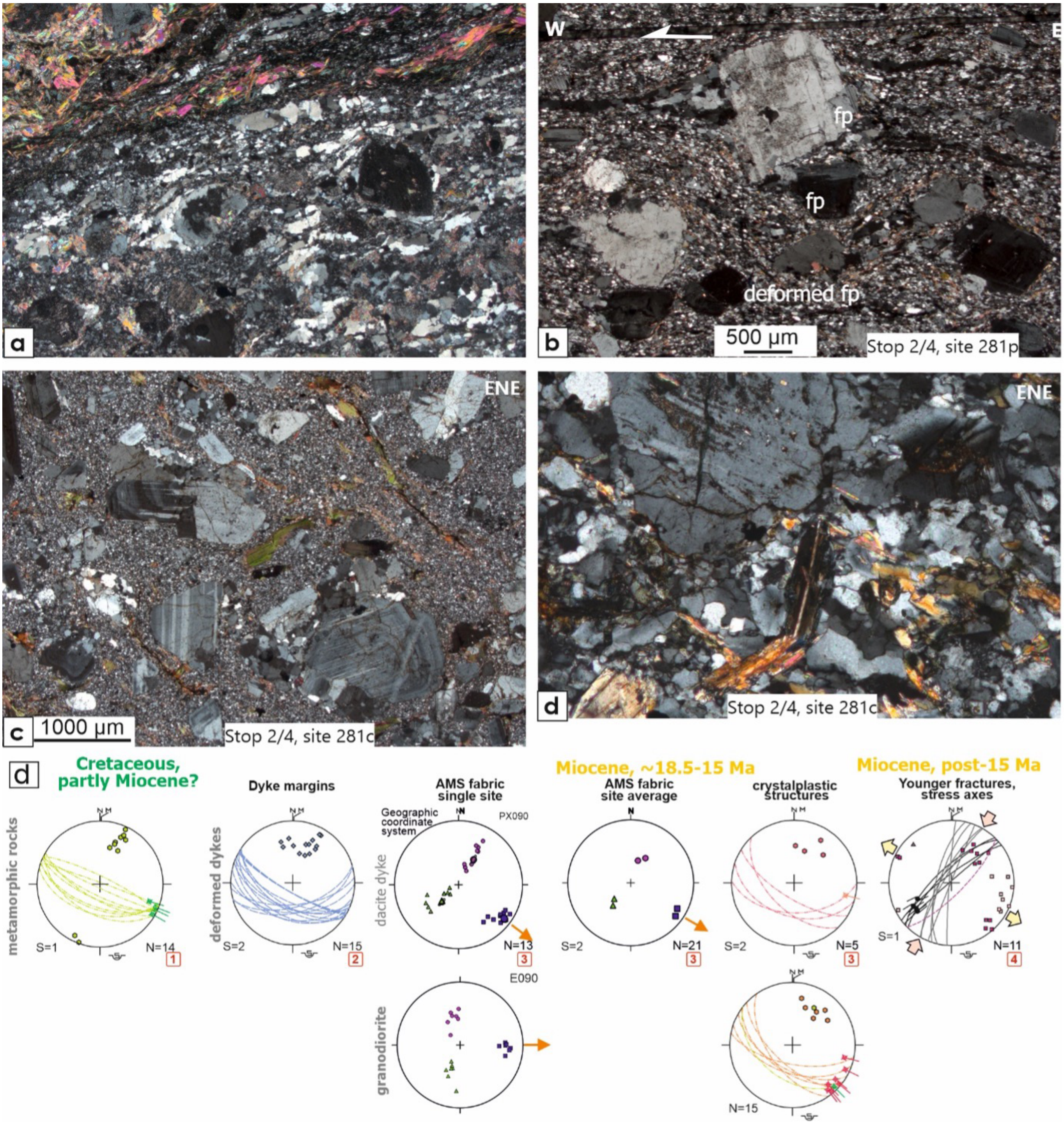

Figure 9: *Deformation features in variably deformed dacite and andesite dykes in Stop 2/4, site 281, SW of Lovrenc na Pohorju, Radoljna creek. a) Contact of granodiorite and metamorphic host rock. The magmatic rock shows foliated texture. Quartz grains are recrystallized with GBM, show undulose extinction, and sub-grains. Vertical view. b) Sigma clasts in foliated andesite dyke, intruded into granodiorite, sub-horizontal view. Note recrystallized quartz grains and zoned undeformed feldspar grains. c) Weakly oriented texture in a dacite dyke intruding metamorphic rocks, just near the northern contact of the granodiorite. Section perpendicular to dyke margin. d) Dynamic recrystallization of primary feldspar phenocrysts at the margin of the same dacite dyke as in c), 20 cm away. Locations of the site see Fig. 2, 3. e) Stereoplots of mesoscale structures in metamorphic rocks, granodiorite, dacitic and andesitic dykes, after Fodor et al. (2020). For legend, see Fig. 7.*

to foliation in host metamorphic rocks for both rock types (Fig. 10). Lineation is gently ESE plunging, similar to the features in stop 2/4. Sinistral shear sense is indicated by quartz lenses (Fig. 10). The temporal relationship of this structure to granodiorite emplacement is not clear – they could be Cretaceous or Miocene, as in Stop 2/4. Foliation in granodiorite is expressed in a thin section and by AMS fabric (Fig. 10).

Structural evolution may be similar to stop 2/4; (1) formation of foliation in host metamorphic rocks, (2) their tilting (folding?) to steep position, (3) intrusion of the granodiorite and mafic dykes, (4) acquisition of AMS fabric and foliation, (5) cooling and post-cooling fracturing. Tilting could be related to pluton emplacement, but this was not further explored nor analysed.

DAY 3, STOP 3/2 – SOUTH OF VUHRED, ROAD WESTWARD FROM BREKOVA KOCA TO SVETI ANTON NA POHORJU:
Strong deformation of Miocene sediments near the contact with basement rocks

This exposes the syn-rift sediments located very close to the contact with underlying metamorphic rocks. The main feature is the strong deformation of the clastic rocks. Near this site, the Kozjak Detachment dips below the NW branch of the Ribnica-Selnica synform (Fig. 2, 3) roughly to WSW (Fig. 4). The underlying rock pile consists of Triassic(?) sandstone, phyllite, (not shown on the map) and amphibolite; the two former units are strongly reduced in thickness. The exposed basal syn-rift beds exhibit

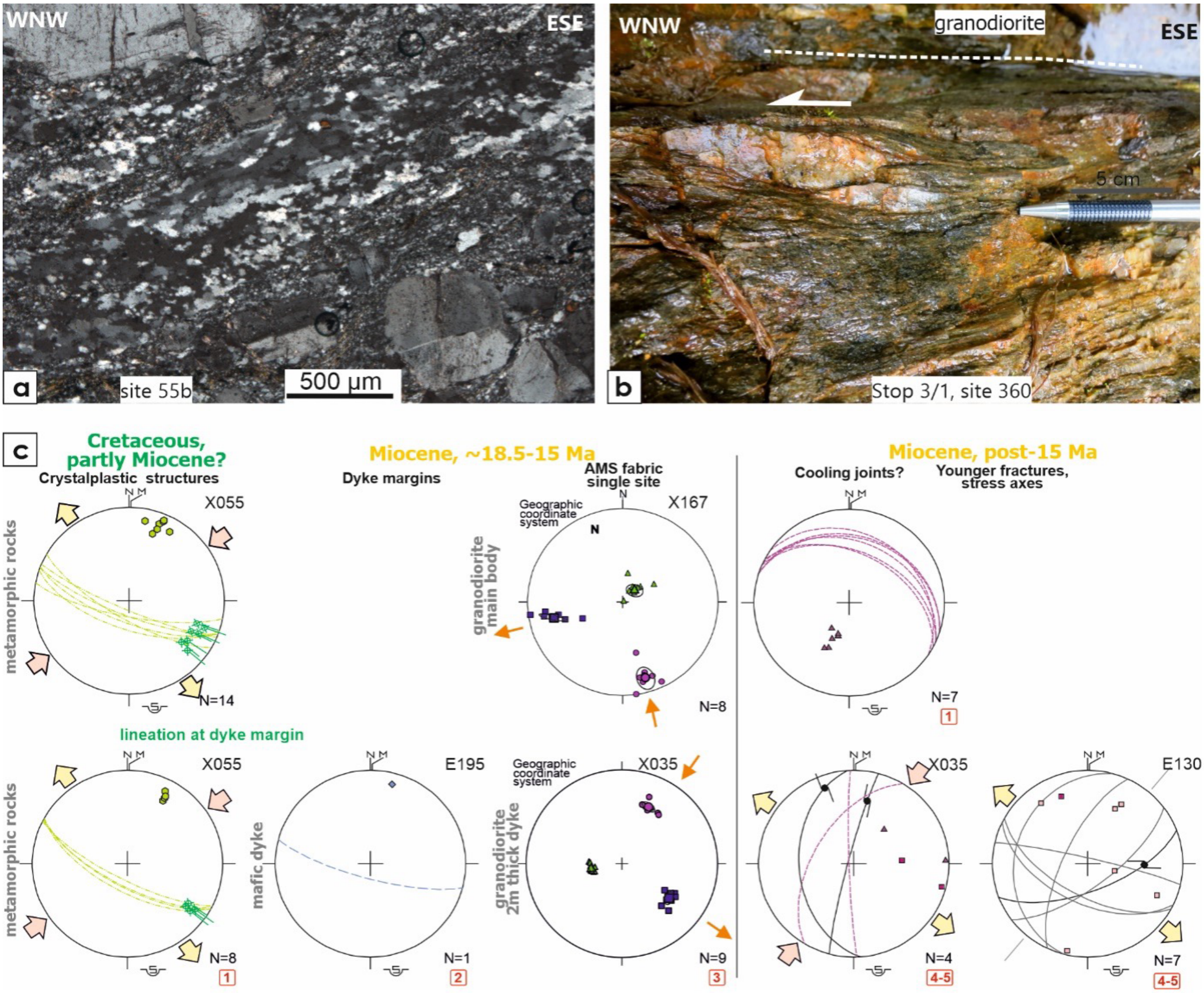

__Figure 10:__ Structures at the northern contact of the pluton, in Stop 3/1, site 360. a) Quartz aggregates recrystallized by sub-grain rotation along the northern pluton margin. b) Map view at the northern contact of the granodiorite, in host metamorphics. Quartz lens indicates sinistral shear sense. c) Stereoplots of the measured structures and AMS data (Fodor et al., 2020).

strong cataclastic deformation with a dense network of fractures with rigid clasts cut by extensional quartz veins (Fig. 11a, c). The veins are oblique to the main shear fractures indicating normal shearing. The organic-rich fine-grained layers are plastically deformed and cut by numerous calcite veins (Fig. 11d). The rotated decimetre-scale dominoes and intervening low-angle faults dip both to NE and W-SW and show no definite shear direction, although top-to-the west shear dominates (Fig. 11b).

With detailed fault-slip analysis several faulting episodes can be deduced, although paucity of well-preserved striae and the scatter of data do not allow for a firm conclusion (Fig. 11e). Two sets of normal faults were formed before the tilt of the layers, by NE–SW and E–W extension. The latter direction of extension affected the rocks after the tilt (observed ca. 100m to the west), while NNE-SSW trending sinistral strike-slip faults also deformed the main outcrop.

AMS data points to WNW–ENE elongation when restored to horizontal bed position (Fodor et al., 2020). Although this direction is between the two early faulting events, the data also points to early extensional strain (Fig. 11e).

