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Abstract Book
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Abstract Book

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Continental subduction in the Western Alps: major issues.

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Continental subduction is hereafter defined as continental, dominantly crustal, material recording high-pressure metamorphism (in most cases at blueschist- and eclogite-facies P-T conditions), without any prejudice upon pre-orogenic position and syn-orogenic burial mechanism. The main questions related to continental subduction in the Western Alps may be summarised as follows:

- In most models, continental subduction is succeeding oceanic subduction, the buoyant continental crust being dragged down by the subducting slab of oceanic lithosphere. Subduction erosion has also been proposed as a major mechanism (e.g. for the Sesia-Dent Blanche nappes). Do these models apply in the Western Alps, in the lack of a 'true' subduction zone?
- Which parts of the continental crust are subducted? Is it the entire palaeomargin, or just parts of it, for example extensional allochthons? What is the role of the inherited structures associated with the rifting history of the palaeomargin?
- What is the age of the *HP/UHP* metamorphism? Is it the same along as well as across the belt, or is this metamorphism diachronous? In the latter case, does this reflect the progressive burial of a single continental plate, or are there several continental domains separated by oceanic domains?
- What are the mechanisms for the exhumation of the *HP-UHP* rocks? Is erosion the driving force for exhumation? What is the record of erosion in the nearby sedimentary basins? Erosion may have been combined to other tectonic processes, like buoyant uprise of the *HP-UHP* bodies, associated or not with plate divergence, slab roll-back, … Collision may have reworked most of the evidence, but a careful analysis of the field evidence provides major clues.

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Building topography in the Northern Hellenides: insights from geomorphic analysis and cosmogenic nuclides

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The Northern Hellenides are located on the eastern margin of the Adria plate, and represent the central segment of the Dinarides-Hellenides orogenic belt. Situated at the junction between continental subduction to the north and oceanic subduction to the south, the Albanian region offers a prime location for studying the interaction between surface and deep geological processes in the Central Mediterranean area. The coexistence of compressive and extensional tectonic styles over short distances strongly contributes to shaping the landscape (Burchfiel et al., 2008), and it is still reflected in the modern focal mechanisms (D'Agostino et al., 2022). Morphological and seismic evidence indicates intense tectonic activity in this region at least since the late Quaternary, a period that is also characterised by intense climatic variability. In this research, we investigate the landscape's response to tectonics and climate by 1) performing an extensive tectonic, geomorphic and fluvial analysis, and 2) calculating basin-wide denudation rates using cosmogenic nuclides.

Basin-wide denudation rates were calculated using cosmogenic Beryllium nuclides across 19 basins distributed throughout various tectonic and geological domains of the orogenic belt. The presence of different lithologies including limestones, ophiolites, silicates, and metamorphic rocks required the use of the in situ 10Be technique for catchments draining quartz-bearing lithologies, and the new meteoric 10Be/9Be technique for areas dominated by quartz-poor lithologies.

Denudation rates exhibit a significant spatial variability ranging from 0.1 mm/yr to over 1 mm/yr, with higher values concentrated in the central part of Albania, where the transition from compressional to extensional domains occurs. The observed spatial variability in denudation rates likely reflects variations in uplift rates. Geomorphological analysis underscores the transient nature of the Albanian orogen, marked by elevated relict surfaces, non-lithological knickpoints, evidence of recent drainage reorganisation and river terraces, reflecting also Quaternary climatic fluctuations. Projections of rivers draining the relict landscape cluster around three ranges of elevation, possibly recording separate episodes of relative base-level changes due to accelerations in rock uplift rates.

We interpret these findings as the result of the interplay between deep crustal accretion, occurring at the regional scale over long periods (>106 years), and the activity of upper crust normal faults at shallower levels since the Pliocene (Guzmán et al., 2013; Pashko et al., 2020). At the local scale, fault activity seems to influence the observed spatial variation of denudation rates. The consistency of denudation rates with incision rates, calculated from river terraces, and with GNSS vertical rates (Serpelloni et al., 2022) further supports our results, offering new insights into the geodynamic evolution of the Northern Hellenides.