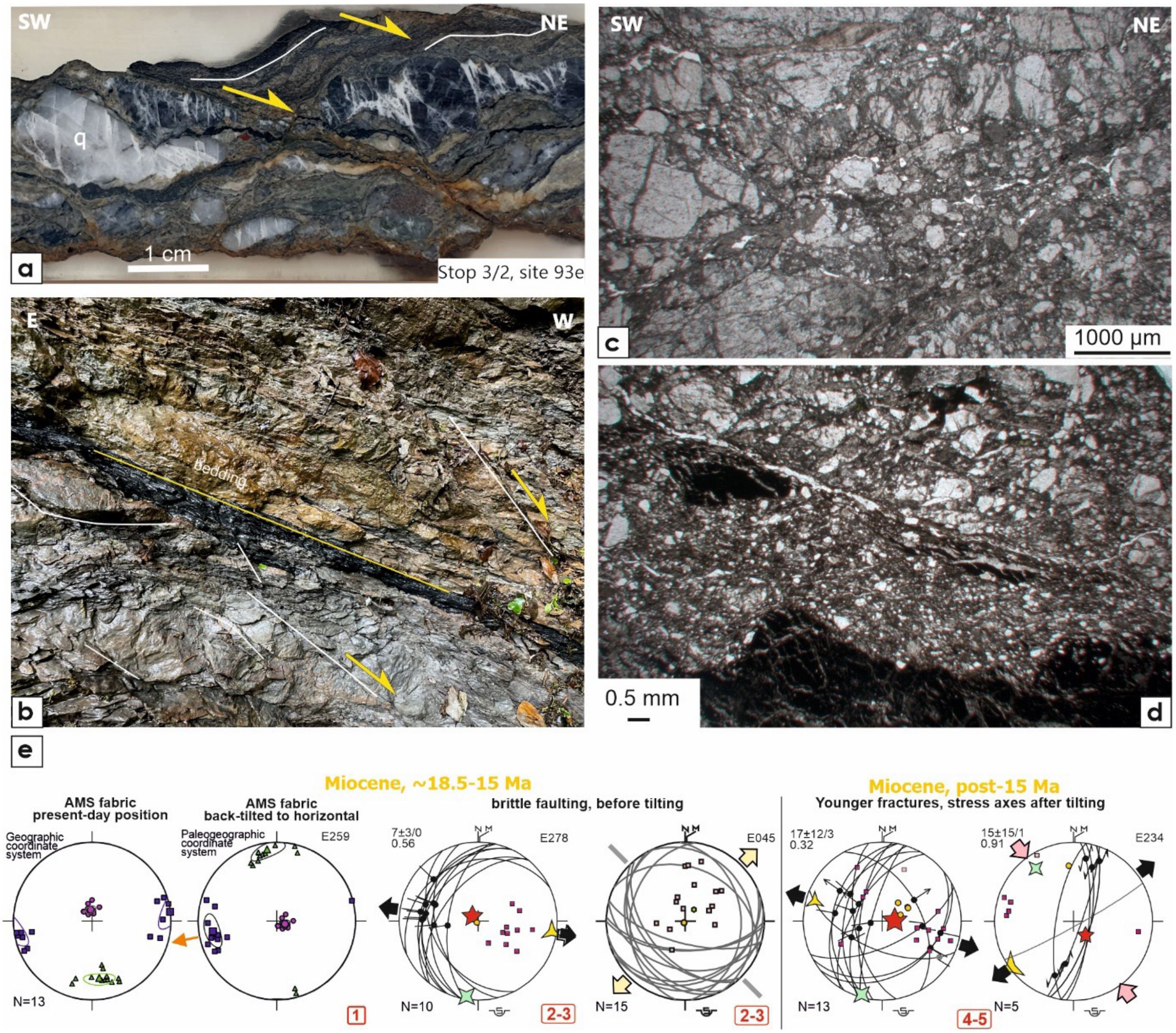

Figure 11: *Brittle structures at Stop 3/2. a) Polished surface of strongly fractured Miocene syn-rift sediments. b) Field view of west-tilted beds dissected by low-angle faults. c) Cataclastic structure of the sample in a). d) Fractured sandstone layers and deformed organic-rich clay dissected by thin calcite veins. e) Stereoplots of fractures and AMS data (completed after Fodor et al., 2020, 2021).*

The pre-tilt fracturing and the AMS fabric formed in connection with the Kozjak Detachment. From these structures it is not evident whether the shearing had top-to-NE or top-to-SW kinematics.

DAY 3, STOP 3/3 – SOUTH OF VUHRED, SVETI ANTON NA POHORJU, FARMS CAVK, HRIBERNIK, LESNIK:

Lovenc fault, geometry, kinematics

This series of outcrops exposes the formations near the Lovrenc Fault, a prominent E-W striking fault of the Pohorje. The fault bounds the mesograde rocks in the south, while the Ribnica-Selnica synform is in its northern side. In the outcrops, steeply dipping Senonian, moderately dipping Miocene sedimentary rocks occur in an N-S section (Fig. 12).

The map view of the fault implies its steep to sub-vertical dip (Fig. 2, 3). In the eastern part, the fault has a few parallel branches which join the N-S trending gently dipping main Pohorje Detachment. In the west, the Lovrenc Fault is connected to the NW-trending normal fault system of the northwestern Pohorje (Primož and Golarjev faults), via direct fault segments, relay ramps, and a postulated E-W trending branch concealed by the dacite body (Fig. 2, 3). In this transitional area, the fault could change laterally to a monoclinal fold because there the contacts between Paleozoic, Cretaceous, and Miocene rocks are steeply dipping or sub-vertical and only slightly disrupted; this is the segment the excursion visits. The fault's displacement varies along the strike and seems to follow the amount of exhumation of the Pohorje Dome, because Triassic rocks occur at the same elevation all along the hanging wall.

Stress data from the hanging wall of the Lovrenc Fault (the R-S trough) indicates two extensional deformation phases with the $\sigma3$ axes trending NE–SW to E–W (D1 phase) and E–W to ESE–WNW (D2 phase) (Fig. 3). The data implies that the Lovrenc Fault acted as a steep dextral fault with a normal slip component during the main syn-rift phase, while the kinematics during the D2 phase is less clear. Alternatively, the fault could also act as a reverse fault or would represent the vertical limb of a contractional fold that could develop during the D3 neotectonic phase of N–S compression. However, fault slip data for the D3 phase always exhibits a strike-slip component and never dip-slip reverse faulting, which makes a single-phase contractional character of the Lovrenc Fault much less viable or likely.

The most plausible kinematic scenario for the Lovrenc Fault is a syn-rift transfer fault, superimposed by contraction and verticalization of the fault (Fig. 12). Because the Lovrenc Fault accommodates the exhumation of the Pohorje Dome, it could also be a stretching fault, like those observed around the eastern Tauern window (Kurz and Neubauer, 1996; Schmid et al., 2013).

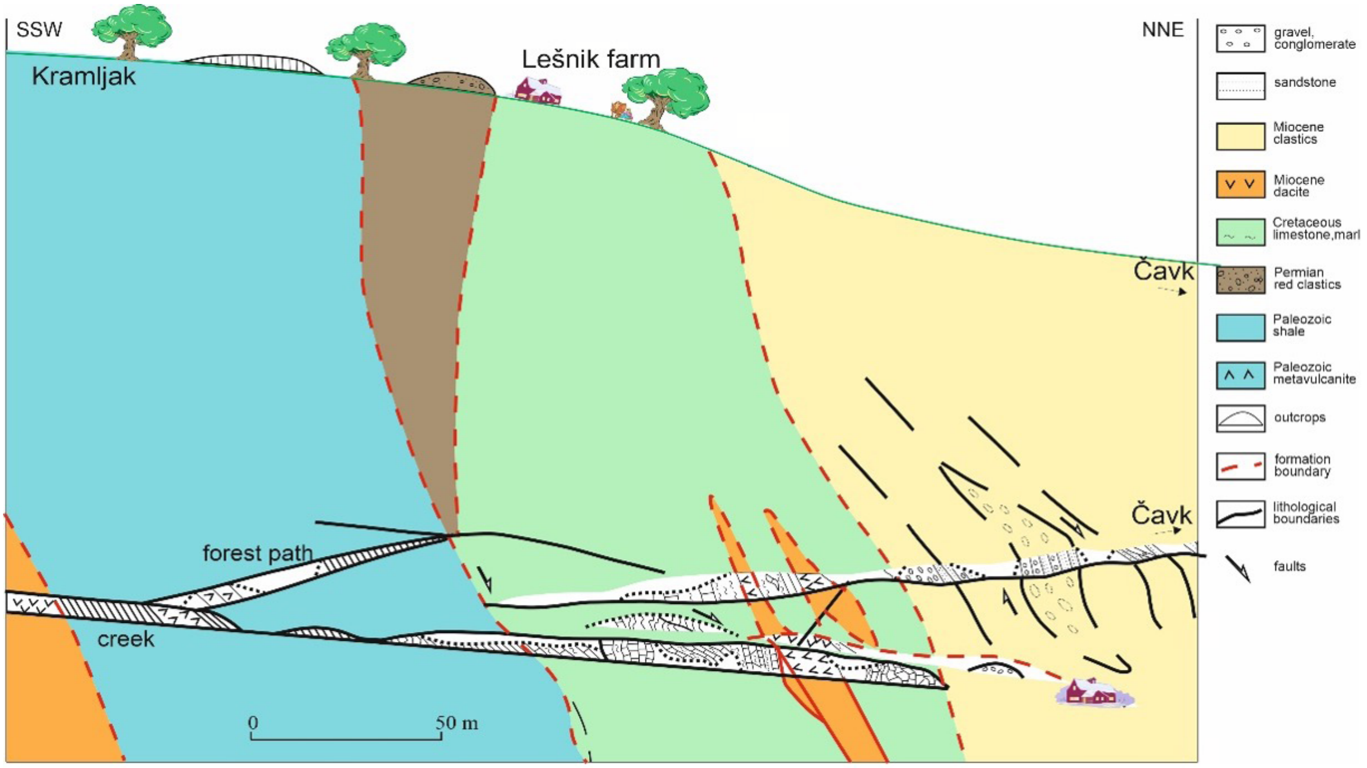

Figure 12: *Observations along the Lovrenc Fault near Stop 3/3. Note the sub-vertical position of Paleozoic and Mesozoic units, and steeply dipping Miocene rocks.*

DAY 3, STOP 3/4 – ČRNI POTOK TRIBUTARY OF THE VELUNJA RIVER: *Sedimentary evolution of the Slovenj Gradec Basin*

The road cut sections provide insight into the Miocene evolution of the Slovenj Gradec Basin in northern Slovenia, which was studied by mapping, section logging, nannoplankton biostratigraphy, and petrography. The results are correlated with the lithological column of the MD-1/05 borehole. The evolution of the basin is connected with the development of the Pannonian Basin System, and the global 3rd order cycles, which influenced the connection with the Mediterranean Sea. Sedimentation started in the Karpatian in a fluvial to lacustrine environment and terminated at the end of the Early Badenian (Fig. 13).

During this period, three transgression–regression cycles were recorded. The first transgression occurred in the Karpatian and corresponds to the TB 2.2. cycle. The sediments reflect the proximity of the hinterland. After a short break in sedimentation, the Early Badenian deposition followed (Fig. 13). It marks the second transgression into the SGB, the first Badenian, correlated with the TB 2.3 cycle. There are signs of a transitional environment, which evolved to marine in advanced stages. At the highstand system tract, the sea flooded the entire Slovenj Gradec Basin. The subsequent diminished quantity and diversity of the microfossils marks the onset of the second regression stage. It is followed by the third transgression, the second in the Badenian, correlated with the TB 2.4 cycle. The late Early Badenian deposition continued in the lower-energy, though occasionally still turbulent environment. Silty sediments with increasingly higher organic matter content indicate a shallowing of the basin, until its final disappearance. Layers of fresh-water coal already bear witness to the existence of restricted swamps. After the Early Badenian, the area of the Slovenj Gradec Basin became dry land, exposed to erosion.

DAY 3, STOP 3/5 – ROAD SOUTH FROM VELENJE: *Dextral faulting along the Šoštanj Fault*

This stop allows for discussion of the evolution of the wide shear belt associated with the Periadriatic Fault and other related faults in this part of Slovenia. This segment of the Periadriatic Fault comprises duplexes of the Oligocene Karavanka tonalite, Permian Granite, Paleozoic rocks, and a thin metamorphic rock belt (Fig. 14a). Fault-slip data and the strike-slip duplexes indicate clear dextral kinematics. The eastern part of the fault is covered with Karpatian sediments of ca. 17.2–16 Ma (Fodor et al., 1998), suggesting that the major displacement is pre-17Ma (Fig. 14a, b). This precisely matches the time constraints from the Pannonian Basin. The southern part of the Slovenj Gradec Basin has been considerably folded (Stop 3/4), which may represent a Pliocene to Quaternary deformation (Fig. 14).

The internal structure of the Southeastern Karavanka Mts. is not known in detail, but here we emphasize their strongly sheared character. The best example is a narrow zone composed of sub-vertical Eocene layers formed due to dextral transpression (Fig. 14a) (Fodor et al., 1998). The Donat Fault is a narrow zone that includes dozens of Permo-Mesozoic and Oligocene strike-slip duplexes (Fodor et al., 1998) and also separates domains of different Cenozoic stratigraphy (Jelen et al., 1992).

The Šoštanj Fault bifurcates from the Smrekovec Fault from the southern side of the Oligocen Karavanka tonalite, then forms the southern boundary of the Velenje Basin, and eastward merges with the PLL Fault (Fig. 2). Fault-slip data on the surface indicates dextral kinematics of the fault (Fodor et al., 1998), while subsurface fault branches displacing the Velenje lignite deposit are considered Riedel shears of the main fault (Vrabec, 1999). Lenses of Mesozoic rocks involved in the fault zone are interpreted as strike-slip duplexes (Fodor et al., 1998). The dextral step of the Paka river and tributaries supports the active role of the fault in the drainage network and may document a Quaternary dextral slip. However, short-duration GPS campaigns were not able to verify recent dextral slip (Vrabec et al., 2006).

The Velenje Basin is a unique element that determines the age of faulting (Fig. 14b). The basin contains up to 1000 m of Pliocene to Quaternary deposits that thicken considerably southward toward the Šoštanj Fault (Brezigar, 1986). The extremely thick basin fill, with the observed en echelon fault zones, demonstrates Pliocene transtensional slip along the Šoštanj Fault. On the other hand, the basin fill covers all the faults of the Southeastern Karavanka and the Donat Fault, demonstrating their pre-Pliocene activity. In this way, the activity of the Donat Fault can be constrained as post-Badenian and pre-Pliocene, ~13-5 Ma. This time span may correspond to a regional contractional or transpressional phase that characterizes the southwestern Pannonian Basin (Fig. 14b).

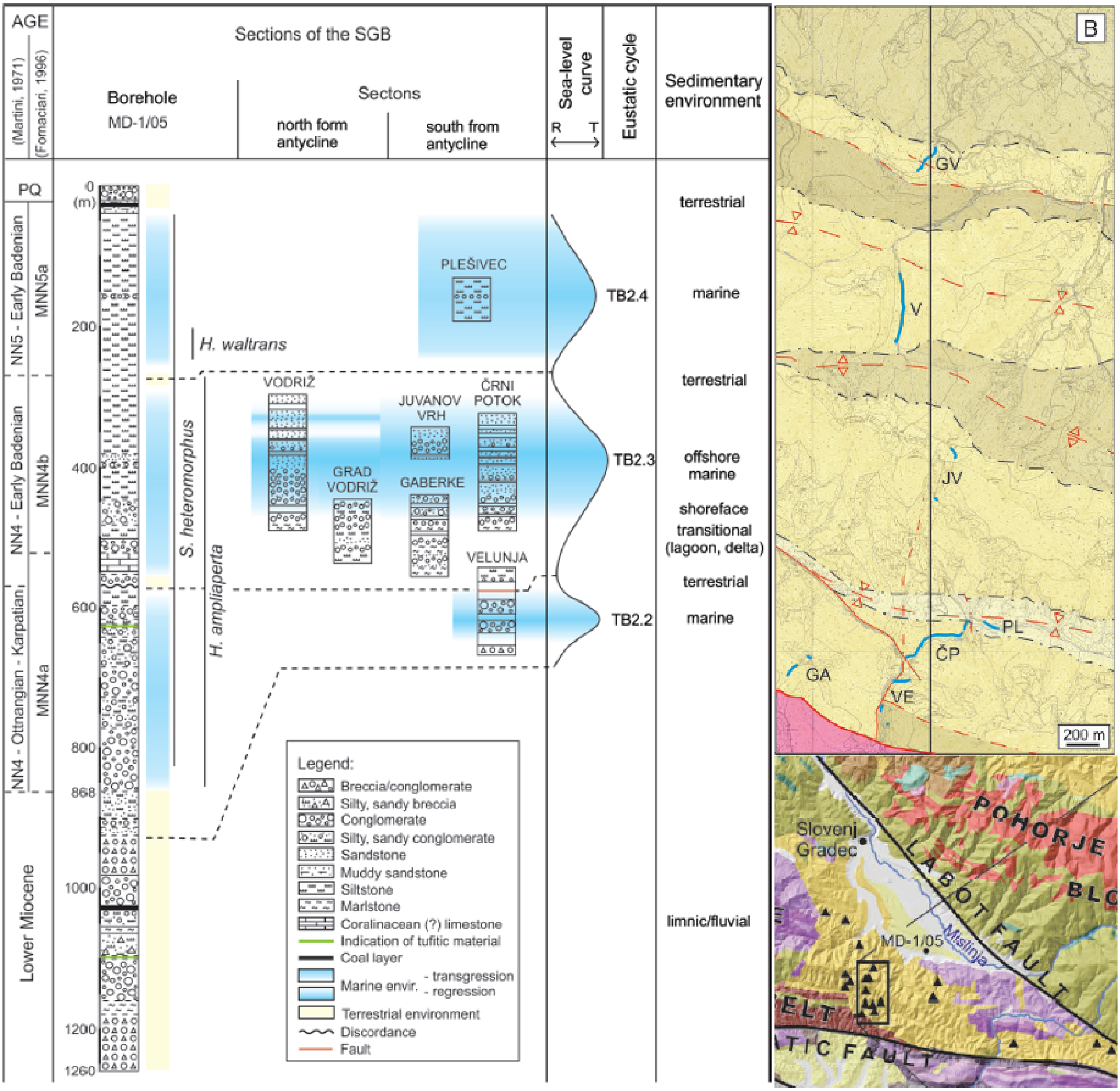

Figure 13: Simplified sedimentological column of borehole MD-1/05 (with the range of biostratigraphic markers) correlated with the sections recorded in the Slovenj Gradec Basin, and their common correlation with the regression-transgression stages in the Karpatian and Early Badenian, correlated to the Haq et al. (1988). There are differences in the type of sedimentary environment, due to the location of the borehole (distal part) and separate sections (marginal part). b) Location of sections on a geologic map that also shows the younger (neotectonic?) folding. Inset shows the wider location of sections and the MD-1/105 borehole. All figures are after Ivančič et al. (2018).

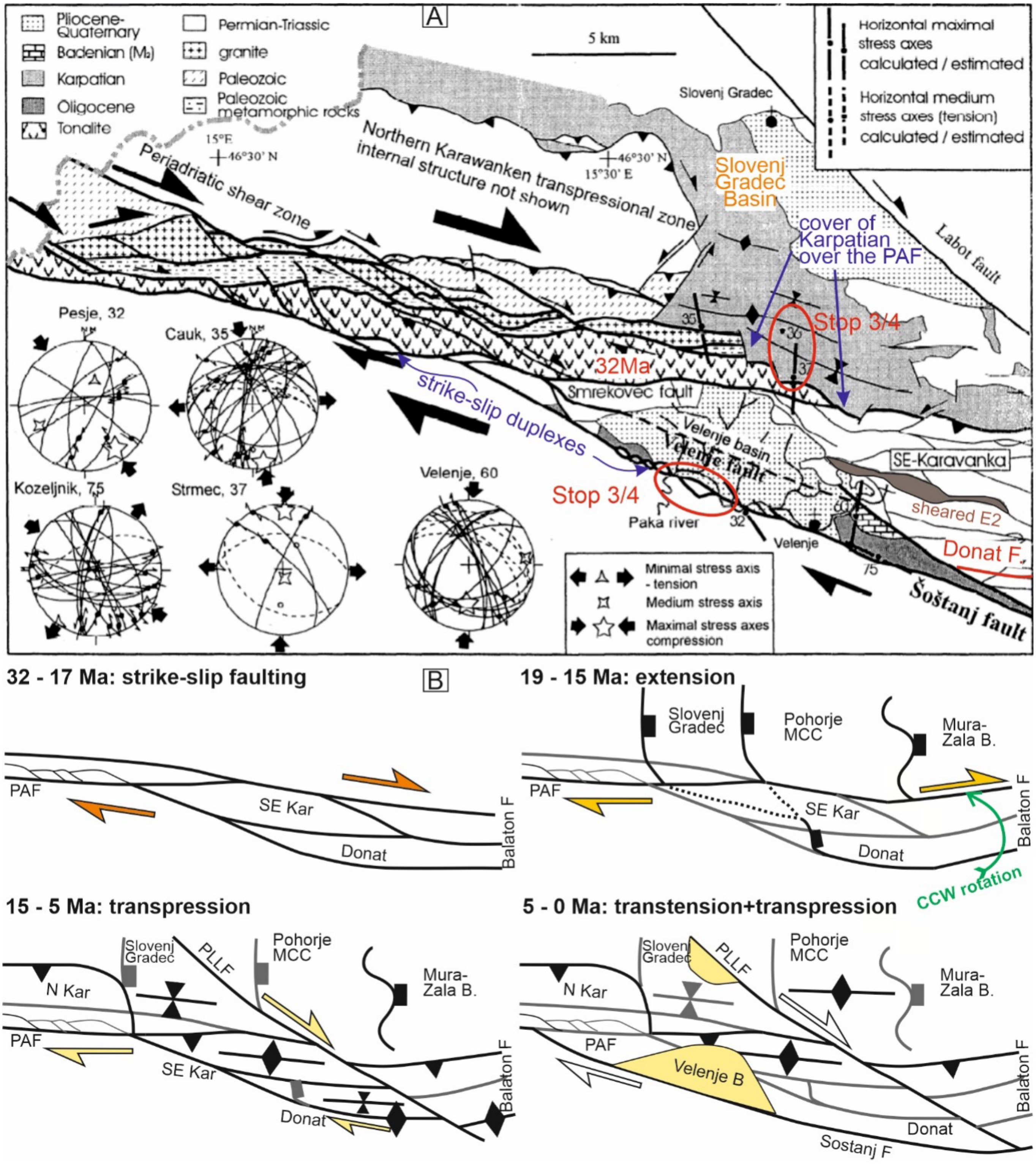

Figure 14: *Fault systems around Stops 3/4 and 3/5, after Fodor et al. (1998). b) Schematic illustrations showing the evolution of some major structures in the transitional segment of the Periadriatic Fault to the Balaton Fault Zone.*

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Marine reptile-bearing Anisian limestone of the Velika planina mountain pasture

FIELDTRIP C

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Introduction

The Early Triassic transgression at the eastern tropical margin of Pangea led to the establishment of a mixed, carbonate-siliciclastic ramp, which to the east gradually sloped towards the Palaeotethys Ocean. The variegated mixture of bedded dolostone, marlstone, carbonate sandstone, siltstone, and oolithic limestone is known as the Werfen Formation. Well-known exposures of it are known from Austria (Krainer and Vachard, 2011), and northern Italy (Posenato, 2008; Brandner et al., 2016), as well as from Slovenia (Novak, 2001) and other countries along the Dinarides mountain chain (e.g., Aljinović et al., 2011, 2018). Towards the top of the Werfen Formation, the siliciclastic component gradually gives way to purely carbonate sedimentation, where a shallow marine carbonate platform developed (Buser, 1989). Although this carbonate platform generally disintegrated only in the latest Anisian or earliest Ladinian (Buser, 1989; Celarc et al., 2013), when the area experienced crustal extension due to the spreading of the Neotethys Ocean, a few tens of meters of early – middle Anisian dark, bituminous and finely-laminated, thin-bedded limestone from the Kamnik-Savinja Alps and the Julian Alps testifies to an earlier formation of (probably normal fault-controlled) intra-platform basins. Named for its occurrence on the Velika planina mountain pasture as the Velika planina Member, this unit yielded some spectacular finds of marine reptiles and fishes, as well as some other fossils (Hitij et al., 2010a; Tintori et al., 2014a).

Outline of the field trip

The fieldtrip will take us into the southern parts of the Kamnik-Savinja Alps. We make our first stop in the town of Kamnik (Fig. 1) for an introduction to the structure of the Kamnik-Savinja Alps (field-stop 1). We continue along the narrow valley of the Kamniška Bistrica River, strewn with glacial deposits, pass the Predaselj canyon, where the river carved its bed into massive (Middle Triassic to lower Upper Triassic) limestone, and finally stop at the Dom v Kamniški Bistrici hut for an introduction to the stratigraphic succession of the Kamnik-Savinja Alps (field-stop 2). Providing the conditions are in our favour, we will then backtrack our way back and take the cable-car to the Velika planina pasture on the Velika planina plateau (field-stop 3). After filling our lungs with fresh air, we take a one-hour easy walk to the southern part of the plateau. Our feet will initially be trampling the Middle Triassic – Carnian platform limestone and dolomite, rich in dasycladacean algae, but, after passing a fault, we then focus on the spectacularly folded beds of the Velika planina Member. We stop at the Jarški dom hut (field-stop 4) for lunch and an examination of the Anisian platform carbonates and the base of the Velika planina Member. The typical facies of the lower part of the Velika planina Member is exposed around the Gojiška planina pasture (field-stop 5). After returning to the cable-car and catching our breath, we descend back down to the valley.

Figure 1: Locations of field-stops (see text for description).