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Deep structure and collisional processes in the Western and Central European Alps

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We investigate both the deep crustal structure of the Western and Central Alps orogenic wedge and the timing and amount of convergence accommodated since 32 Ma. The new structural interpretations are based on the most recent geophysical models (Vs and Vp tomography mainly) coupled to geological surface information. We show that first-order similarities in collision kinematics can be described from the Western to the Central Alps. After the subduction-collision transition (37-32 Ma), from around 32 Ma and until 22-20 Ma, the shortening consists of distributed deformation throughout the doubly verging orogenic wedge. From around 20 Ma until recent times, the orogen was controlled by localized west- or northwest-verging thrusts below the External Crystalline Massifs. This probably witnesses localization processes in the proximal European crust (i.e., below the Penninic Frontal Thrust) on a 10 Myr timescale. These structures (both distributed and localized ones) root in middle- to lower crustal low velocity (Vs) zones interpreted as a thick shear zone acting as a deep, crustal decollement. The low seismic velocity is most probably controlled by active fluid circulations, structural anisotropy, and/or metamorphic Alpine paragenesis (amphibolite facies). Thus, the 10 Myr timescale may correspond to characteristic time for the localization processes within the deep, ductile decollement.

Along-strike significant differences from Western to Central Alps can also be highlighted. Beyond collisional magmatism and amphibolite facies metamorphism only present in the Central Alps, kinematical differences can be quantified. In the Western Alps, after the first phase of collision, at around 20 Ma, the orogenic wedge consisted in a West-verging wedge while in the Central Alps, North- and South verging structures remained active. These differences imply significant contrasts in terms of convergence rates that can be quantified through balanced cross sections with realistic inherited Mesozoic structures. In Central Alps, convergence rates were about 1.2 +/- 0.2 cm/yr from 32 to 22 Ma and about 0.3 +/- 0.1 cm/yr from 22 to 0 Ma. This strongly suggests that before collision s.s., i.e. before 32 Ma, the convergence rate was higher than 1.2 cm/yr.

While similarities in terms of structural styles and kinematics in both parts of the orogen most likely reflect crustal rheology and localization processes, the differences allow discussing the influence of both the inherited Mesozoic structure and the kinematics of Adria after the subduction phase.

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Two Paleozoic orogenic cycles preserved in the Central Alpine basement (Central Alps, Switzerland)

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We investigated the Paleozoic evolution of basement units in the northern and southern Aar Massif to provide new insights into its Ordovician and Carboniferous (Variscan) tectonic and metamorphic evolution. The northern and the southern basement units contain former large volumes of melts (more as 80%), which locally develop a granitoid character, and therefore are partly interpreted as granites and partly as diatexites. The dominant quartz-feldspathic composition of the units in combination with the Alpine overprint does not allow a detailed quantitative determination of the physical conditions of metamorphism.