STOP 1 – KAMNIK: Geological structure of the Kamnik-Savinja Alps

The Velika planina plateau is situated in the southern part of the Kamnik-Savinja Alps (KSA), which structurally belong to the eastern Southern Alps (Placer, 1999). The KSA and the neighbouring Karavanke range together form a transpressive structure between the two major Neogene dextral strike-slip faults: the Periadriatic fault and the Sava fault (Fig. 2). The lens-shaped domain between the two faults is dissected by sinistral NE-SW-striking faults, along which significant vertical-axis rotations occurred, as demonstrated by paleomagnetic data (Fodor et al., 1998). This transpressive deformation, which is likely post-6 Ma in age, complicates the original geological relationships, which are still poorly understood. Many geological, geomorphological, and geodetic indicators demonstrate that this system is tectonically still active. According to Placer (1999) and Celarc et al. (2014), the entire area of the KSA belongs to the Julian Nappe, a part of the late Neogene South-Alpine thrust system. After the nappe emplacement, between 10 and 20 km of dextral displacement on the Sava fault separated KSA from the Julian Alps.

The Mali Grad viewpoint provides an excellent panorama of the central KSA. At the foot of the mountains the Sava fault makes a restraining bend, which folded the thick succession of Miocene sediments of the Tunjice Hills in its foreland into an overturned syncline. The steep southern slopes of the Velika Planina plateau dominate the eastern half of the panorama. In the central part, the barren peaks of Mts. Skuta, Turska gora, Brana, and Planjava reach up to 2500 m in elevation. These peaks are built exclusively of mid- to late Triassic carbonate rocks.

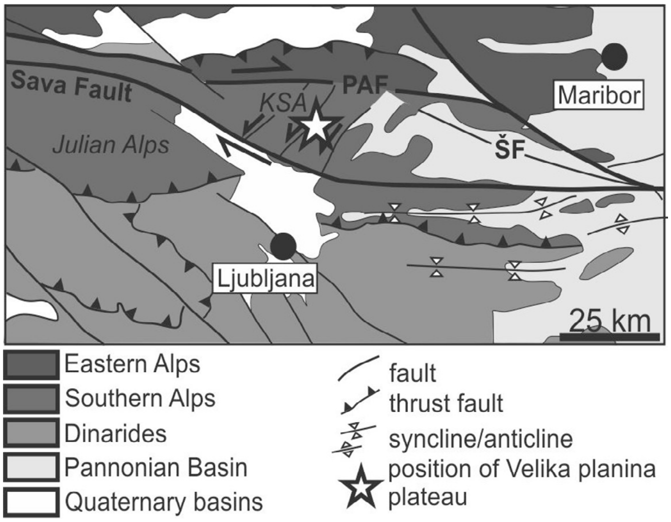

Figure 2: *Generalized geological structure of northern Slovenia with the Velika planina plateau marked with a star. PAF – Periadriatic Fault; ŠF – Šoštanj Fault.*

STOP 2 – DOM V KAMNIŠKI BISTRICI: Triassic stratigraphy of the Kamnik-Savinja Alps

The Triassic succession in the Kamnik-Savinja Alps starts with the Lower Triassic Werfen Formation, comprising bedded micritic limestone, subordinately marly limestone, siltstone, and oolithic limestone (Mioč, 1983; Celarc, 2004). The Werfen Formation is followed by light grey thick bedded to massive dolomite (locally limestone) with oncoids, stromatolites, bivalves, and gastropod lumachellas, equivalent to the Lower Serla Dolomite (Fig. 3). The peritidal facies laterally and vertically abruptly pass into an early to middle Anisian succession of dark platy and finely laminated limestone of the Velika planina Member (Hitij et al., 2010a). The latter gradually grades back into peritidal facies. The Lower Serla Dolomite upwards passes into marlstone, mudstone, thin- to medium-thick bedded limestone and dolomite of the middle to upper Anisian Strelovec Formation (Miklavc et al., 2016). The Strelovec Formation is concordantly overlain by the upper Anisian Contrin Formation, comprising shallow marine bedded and massive limestone, or locally dolomite. Near the top, the Contrin Formation locally constraints small half-grabens filled with upper Anisian red radiolarian-bearing limestone of the Loibl Formation, upper Anisian and/or lower Ladinian volcanics and volcaniclastics, polymictic breccias, marls and hemipelagic limestones of the Buchenstein Formation (Celarc et al., 2013). Massive limestone of the Ladinian Schlern Formation follows. At the top, the platform carbonates locally truncate at the upper Ladinian volcaniclastics, platy cherty limestone, and calca-

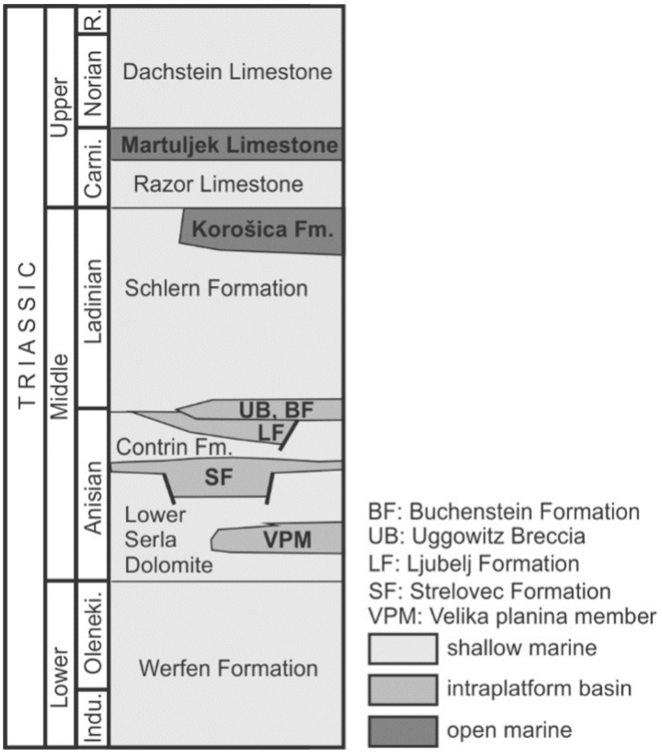

Figure 3: *Stratigraphic successions for Triassic units in the Kamnik-Savinja Alps (from Žalohar and Celarc, 2010).*

renite of the Korošica Formation (Jurkovšek, 1984; Celarc, 2004; Žalohar and Celarc, 2010), or end with breccias, which mark a stratigraphic gap with the lower Carnian Razor Limestone. The later comprises peritidal limestone in Lofer cycles and is similar to the Norian-Rhaetian Dachstein Limestone. The two peritidal units are separated by the upper Carnian Martuljek Platy Limestone, which is relatively rich in conodonts, ammonoids, and brachiopods (Ramovš, 1986; Celarc and Kolar-Jurkovšek, 2008; Celarc et al., 2014).

From the Dom v Kamniški Bistrici hut, a panoramic view opens towards the Kamnik-Savinja Mountains. The highest visible summits belong to Mt. Grinovec (2558 m) and Mt. Skuta (2532 m) (Fig. 4). The lower slopes of the mountains are made of lower Carnian Razor Limestone. Its sedimentological characteristics have not yet been studied in the Kamnik-Savinja Alps.

In the Julian Alps, this unit comprises bedded as well as massive reef limestone (Ramovš, 1987; Celarc and Kolar-Jurkovšek, 2008). The bedded limestone appears as thick-bedded peritidal limestone organized into asymmetric cycles 1–1.5 m thick. The subtidal parts comprise packstone and grainstone with peloids, intraclasts, oncoids, gastropods, bivalves, corals, dasycladacean algae, and foraminifers. The intertidal facies contain stromatolites, fenestrae, and small palaeokarst cavities. The Razor Limestone is sharply overlain by the upper Tuvalian – lower Norian Martuljek platy limestone (Ramovš, 1989), marking a major drowning unconformity (Ramovš, 1989; Celarc et al., 2014). A relatively thin unit (25 m) consists of red and grey limestone with slightly nodular to planar bedding. The limestone is slightly dolomitized packstone with glauconite, rare fragments of bivalves, filaments, lagenide foraminifers, and peloids. Fine-grained bioclastic wackestone and packstone with filaments, brachiopods, and foraminifers prevail in the upper part of the unit.

On Mt. Kočna, two members of the Martuljek platy limestone can be distinguished. The lower member is identical to the already described facies below Mt. Skuta, while the upper member comprises a lot of grains redeposited from shallow water, such as corals and crinoids (Celarc et al., 2014). Upwards, the Martuljek Platy Limestone is sharply overlain by the lower to upper Norian limestone with chert (Ramovš and Jamnik, 1991; Jamnik and Ramovš, 1993; Celarc et al., 2014), occupying most of the high karst plateau visible from the hut. The limestone with chert is approximately 150 m thick. Ramovš and Jamnik (1991), and Jamnik and Ramovš (1993) compared it to the Hallstatt facies of the Northern Calcareous Alps. Two members can be distinguished. The lower member is composed of medium-bedded limestone with chert nodules and lenses. The limestone is fine-grained bioclastic packstone with filaments, subordinately wackestone with brachiopods, crinoids, peloids, sponge spicules, and radiolarians. The upper member consists more of thick-bedded and lacks chert. It is bioclastic, intraclastic, and peloidal grainstone. Reef breccia is common in the uppermost part, marking a gradual transition into the slope and reef crest of the Dachstein reef limestone. The latter forms the peaks and uppermost slopes of Mt. Skuta and Mt. Kočna. Reef slope and crest are nearly impossible to distinguish macroscopically, and together they comprise a unit at least 400 m thick. Corals predominate over sponges as reef builders. Subordinate are sponges. Sponges and microbialites act as binding organisms. Microproblematica (Baccanella floriformis Pantić) is common within the sediment. Bedded peritidal Dachstein Limestone is present on the top and on the NW slopes of Mt. Kočna. The bedding and facies here are nearly identical to the far older Razor Limestone (Celarc et al., 2014).

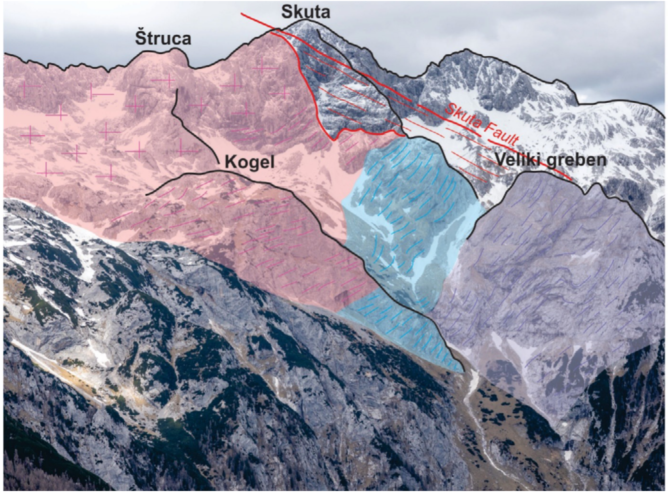

Figure 4: *Panoramic view of Mt. Skuta (2532 m) and its geological features*

STOP 3 – VELIKA PLANINA PASTURE: "Cordevolian limestone and dolomite"

The Velika planina plateau has been geologically mapped by Teller (1898a, b), Premru (1983a, b), and Vičič (2014). The northern part is dominated by shallow marine dolomites and subordinate limestones of the "Cordevolian limestone and dolomite". To the south, this unit is in fault contact with the Anisian Lower Serla Dolomite and the Velika planina Member. Further south, the former is in normal stratigraphic contact with the Lower Triassic Werfen Formation. This sequence is part of the same tectonic block, which is thrusted over the Middle Triassic dolomite. Lineation on the thrust plane indicates initial thrusting to the SW, overprinted by younger thrusting to the S. The area is additionally transacted by steep faults of SSW-NNE, NE-SW, NEE-SWW, and NW-SE strikes, respectively. It is unclear whether some of these are reactivated synsedimentary faults.

The "Cordevolian limestone and dolomite" unit comprises undifferentiated massive platform carbonates of approximately Ladinian to early Carnian age. Due to the lack of leading fossils, poor paleontological determinations, predominant fault contacts with the neighbouring units, and a general lack of interest in research, these platform carbonates have not yet been satisfactorily resolved and divided into formations. Dasycladacean algae are commonly present, but their determinations are dubious. The limestone and dolomite from Velika planina are probably equivalent to the Schlern Formation or the Cassian Dolomite from the Italian Dolomites (Celarc, 2004). Dasycladacean algae, encrusted by microbialite, foraminifers (Duostominidae, Aulotortus sp., Cucurbita sp.), ostracods, and bivalves have been recognized in thin sections. Other common grains are peloids and oncoids.

STOP 4 – JARŠKI DOM HUT: Lower Serla Dolomite

The base of the Velika planina Member is represented by the Lower Serla Dolomite. A large variety of facies of this dolomite can be seen below the Jarški dom hut, where the unit is some tens of meters thick. The dolomite is light grey, thick bedded to massive. Macroscopically, it contains numerous oncoids, stromatolites, bivalve and gastropod lumachellas (Fig. 5). Foraminifer Citaella dinarica (Kochansky-Devidé and Pantić) indicates lower to middle Anisian age. The overlying Velika planina Member is exposed immediately above the hut and along the road, where intraformational (flat pebble) breccias can be seen.

STOP 5 – GOJŠKA PLANINA PASTURE: Velika planina Member

The Velika planina Member has been divided into two parts. The lower part of the succession is easily recognisable as dominated by thin bedded bituminous and finely laminated mudstone (Fig. 6). Some nice outcrops of this facies are present along the path from the Velika planina pasture to the Mala planina pasture. A small exposure can be examined there along a small road cut.

The laminae in the finely laminated mudstone are mostly horizontal and parallel to each other. The light brown laminae are up to 2.5 mm thick, while the darker are even thinner. Both are texturally mudstone. The darker laminae likely represent microbial mats on the basin floor.

Also present are laminae of sparse wackestone up to 1 cm thick with small peloids, *Earlandia*, small lagenid and miliolid foraminifers, ostracods, and thin-shelled bivalves. Elliptical horizontal and vertical burrows are rarely present. Also common in the lower part of the Velika planina Member is the *Earlandia* mustone, characterised by this foraminifer and not so clearly laminated. Subordinate to mudstone are peloid wackestone with ostracods, intraclastic-peloid wackestone to packstone, intraclastic-bioclastic grainstone, and rare bivalve rudstone. These are interpreted as distal turbidite deposits.

The laminated facies yielded some remarkable fossils (Fig. 7). The most common fossil is the *Chondrites ichnofossil*. The bivalve of the genus *Modiolus* and the lingulid brachiopods have accumulated in some beds. Rarer is the bivalve *Bakevellia costata*, articulated sea lilies, small ammonoids, other small inarticulated brachiopods, and crustaceans. The most spectacular finds belong to sauropterygian marine reptiles of the order Nothosauroidea (Hitij et al., 2010a), and actinopterygian fishes (Tintori et al., 2014a) and a coelacanth. Genera *Saurichthys*, *Eosemionotus*, *Placopleurus*, and *Furo* have been identified. Coprolites are abundant as well.
Sedimentary textures are commonly disrupted by slumping, which is common in the lower and middle part of the Velika planina Member but was not observed in its uppermost part.

Interpretation of the Velika planina Member

The upper part of the Velika planina Member was logged north of field-stop 4, around the Dovja Raven. Upwards, the bedding becomes thicker and the lamination less pronounced. Wavy lamination, birdseye fenestrae, and oncoids gradually appear. Along with microbial bindstone (stromatolite), grainstone with bioclasts and peloids, and oncoid floatstone predominate. Upwards, bedded limestone gradually gives way to massive limestone. This gradual transition of the Velika planina Member into the bedded peritidal limestones suggests only a basin of only minor depth, which supposition is also supported by

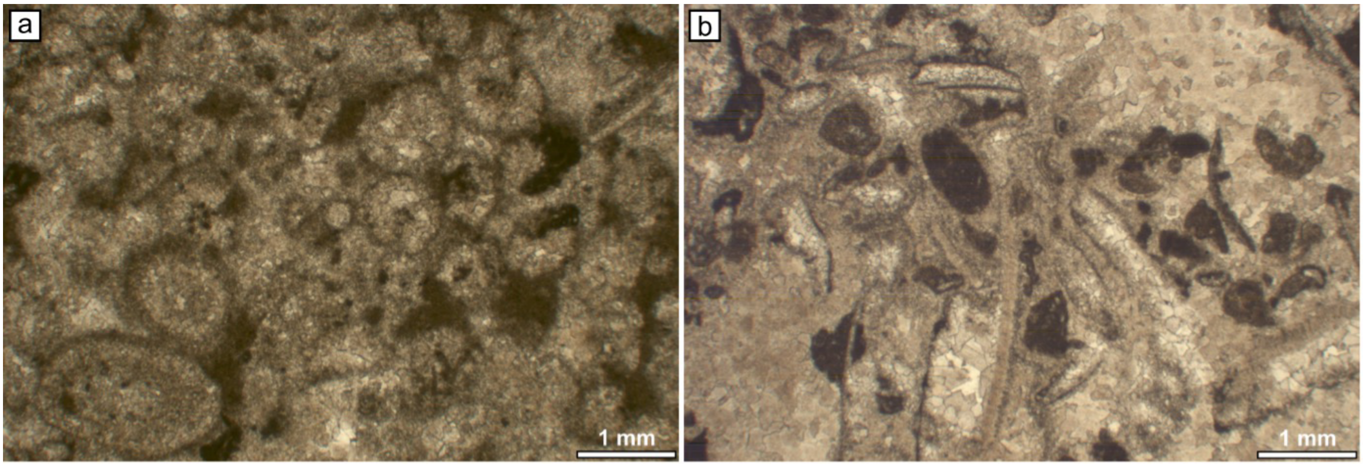

Figure 5: *Microfacies from the Lower Serla Dolomite below the Velika planina Member*

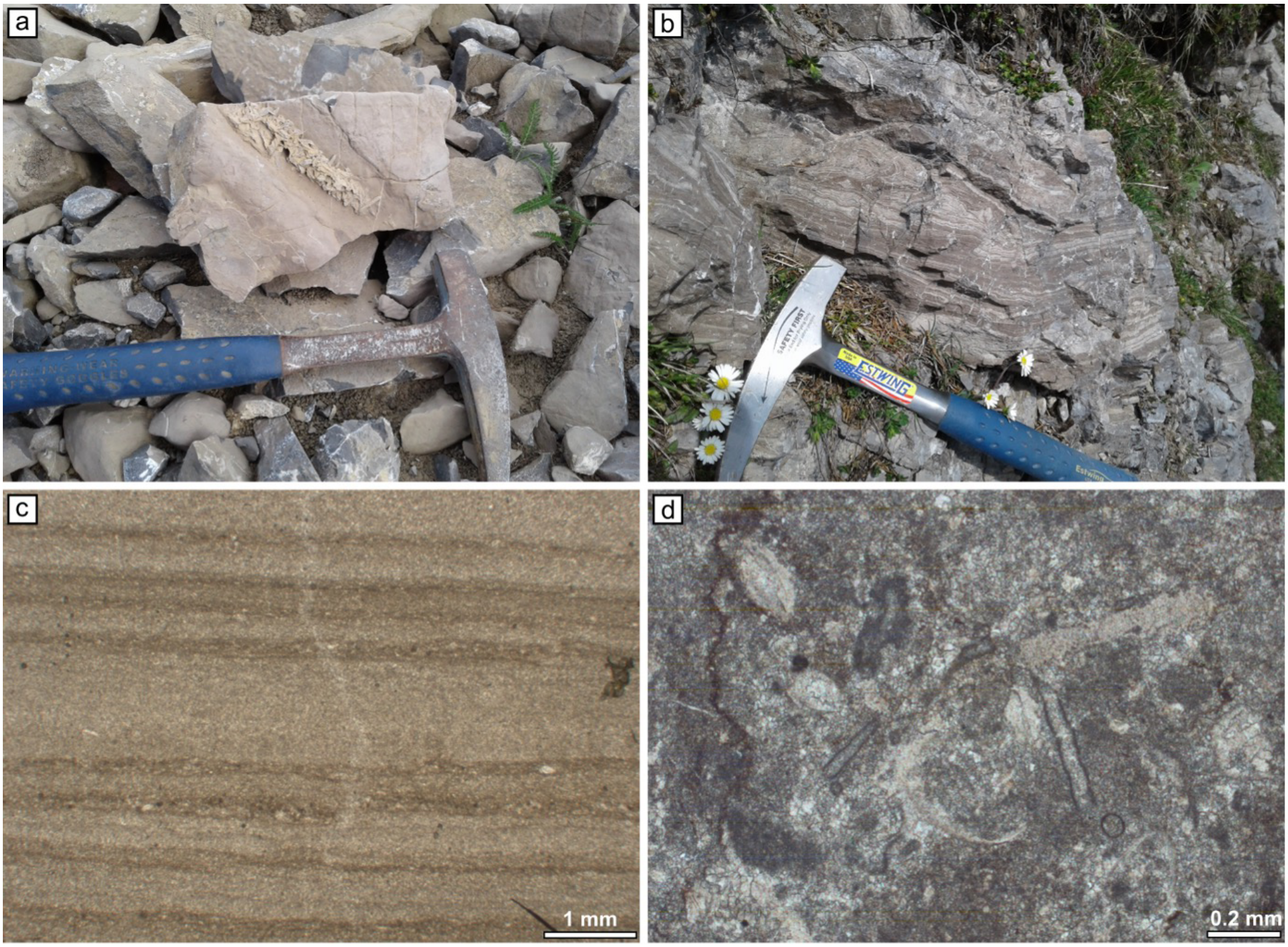

Figure 6: *Lower part of the Velika planina Member. a: Platy limestone with celestine crystals. b: Slumped finely laminated mudstone. c: Finely laminated mudstone. d: Wackestone with ostracods and Earlandia foraminifers. Fossils probably represent autochthonous biota living in oxygen-poor conditions.*

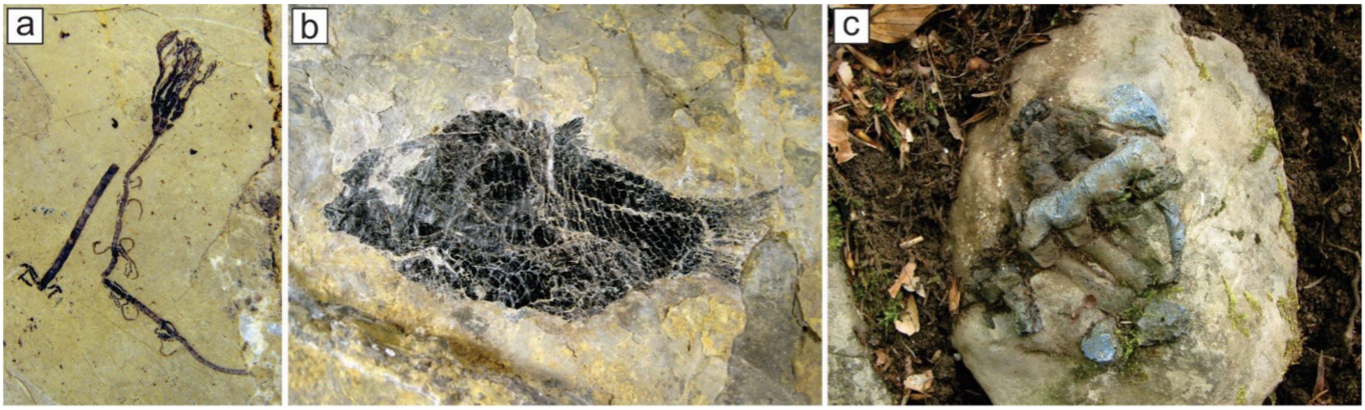

Figure 7: *Fossils from the Velika planina Member. a: An undescribed species of crinoids. Length of the crown is 9 mm. b: The oldest occurrence of actinopterygian fish Eosemionotus sp. Length of the specimen 6 cm. c: Sacral part of a sauropterygian. Length of the specimen is 9 cm.*

other observations, such as the lack of prominent breccias at the base, the near-absence or even lack of open-marine plankton and nekton, such as radiolarians and ammonoids, the composition of the vertebrate fauna (i.e. the finds of nothosauroids, which were limited to shallow intraplatform basins and shallow epicontinental seas; Rieppel, 1999; Černansky et al., 2018), and the gradual transition towards the platform facies at the top. Slumping is common in the lower and middle part of the member, but not in the uppermost part, again suggesting a gradual levelling of the topography as the basin filled. This is confirmed by the change in the facies association.

The intraclastic breccias at the base of the member are interpreted as indicators of the initial subsidence of the basin floor, which took place sometime during the early to middle Anisian. In the initial stage of the basin's evolution, the water column was likely stratified, and hypoxic to anoxic conditions prevailed at the bottom. This is supported by the preservation of articulated skeletons of vertebrates and rare sea lilies, the lack of large and diverse bioturbations, and the near absence of benthic organisms. As mentioned, however, some levels are slightly bioturbated. Ostracods, *Earlandia*, and lagenids likely represent autochthonous biota, as suggested by the preservation of both valves in ostracods and the random orientation of the microfossils. *Earlandia* is interpreted as a benthic opportunist (Krainer and Vachard, 2009), and thin-shelled lagenids are tolerant of low-oxygen conditions (Stockar, 2010). Chondrites, which is also typical for poorly ventilated sediments (Bromley and Ekdale, 1984).