A detailed laser ablation ICPMS geochronological study provides evidence for two episodes of high-temperature metamorphism and anatexis: Both localities are dominated by *Ordovician-age zircon*, occurring as (i) oscillatory-zoned (OZ) thick rims overgrowing ubiquitous Neoproterozoic (~600-800 Ma) cores; (ii) as entire OZ and sector-zoned (SZ) grains of magmatic appearance, or as (iii) OZ and SZ cores overgrown by thin OZ rims of younger age. Mean weighted $^{206}Pb/^{238}U$ ages from OZ zones cluster between 447 and 455 Ma (± ~2-3 Ma internal error). Zircon from the "Erstfeld gneiss" in the northern Aar massif almost lacks any record of a Variscan-age metamorphic overprint. A pervasive ductile fabric in the rock is interpreted as the result of a solid-state deformation during Variscan medium-grade metamorphism. Beside the dominant record of Ordovician magmatism, the samples from the southern part of the Aar massif contain zircon with U-rich, often OZ rims that crystallized during a *Variscan high-temperature overprint* in the presence of melt. The age of the Variscan overprint is poorly defined due to superimposed lead loss. These rocks have been variably mapped as diatexite or granite (e.g., the Strem granite in the eastern part of this zone). They contain subhedral allanite, as well as allanite overgrowing britholite. This indicates the presence of a melt fraction in the stability field of allanite, probably during the Variscan cycle. The studied units are the country rocks of pulses of Variscan magmatism at 335, 310 and 300 Ma [1]. In-situ U-Pb ages of U-rich zircon rims from the country rocks range from 320 to 310 Ma, roughly coinciding with the emplacement time of the intrusive rocks. We therefore conclude that the units investigated from the northern and southern parts of the Aar massif underwent extensive anatexis in Ordovician time, but were at different crustal levels during the Variscan orogeny.

We also carried out in-situ analysis of the zircon Hf isotopic composition in the same growth zones that were dated by U-Pb. The variation in eHf in inherited Neoproterozoic cores, Ordovician growth zones and Variscan rims is quite similar, providing evidence for a process of crustal recycling without the participation of a mantle component, neither during the Ordovician nor during the Variscan cycle. This raises questions about the nature of the thermal energy required to cause such large-scale crustal melting. Further studies will need to focus on the question of the source of heat (and water) for such melting events.

[1] Ruiz et al. (2022) Swiss Journal of Geosciences, 115,

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Shaping the crustal structure of the SW-Alpine Foreland: Insights from 3D Geological modeling

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Reactivation processes play a significative role in the localization of deformation but still remain hard to establish at the lithospheric scale. In this work, we built a 3D structural model, which enables to bridge the gap between the main tectonic structures observed at the surface and the geometry of the major interfaces (the Moho and the top of the basement) inferred by geophysical data acquired in the external Western Alps and their foreland. The geometry of these tectonic structures is interpreted in relation to their geodynamic evolution. The main results of this study highlight: (1) a strong contribution of thick-skinned Pyrenean-Provence and Alpine tectonics, (2) a lithospheric rooting of Variscan shear zones and related faults, and (3) the regional-scale influence of these inherited structures on the post-Paleozoic strain localization of the study area. Our 3D model shows that the pattern of Variscan shear zones, that were developed at the end of the Paleozoic involved the whole crust, as emphasized by the Moho offsets. These shear zones were reactivated and localised Meso-Cenozoic deformation. The Variscan deformation pattern controlled the geometry of extensional basins, the propagation of Pyrenean-Provence deformation, and finally the Alpine deformation at crustal scale. Our 3D model shows minor crustal thickening (ca. 40 km) located below the Pelvoux External Crystalline Massif, which probably resulted from both Pyrenean and Alpine tectonic phases. In contrast, the southern part of the Alpine front shows a thinned crust (ca. 18 km) resulting from extensional Meso-Cenozoic phases between the Cevennes margin and the Durance basin.

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Revealing the temporal dynamics of fault reactivation in the W-Alpine foreland using in-situ U−Pb dating on calcite

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Long-term study of fault system activity is crucial for understanding the dynamics of orogeny structuring and the formation of peripheral basins, the impact of tectonic inheritance, seismic hazard assessment, and the estimating the coupling of deformation and erosion. At the junction of several orogenic domains, the foreland basin of the Western Alps exhibits a complex structural pattern inherited from the superposition of tectonic events since the late Paleozoic. Despite this knowledge, the absolute age of fault formation and reactivation remains poorly understood, primarily due to the difficulty of dating uranium-poor minerals typically found in sedimentary environments. This study proposes an integrated approach of structural analysis of deformations in the field combined to the recently developed U-Pb in-situ dating method on syn-tectonic calcite to fill this gap. By focusing on the subalpine massifs (from the Vaucluse massif to the Bornes massif), this work aims to constrain the dynamics of the Alpine foreland structuring over a wide temporal and spatial scale. Additionally, this study area presents diverse geodynamic characteristics, making it an ideal site to test the applicability of recent U-Pb in-situ dating methods.