Higher up in the succession, bedding becomes thicker and lamination less pronounced. Bioturbation is more common, and several indicators of small depth gradually appear (wavy stromatolites, fenestrae, and oncoids). Finally, the Velika planina Member gradually gives way to well-aerated massive limestone.

Conclusion to the field trip

The Velika planina Member is a relatively "newly" researched lithostratigraphic unit in Slovenia. Many more spectacular fossil finds can be expected from this unit and many stratigraphic questions raised. The similar yet younger and more widespread Strelovec Formation from the middle to upper Anisian testifies to another episode of crustal extension and eventually unsuccessful differentiation of the shelf. Finally, the late Anisian (?) to early Ladinian extension resulted in the creation of horst-and-graben topography and long-lasting deeper sedimentary basins, such as the Tolmin Basin (the Slovenian Basin, s.str.) and the Bled Basin, which are the subject of other field excursions.

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Lower to Middle Jurassic limestone succession at the margin of the Ljubljana Moor: From microfacies to the Romans

FIELDTRIP D

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Introduction

Large, thick masses of Mesozoic carbonates that form the northern Dinarides (southern Slovenia) deposited on isolated the intraoceanic Southern Tethyan Megaplatform and its successor, the Adriatic Carbonate Platform (Vlahović, 2005). The topic of this field trip is a small part of this succession, namely the Lower Jurassic Podbukovje Formation, which is exposed in many places along the southern rim of the Ljubljana Moor Basin (Fig. 1). Structurally, this area belongs to the External Dinarides – more precisely to the Hrušica Nappe (Placer, 1999).

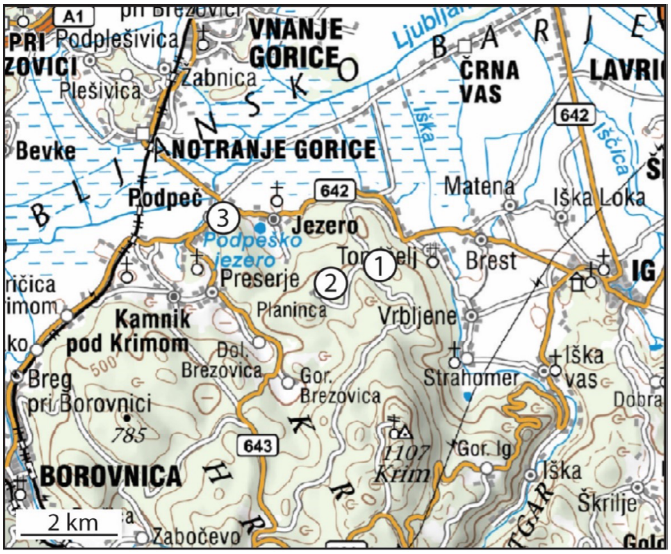

Figure 1: *Topographic map with field trip stops marked*

Lower Jurassic stratigraphy of the Krim-Mokrec Mountains

The Lower Jurassic sedimentary succession, deposited concordantly on the Upper Triassic Main Dolomite Formation and overlain by the Middle Jurassic Laze Formation, consists of limestone and dolomite. The Lower Jurassic succession is called the Podbukovje Formation and consists of five members. From oldest to youngest, these are: 1) the Krka Limestone Member, 2) the Orbitopsella Limestone Member (Orbitopsella beds as defined by Dozet and Strohmenger, 2000), 3) the Lithiotid Limestone Member, 4) the Oolitic Limestone Member, and 5) the Spotty Limestone Member (Fig. 2). The Podbukovje Formation is best correlated with the Calcari Grigi Group from the Trento Platform in NE Italy, and with successions from the NE parts of Dinarides.

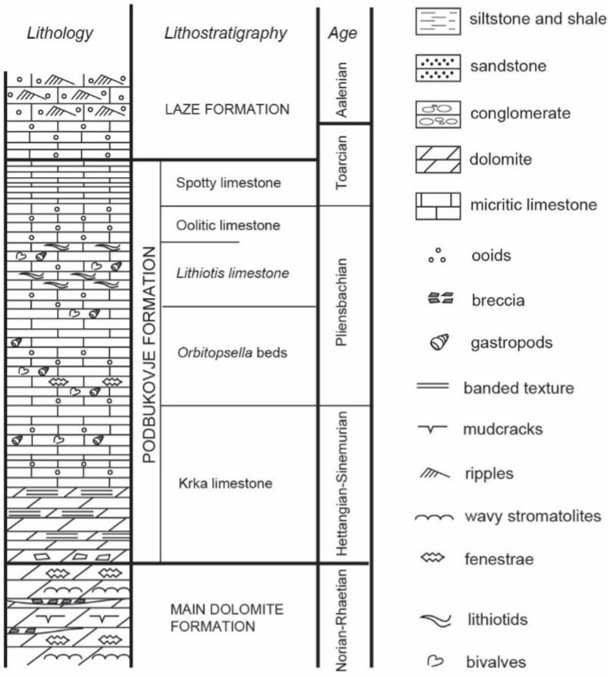

Figure 2: *Stratigraphic composition of the Podbukovje Formation*

The Krka Limestone Member is Hettangian to Sinemurian in age and consists mainly of micritic limestone and rare beds with fragments of molluscs. The lower parts of this member are commonly dolomitized. Micritic and stromatolitic limestone deposited under shallow subtidal and peritidal conditions of the inner restricted parts of the platform. Thicker oolitic beds of limestone are subordinate, but their proportion increases higher up (Dozet and Strohmenger, 2000; Dozet, 2009). According to Ramovš (1990, 2000), some of the micritic beds were exploited as a local source of stone during Roman rule.

Possible quarries may have been located near Staje, where the remains of a Roman settlement have been uncovered (Rožič et al., 2018).

The Orbitopsella Limestone Member was deposited during the late Sinemurian and lower Pliensbachian. This member consists of grey to dark grey micritic limestones. Micritic limestone alternates with oolitic, intraclastic, and bioclastic limestone. The limestone deposited in a confined, shallow marine environment (Dozet and Strohmenger, 2000; Gale and Kelemen, 2017). The Orbitopsella Limestone Member from the northern tip of the St. Anna hill in Podpeč was commonly used in the architecture of Roman Emona (modern Ljubljana) (see field-stop 3).

The most distinctive part of the Podbukovje Formation is the Pliensbachian Lithiotid Limestone Member. This member and its equivalents (e.g. Rotzo Formation from the Trento Platform) are characteristic of many tropical and subtropical carbonate platforms. The main feature consists of numerous occurrences of lithiotid bivalves. Other important fossils from this member are brachiopods and small megalodontid bivalves. Limestone is grey to dark grey, thick-bedded and micritic, biomicritic to biosparitic. This member formed in an internally differentiated lagoon under subtidal and intertidal conditions (Dozet and Strohmenger, 2000; Gale, 2015; Gale and Kelemen, 2017). Positioned immediately south of the antique quarry, this member became an important source of natural stone and lime during the 19th and 20th centuries (Ramovš, 2000). Numerous architectural elements were produced from it. Lithiotid facies, characterised by white shells surrounded by almost black micritic limestone was particularly valued. It is said that this was the favourite decorative stone of renown Slovenian architect Jože Plečnik.

The Oolitic Limestone Member is late Plienbachian in age and consists of thick to very thick beds. Grains are dominated by large tangential ooids up to 1 mm in size (Dozet and Strohmenger, 2000). It (or the Lithiotid Limestone Member) is followed by the Spotty Limestone Member. This limestone is dark grey and mostly micritic, with some bioturbations. Fossils (foraminifera, algae, echinoderms) are of low diversity. The sediment was deposited in a ramp environment under unfavourable conditions that accompanied and followed the Toarcian Anoxic Event (Sabatino et al., 2013). Due to the thin nature of the beds, this member was also a common source of stone plates, that were often left unshaped or were only partly shaped and used for pavements or to cover the Roman cloaca.

The Podbukovje Formation is overlain by the Laze Formation, comprising brown to dark grey oolitic limestones in the lower part, followed by light grey medium-thick beds of oolitic limestone higher up. Ooids are 0.5 mm to 0.75 mm in diameter and have a radial structure. Round intraclasts, bioclasts, pellets, and foraminifera also occur. The limestones were formed in subtidal and intertidal environments near tidal channels (Dozet and Strohmenger, 2000; Dozet, 2009).

STOP 1 – TOMIŠELJ: Hettangian – Pliensbachian succession

The road-cut follows the transition from the upper part of the Krka Member to the Orbitopsella, and from there to the Lithiotid Limestone Members of the Podbukovje Formation. The Krka Member is characterised by fine-grained and in places stromatolitic limestones (Fig. 3), locally cut by bodies of mud-supported breccias. The latter are interpreted as Neptunian dykes, and may be more than 50 m wide (Gale and Rožič, in prep.). The presence of Neptunian dykes in this area is explained by the incipient extension of the crust in this area related to the initial opening of the Southern Penninic Ocean. The extension is more pronounced to the north, in the area of the Slovenian Basin and on the Julian Carbonate Platform.

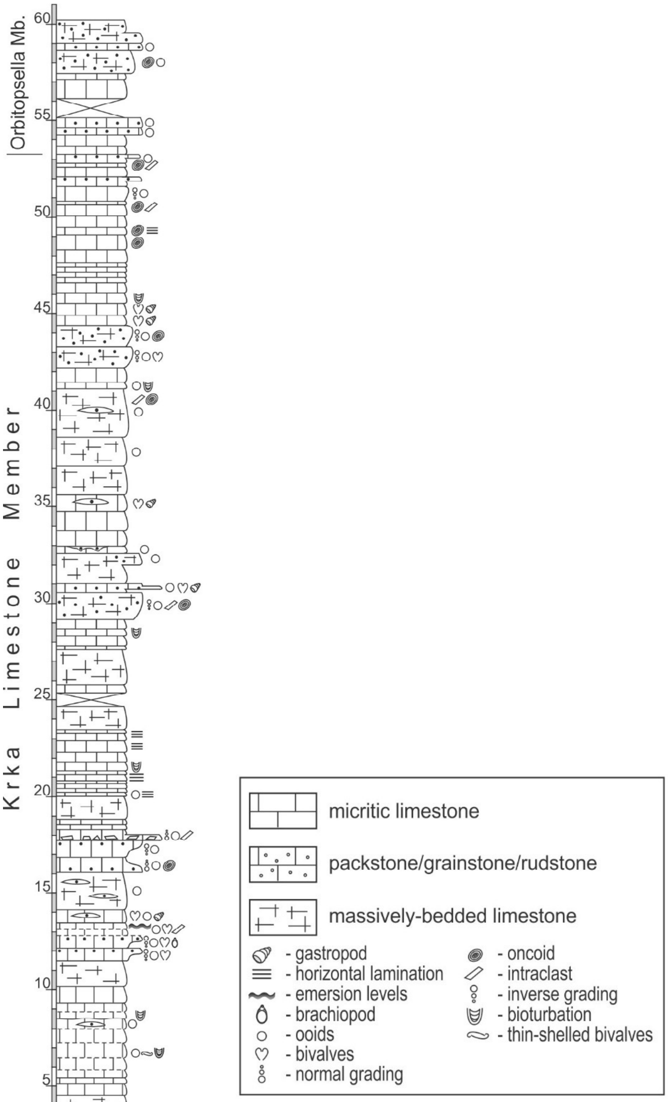

Figure 3: *The middle part of the Tomišelj section, logged in greater detail by Gale and Kelemen (2017)*

The Orbitopsella Limestone Member is characterised by thicker beds of light grey micritic and fine-grained oolitic ("peloidal") limestone. Bioclasts are small and of low diversity. Bivalve floatstone is present in a single level. The foraminiferal assemblage consists of *Amijiella amiji*, *Ammobaculites* spp., *Coronipora* sp., *Duotaxis metula*, *Everticyclammina praevirguliana*, *Involutina* sp., Nodosariidae, ?*Lituolipora termieri*, ?*Lituosepta recoarensis*, *Meandrovoluta asiagoensis*, *Ophthalmidium* sp., *Pseudopfenderina butterlini*, *Siphovalvulina* spp., *Trocholina* spp., Valvulinidae and *Textulariidae* (Gale and Kelemen, 2017).