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Mesozoic tectonic events in the southern European basement revealed by thermochronology - insight for margin paleogeography (Pelvoux and Maures-Tanneron massif)

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It is now well established that the tectonic structure and thermal properties inherited from the orogens and rifting play an important role in the subsequent collision. This study focuses on the thermal inheritance of crystalline massifs from the SW Alps (Pelvoux and Maures-Tanneron) and their geodynamical implications during the Mesozoic continental rifting. Thermochronometers, including U-Pb/Apatite, Zircon fission tracks (ZFT) and Apatites fission tracks (AFT), (U-Th)/He on zircon and apatite (Zhe, AHe), their QTQt modelling and Rb/Sr dating on phengite in one shear zone, show successive tectonic events. The ZFT in the Pelvoux indicates a complex thermal history with central ages ranging from 158 to 45 Ma, thereby revealing significant resetting and cooling in the Jurassic and Eocene periods. The thermal modelling of a separate block of the massif highlights a thermal history emphasized by three distinct periods of: (1) Jurassic-lower Cretaceous heating associated with the Alpine Tethys and Valaisan opening, (2) pre-Alpine upper Cretaceous to Priabonian cooling linked to tectonic inversion of the European margin, which agrees with onset of Pyreneo-Provençal phase of shortening during the upper Cretaceous as revealed by a Rb/Sr age of 79.7 ± 3.7 Ma in an E-W (top-to-the-South) shear zone, (3) Miocene Alpine cooling/exhumation event. In contrast, in the Maures-Tanneron Massif multiple thermal events are highlighted by thermochronology, including (1) a cooling phase at approximately 200 Ma associated with CAMP volcanism preserved in the Tanneron massif, which is followed by (2) a Mesozoic (120 Ma) cooling event, after which the massif remained close to the surface until a final Eocene cooling phase. These results provide insights on how the architecture of rifted domains of the European margin in the wide plate boundary between Adria, Iberia and Europe controlled exhumation between the Alps and the Pyrenees-Provence orogenic systems.

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Oceanic detachments in Tethys realm: core complexe or not?

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Oceanic detachments are large-offset normal faults along the flanks of mid-ocean ridges. They represent a mode of accretion of the oceanic lithosphere that is fundamentally different from classical "magmatic" models, resulting in lithospheric composition and structure that are strikingly different from the classical model of a layered magmatic oceanic crust. Oceanic detachments, which exhume deep lithosphere, forming oceanic core complexes (OCCs), are scientifically interesting because they represent tectonic windows to deep-seated rocks and processes (mantle flow, melt generation and migration, strain localization, and crustal accretion) at mid-ocean ridges (*Escartin & Canales, 2010*).

In this ongoing study, we propose to compare two different ophiolitic series from the Tethys realm: The Chenaillet (Western Alps) and the Troodos (Cyprus) ophiolites. The two ophiolitic massifs are well known for the quality of their outcrop and the evidences of oceanic processes are still well preserved. This is particularly evident in their magmatic, tectonic and hydrothermal structures and textures. Both massifs have been little affected by events subsequent to their emplacement, excepted by the formation of some folds on a more or less large scale. In both cases, detachment-type intra-oceanic tectonics have been described in the literature (Troodos: *Hurst et al. 1994*; Chenaillet: *Manatschal et al. 2011*). Furthermore, both have been interpreted as oceanic core-complexes on the basis of isotopic (δD, $\delta^{18}O$) studies (Troodos: *Nuriel et al. 2009*; Chenaillet: *Lafay et al. 2017*).