The section continues to the Pliensbachian and ends within the Lithiotid Limestone Member.

STOP 2 – LEDENICA CAVE: Pliensbachian – Aalenian succession

The sedimentological section Ledenica – Planinca represents the uppermost part of the Podbukovje Formation. It is composed of the Oolitic Limestone Member at the base of the section, the Spotty Limestone Member (Fig. 4), and the Middle Jurassic Laze Formation. The Oolitic Limestone Member is characterised by oolitic packstone to grainstone with benthic foraminifera and bivalve fragments. The transition from Oolitic to Spotty Limestone Member is sharp. Toarcian age of the Spotty Limestone Member was determined based on its superposition and its distinct change in foraminifera assemblage. The present facies in this member are mudstone, peloidal mudstone to packstone, and ooidal wackstone to packstone with rare echinoderms. Several ferruginous hardgrounds and marly limestone layers were observed. Based on the measurements of carbon isotopes, the contact with the Oolitic Limestone Member is discordant, as negative carbon excursions are missing.

Figure 4: *Spectacular outcrop of the Spotty Limestone Member in the Ledenica cave*

STOP 3 – PODPEČ QUARRY: Pliensbachian succession of the Global Heritage Stone

The Podpeč quarry has been studied from geological (Buser and Debeljak, 1995; Debeljak and Buser, 1997; Gale, 2015; Gale and Kelemen, 2017; Brajkovič et al., 2022) and archaeological perspectives (Djurić et al., 2022). Based on the dating of stone monuments from Emona, the Pliensbachian limestone succession at Podpeč was certainly quarried between the 1st and 3rd centuries AD (Djurić et al., 2022). The production of stone from this area, however, might stretch even further back in time to the earliest beginnings of the Roman colony (Djurić & Rižnar, 2017). According to Djurić et al. (2022), the Roman quarry was positioned at the northernmost tip of the St. Ana hill, topographically closest to the floor of the Ljubljana Moor. The further development of the area from the 4th century to the 19th century is obscured by the lack of historical data. The Franciscan cadastre of 1823 records two quarry parcels in the area of the modern quarry. The quarries gained greater use and recognition during the construction of the Southern Railway between Vienna and Trieste (Trst) in the middle of the 19th century, and after the devastating Ljubljana earthquake of 1895. Quarrying probably peaked at this time, as the material was needed for construction (Kramar et al., 2015) and lime production (Bras, 1977). In the first half of the 20th century, the limestone quarried at Podpeč became a favourite of the renowned Slovenian architect Jože Plečnik. The already mentioned facies with lithiotid bivalves decorates many of the buildings designed by him (Ramovš, 2000). During the 20th century, most of the smaller quarries ceased operation. The main quarry at Podpeč remained active until 1967, at which time it was owned by the Mineral company (Kramar et al., 2015; Djurić et al., 2022).

Throughout history, limestone from the Podpeč quarries was valued and used for its good physical properties, low water porosity, and high strength, which make it suitable for both indoor and outdoor use (Mirtič et al., 1999), and was proposed as a location of the global heritage stone (Kramar et al., 2015).

Figure 5: *The historic "Špica" outcrop within the quarry at Podpeč, where numerous foraminifera, lithiotids, megalodontid bivalves, and brachiopods have been found*

Limestone beds in the quarry run in a W-E direction and are almost vertically inclined (Fig. 5). They comprise various types of limestone: micritic, oolitic, bioclastic, including lumachellas of lithiotid bivalves, megalodontid bivalves, and brachiopods. At the microscopic level, the limestone is rich in green algae and foraminifera, including *Orbitopsella praecursor, O. primaeva, Amijiella amiji, Siphovalvulina* spp., *Meandrovoluta asiagoensis, Duotaxis metula, Involutina farinacciae, Lituolipora termieri, Bosniella oenesis, Pseudopfenderina butterlini,* and *Everticyclammina praevirguliana*. The lithiotids are dominated by *Cochlearites* and *Lithioperna*. *Lithiotis* is rare and limited to the upper part of the quarry. Shells are usually in a parautochthonous position, and rarely preserved *in vivo*.

STOP 4 - LJUBLJANA:
Lapidarium of the National Museum of Slovenia

In the absence of other (written or pictorial) sources, stone products indirectly provide information on the development, economic activity, trade, and importance of former settlements and cultures (Djurić and Rižnar, 2017). Knowledge about the provenance of stone and its properties links the geological and archaeological disciplines. Research on the provenance of the natural stone used in Emona (present-day Ljubljana) began as early as the 19th century (Müllner, 1879). Most of the stone used was local. Carboniferous limestone from the area of Ljubljana castle hill was mainly used for city construction, while the Lower Jurassic Podbukovje Formation was primarily sourced for limestone used for architectural and sepulchular applications. As it contains several petrologically indistinguishable facies types, a spatially more precise definition of the provenance of stone products is possible only through multidisciplinary knowledge of the source areas and specific rock properties. Using a multilevel approach (I. Petrology and paleontology; II. Geochemistry; III. Chemostratigraphy), we were able to determine the provenance for all facies types present in the Podbukovje formation, even those made from uncharacteristic micritic limestone (Brajkovič et al., 2021, 2022).

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Geological tour of Ljubljana

FIELDTRIP E

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Introduction

This guided tour is intended to help you learn about the cultural history of a Middle-European city, as written in natural (building and ornamental) stone. It will showcase the City of Ljubljana as a small open-space geological museum. Natural stone is here presented as a window between natural and cultural heritage. Its great variety enables the study of its geological features (rock type, fossils, structures) and technical properties. On the other hand, it documents Ljubljana's interesting history from the Antiquity through modern times. Here we learn about the most important touristic landmarks of Ljubljana through the types of stone used and the quarries where they originate.

The highlight of the tour is the stone-built cultural monuments designed by the renowned architect Jože Plečnik (1872–1957). Very few cities in Europe are marked in such a degree by the architecture and urbanistic solutions of a single architect. Jože Plečnik valued natural stone greatly and used it in his most monumental works in Ljubljana. Moreover, his post-World War II work is a good example of the sustainable re-use of natural stone as a building material and as ornamental architectural element. All of these considerations led to the inscribing of "The works of Jože Plečnik in Ljubljana – Human Centred Urban Design" on the UNESCO World Heritage List in 2021. Here, the architectural heritage of Jože Plečnik is presented from a different angle, adding another dimension of understanding and appreciation of his opus.

A short history of Ljubljana and the use of natural stone

The Ljubljana region was already settled by pile dwellers before 2,000 BC. Excavations have shown that the quartz sandstone rubble was occasionally used to construct the earliest Late Bronze Age settlement (10th–9th c. BCE), but also appeared in later Early and Late Iron Age settlements in foundations, drywalls, and retaining walls. The source of this building material should certainly be sought in the quarry (or quarries) located in the immediate vicinity of these settlements, somewhere on the southern slopes of Ljubljana Castle Hill (Djurić and Rižnar, 2016).

The first settlers to use large quantities of stone for building were the Romans. The first Roman settlement was a military stronghold called Colonia Iulia Emona, built in the 1st century AD. It was protected with a wall, whose remains are best seen today along Mirje. The Romans had already opened most of the quarries in the surroundings of the Ljubljana Basin, which were excavated long after World War II. They had quarried Upper Carboniferous quartz sandstone and conglomerate on the southern slopes of the Ljubljana Castle Hill. They had found high quality Lower Jurassic Podpeč Limestone on the southern margins of the Ljubljana Moor (see this Guidebook, Field Trip D) and Glinice Limestone on the northern outskirts of Ljubljana at Podutik, which could also have been sources of lime the Romans used in construction (Ramovš, 1990, 2000). Traces of the Roman transport of heavy products from either the Podutik or Podpeč quarries have not been preserved. However, several hypotheses been made regarding that part of the production cycle in the past. As for the Podpeč Quarry, it has always been – and still is – believed that its products were mainly transported along the Ljubljanica River. It is also supposed that the course of the river was altered in length by roughly 6 km, from Podpeč towards Vrhnika, to flow in the immediate vicinity of the quarry for purposes of easier transport. Today, this supposition is widely accepted, despite its rather shaky grounds (Djurić and Rižnar, 2016). There were also white to yellowish varieties of detritic Neogene limestone, which came from a number of sources in the vicinity of Moravče and was probably only used later, in the 3rd century. The limited use of Peračica Tuff for construction purposes has not yet been determined chronologically, while the colourful, mostly calcareous Škofja Loka Conglomerate was used for architectural elements in Late Antiquity. As for interregional rocks, the use of Cretaceous Aurisina Limestone from Italy has been proven, at least for the earliest period of the Roman colony, while white Eastern Alpine marbles were used in the period for the construction of the defensive walls of Emona (from Gummern) and later for funerary monuments and architectural elements (from Pohorje). Mediterranean marbles have only been documented as floor and wall veneers (Djurić and Rižnar, 2016).

In the 6th century, Roman Emona was destroyed by the barbaric invasions of the Huns. All of the inhabitants left, and the town sank into oblivion. The name Ljubljana was first mentioned in the mid-12th century. In 1335, the town passed into the hands of the Habsburgs and became an important stronghold on the way to the sea, and in the hinterland on the border toward the Ottoman Empire. In 1461, the diocese of Ljubljana was established, and the church of St. Nicholas became the cathedral. Medieval Ljubljana evolved around three squares: first around the square of Stari trg, then around the square of Mestni trg, and around Novi trg square on the other side of the Ljubljanica River. Houses in medieval times were largely constructed of wood, and stone was only used for the walls, independently surrounding all three parts. The medieval walls on Vegova Street were built atop roughly the exact site of the former Roman wall; however, Emona was located to the west, and medieval Ljubljana to the east of the wall. Until 1484, when the City Hall was built on the same site it occupies today, the medieval town centre was at Trača, next to the Cobblers' Bridge (Spanžel et al., 2020).

In 1511, a major earthquake (the Idrija Earthquake, estimated M6.8, X EMS), struck Ljubljana and caused a great deal of damage all over Carniola. During the restoration process, narrow medieval houses were linked, and roof ridges were oriented parallel to the street.

In the 17th and 18th centuries stone buildings began to replace the wooden ones. What proved more defining were the religious conflicts that arose when the triumphant Counter-Reformation introduced the Baroque. For the Jesuits, who came to Ljubljana in 1597 and decisively contributed to the defeat of the Reformation, both Gothic and Renaissance architecture were unacceptable. Only Baroque churches, with their magnificence and ceremonial grandeur, had the power to inspire in rituals of worship. Baroque art was therefore more than simply a matter of taste; it was a symbol of affiliation with the Roman Catholic church. The Baroque reached its peak at the beginning of the 18th century when, also on the initiative of the Academia Operosorum Labaciensis (1693–1701), some prominent Italian artists, mainly from the neighbouring Venetian Republic, came to work in Ljubljana: architect Andrea Pozzo and sculptors Francesco Robba and Jacopo Contieri, to name but a few. Houses were raised with a third floor and dressed in luxurious Baroque façades. Interiors were decorated with arcaded courtyards and staircases. They also renovated or built most of the churches in the Baroque style, including the cathedral, as well as the new town hall (Spanžel et al., 2020). This period proved a major milestone in terms of the use of stone in Ljubljana. The dark Upper Triassic limestone quarried on the slopes of Lesno Brdo/Drenov Grič (west of Ljubljana) was very popular in Ljubljana and vicinity from the end of the 17th century onwards (Ramovš, 2000). Lesno Brdo limestone is distinguished by its uniform black colour, which is animated by numerous white calcite veins. It formed in the shallow lagoon environment in the Late Triassic (Carnian) and it often contains numerous fossils, especially bivalve shells. Interlayers of the softer black marlstone are less resistant to weathering and give way to decomposition. The entrance portal to the Seminary Palace with its two stone giants is one of the finest Baroque portals in Ljubljana.

In addition to the black Lesno Brdo Limestone, variegated, red, pink, and grey limestone are also still quarried near Lesno Brdo. This type of limestone is slightly older than black limestone and formed during the same age and in a shallow reef environment, much like Hotavlje Limestone, as described later.

The end of the 18th century brought the Age of Enlightenment, a period that rediscovered antiquity, among other things. In terms of architecture, it marked the emergence of Classicism, which returned to the models of Greek antiquity. In Ljubljana, they started to pull down the wall that had halted expansion of the town.

After Napoleon's wars with the Austrian monarchy, Ljubljana was occupied by the French, and for a short period (1809–1813) became the capital of the Illyrian Provinces. While this was not an important period in terms of architecture it had far-reaching implications for Slovenian national awareness, as it was the first time ever that the Slovenian language was taught in higher schools. For this reason, Napoleon has never been seen as an oppressive occupier, and the inhabitants of Ljubljana even erected a monument in his honour. The four years of the Illyrian Provinces represented the only break in the Habsburg regime, which lasted a whole 579 years, from 1335 to 1918 (Spanžel et al., 2020).

After Napoleon's defeat the town rose from anonymity once again. In 1821 it hosted the congress of the Holy Alliance, an association of triumphant states striving to maintain the monarchic system. For this occasion, the site of the abandoned Capuchin monastery was transformed into Congress Square, which served to host public events and parades. This was a period marked by the first attempts at a systematic designing of the town. Biedermeier, a reflection of the simple and comfortable style of the Viennese middle class, dominated in art.

In 1848, a railway was built from Vienna to Ljubljana, and in 1857 it was extended south to the port of Trieste. The train was a symbol of a new era based on industrialization. It triggered an accelerated development of cities and posed new challenges for architecture. Work was now divided between architect and engineer. The latter designed a frame that the architect-artist adorned with an appropriate façade. Classical architectural elements gradually embraced neo-Renaissance, neo-Romanesque, and neo-Gothic elements. During this fertile period, a number of important institutions were built in Ljubljana: the Provincial Museum, the National Hall, the Philharmonic Hall, and the Palace of the Provincial Government (Spanžel et al., 2020).

The 1895, a hugely destructive earthquake ("the Big Ljubljana Earthquake", M6.1, VIII–IX EMS) proved a turning point in Ljubljana's development. Some ten percent of the city's buildings were severely damaged or destroyed. The whole of the monarchy assisted in the rebuilding effort, and what had started as utter destruction became an opportunity for new development. A young architect, Maks Fabiani, who at the time worked for Professor Otto Wagner at the Vienna Academy, took the initiative to propose an urban design plan. It was Fabiani who introduced the Viennese Secession style, closely related to Art Nouveau, to Ljubljana. During this period of national awakening, when Slovenians were establishing their own cultural institutions in parallel to the existing German ones, the choice of architectural style became a sign of nationality (Spanžel et al., 2020). In the mere first 14 years after the earthquake, more than 400 buildings were built and more than 600 were renovated. Most of Ljubljana's bridges, monuments, parks, and main buildings date back to the post-earthquake development. Already two years after the earthquake, the first Austro-Hungarian seismological observatory was established in the basement of the Realka High School on Vegova Street in Ljubljana.

The post-earthquake (1895) renovation allowed Ljubljana to develop from its earlier provincial appearance into a modern European city. After the dissolution of the Austro-Hungarian Monarchy the city became the capital of Slovenia – and the people's capital; and was looking for its own architectural identity, which was to be shaped by architect Jože Plečnik. He was certainly one of the most talented of Otto Wagner's students. Prior to World War I, he had already designed several buildings in Vienna, the most important being the Zacherl House (1905). The Vienna Academy had even proposed Plečnik as Wagner's successor, but for political reasons the proposal was not approved. In 1911, Plečnik moved to Prague to teach at the college of arts and crafts, and in 1920 was appointed by President Masaryk as chief architect for the restoration of Hradcany with Prague Castle, which was to be transformed into a symbol of the new, democratic state. Despite this prestigious position, Plečnik returned to Ljubljana in 1921 when he was offered the post of professor at the newly founded school of architecture. It was in Ljubljana that he wanted to see his vision of the nation's capital come to life. He respected the qualities of the old quarter of Ljubljana, the natural, architectural, and historic characteristics with their intangible aspects, which he emphasised with both small and large interventions. He interpreted anew a series of public spaces (squares, parks, streets, promenades, bridges) and public institutions (national library, churches, markets, funerary complex), which he sensitively integrated into the pre-existing urban, natural, and cultural context and which contributed to the city's new identity. The dialogue between the architect and the town developed to the extent that today Ljubljana is known as "Plečnik's Ljubljana" (Spanžel et al., 2020).

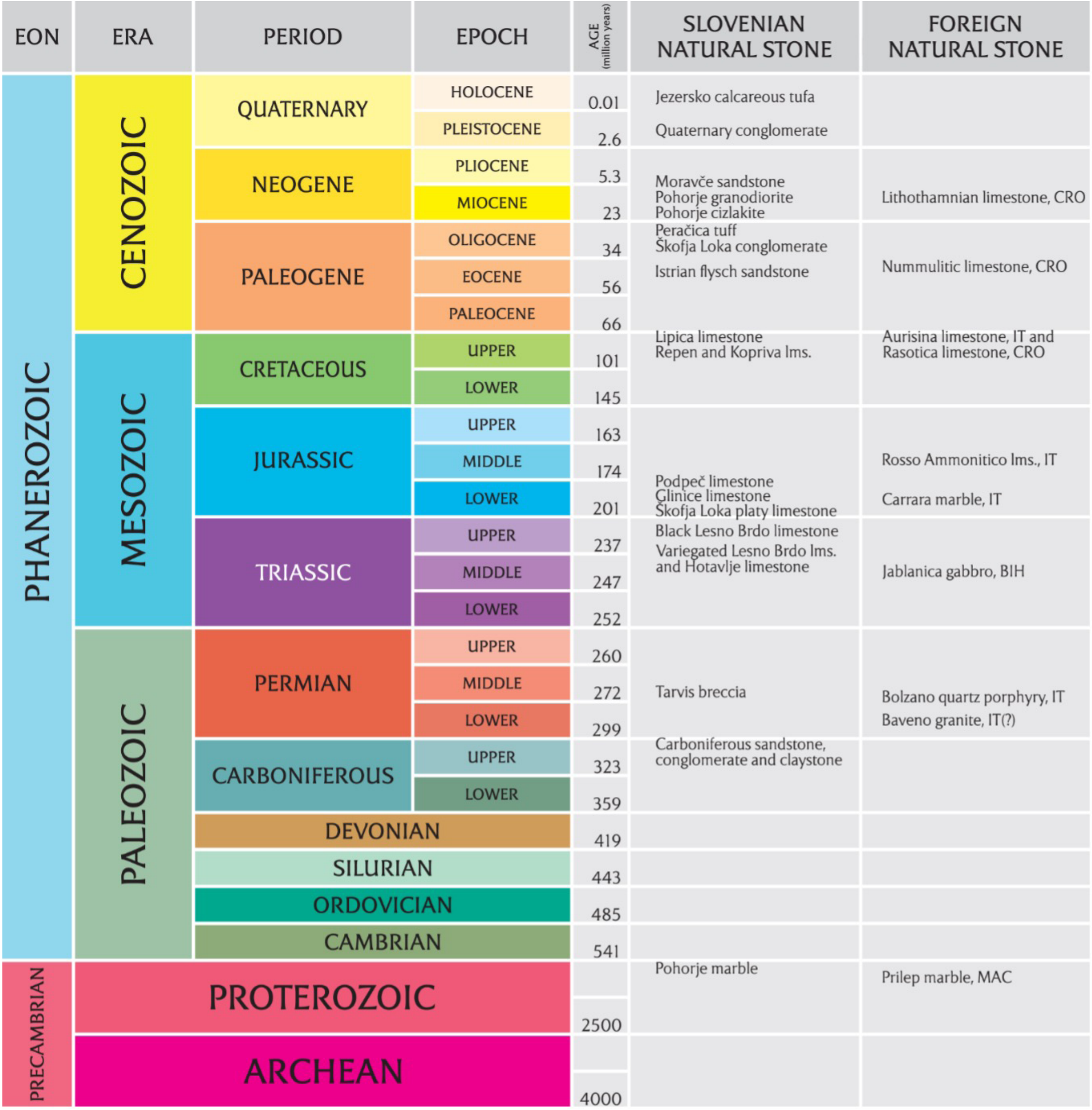
It can be said that the most iconic Plečnik's building in Ljubljana, the National and University Library, is his monument to Podpeč Limestone. He used it in the façade, the entrance lobby, the staircase colonnade and the large lobby. The exterior is made of this lagoonal limestone, most of it without the typical lithitoid bivalves. On the polished interior surfaces, however, their white cross sections are beautiful adornments to the otherwise deep, dark stone. Plečnik, as well as some other architects, used this stone in many other prominent buildings, such as in the Parliament building, Nebotičnik (Ljubljana Skyscraper), the Montanistika building, City Hall, etc. (Kramar et al., 2014).

One of the most appreciated decorative stones in Ljubljana was, and still is, the Upper Triassic Hotavlje Limestone. This reef limestone is characterized by its non-homogeneous texture and richly varied colour, which ranges from dark grey to grey and pink, to scarlet red. The colours are further enriched by veins of reddish claystone and green tuff. Larger nests are filled with bright calcite, tiny grains of pyrite, and yellow or purple rhombohedral dolomite crystals, which formed during diagenesis. Its larger-scale quarrying begun after WW II; however, the first stone-cutters' products from this limestone are documented from the early 18th century (Ramovš, 1995). Today, this limestone is still being excavated in the underground galleries of a large modern quarry. In the interior of the Cankarjev dom, the largest culture and congress centre in Slovenia, as many as 2000 m^2 of surface is covered with panels of Hotavlje Limestone.

Some of the most widely used stones in modern Ljubljana are various "karst stones", the common name for light-grey limestones of Cretaceous age with cross sections of rudist bivalves. They come from the quarries of Aurisina/Nabrežina near Trieste, Lipica, Doline, and Kazlje in Slovenian Kras, and Rasotica on the Croatian island of Brač. In Lipica in Kras, two different grey limestones are quarried; they are called "uniform" (Lipica unito) and "rosy" (Lipica fiorito) limestone. In Lipica unito, rudist bivalves are finely crushed and give the impression of a unified grainy rock, while in Lipica fiorito, the cross sections of whole rudists resemble flower petals. The Repen and Kopriva limestones from the Doline quarry are very fine grained and considered the highest quality calcareous natural stones in Slovenia (Mirtič et al., 1999). The Karst limestones were used in the construction of several important buildings and monuments in many other European Countries, and around the world. Nowadays, they are most commonly used in the construction of façade cladding, pavements, staircases, indoor and outdoor flooring and wall cladding, and are also held in high esteem by sculptors.

We tore the stone from our mountains, our hands formed and smoothed it: saxa loquuntur (rocks speak). – Arch. Jože Plečnik, 1926

We welcome you to learn more about the natural stones of Ljubljana from the booklet A geological tour of Ljubljana: natural stone in cultural monuments. Available as a PDF at:
www.ljubljana.si/assets/Uploads/Geoloski-sprehod-po-Ljubljani-ANG.pdf



EON	ERA	PERIOD	EPOCH	AGE (million years)	SLOVENIAN NATURAL STONE	FOREIGN NATURAL STONE
PHANEROZOIC	CENOZOIC	QUATERNARY	HOLOCENE	0.01	Jezersko calcareous tufa Quaternary conglomerate	
			PLEISTOCENE	2.6		
		NEOGENE	PLIOCENE	5.3	Moravče sandstone Pohorje granodiorite Pohorje cizlakite	Lithothamnian limestone, CRO
			MIOCENE	23		
		PALEOGENE	OLIGOCENE	34	Peračica tuff Škofja Loka conglomerate Istrian flysch sandstone	Nummulitic limestone, CRO
			EOCENE	56		
			PALEOCENE	66		
	MESOZOIC	CRETACEOUS	UPPER	101	Lipica limestone Repen and Kopriva lms.	Aurisina limestone, IT and Rasotica limestone, CRO
			LOWER	145		
		JURASSIC	UPPER	163	Podpeč limestone Glinice limestone Škofja Loka platy limestone	Rosso Ammonitico lms., IT Carrara marble, IT
			MIDDLE	174		
			LOWER	201		
		TRIASSIC	UPPER	237	Black Lesno Brdo limestone Variegated Lesno Brdo lms. and Hotavlje limestone	Jablanica gabbro, BIH
			MIDDLE	247		
			LOWER	252		
	PALEOZOIC	PERMIAN	UPPER	260	Tarvis breccia	Bolzano quartz porphyry, IT Baveno granite, IT(?)
			MIDDLE	272		
			LOWER	299		
		CARBONIFEROUS	UPPER	323	Carboniferous sandstone, conglomerate and claystone	
			LOWER	359		
		DEVONIAN		419		
		SILURIAN		443		
		ORDOVICIAN		485		
		CAMBRIAN		541		
PRECAMBRIAN	PROTEROZOIC			2500	Pohorje marble	Prilep marble, MAC
	ARCHEAN			4000		

Figure: *List of Slovenian and foreign natural stones used in Ljubljana with their stratigraphic position (Novak, 2016)*

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Mangart Saddle, photographed in direction to the south.