This interpretation is identical for two ophiolitic massifs, despite significant differences in their crustal structure and geodynamic settings. The Troodos massif represents a complete supra-subduction ophiolitic series, characterised by the presence of well-developed layers of oceanic crust. In contrast, the Chenaillet massif, originating from the Piemont ocean, is predominantly composed of serpentinite and basalt, with widespread distribution of gabbros.

The objective of this study is to gain insight into the dynamics of these detachments by analysing new field data, petrological data and geochemical data. This will enable us to understand the relationship between the detachments and magmatic and hydrothermal processes. It can be demonstrated that, despite exhibiting certain similarities, these two detachments are in fact quite distinct and do not play the same role in the formation of the oceanic crust. The Chenaillet Massif provides an illustrative example of an OCC, whereas the detachments of the Troodos Massif post-date the formation of the oceanic crust and are linked to ridge jumps.

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Kinematics of the Western Alpine arc: insights from paleomagnetic data and vertical axis rotations.

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Orogenic arcs result from processes ranging from structural inheritance, to molding around arcuate indenters, and/or oroclinal bending of an initially straight mountain range. Most kinematic models for the formation of the Western Alpine arc (WAA) propose a syn-collisional development under the effect of NW- or Wward Adriatic indentation (Brunsmann *et al.*, 2024, for review). This indentation is sometimes associated with a 25° counter-clockwise rotation of the Adriatic indenter, based on GPS- (e.g. Nocquet, 2012), seismotectonic (Bauve *et al.*, 2014), and paleomagnetic data (e.g. Collombet *et al.*, 2002). Paleogeographic reconstructions based on retro-deformation of collisional shortening imply the existence of a pre-collisional proto-arc (e.g. Bellahsen *et al.*, 2014).

Paleomagnetic analyses allow us to study vertical axis rotations, and to discuss them in the frame of orogenic arc development. We present the analysis of an exhaustive compilation of Alpine paleomagnetic data highlighting that on the 1st order vertical axis rotations affect the formation of the WAA as follows:

1) in the Adriatic plate (Southern Alps, Istria, Pô plain) paleomagnetic data contradict a post-Miocene counter-clockwise rotation of 20-25° of the indenter, showing that the latter does not undergo significant rotation during Alpine collision (<10°).

2) The orogenic internal, subduction wedge undergoes counterclockwise rotations that increases southward of the arc, following the progressive rotation of the main tectonic structures, striking NE-SW in the north and WNW-ESE in the south. The relation between the direction of the main structures and vertical axis rotations of post-Oligocene age in the Internal Zone suggests that the arc was amplified during collision. However, the rotation of the main tectonic structures is greater than the rotation of the Oligocene paleomagnetic directions, implying the existence of a pre-collisional, proto-arc.

3) There is no significative relation between main tectonic structures of the External Zone and the rotation of the paleomagnetic directions along the WAA, and no rotation is measured in the Permian rocks of the Argentera massif. This implies that the arcuate morphology in the European margin is mainly inherited from a pre-collisional phase.

Vertical axis rotations in the western Alps therefore indicate the collisional amplification of an early arc whose morphology is inherited from the subduction period. It also shows that E-W structures in Ligurian region are controlled by the orocline formation but also by left-lateral shear and Apennine slab retreat.

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Neotectonics in the Corsica-Sardinia block: relationships between surface processes and lithospheric structure

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The Corsica-Sardinia block (CSB) is set in the middle of western Mediterranean between two highly stretched lithospheric domains, the Balearic and Tyrrhenian basins, that opened because of the progressive eastward migration of the Apennine front and roll-back of the Neotethys slab. The main tectonic features recorded in the CSB are Oligocene-Miocene strike-slip faults with either NE-SW orientation in Corsica and northern Sardinia and NW-SE orientation in southern Sardinia. Several evidence indicate multiple reactivation of these trans-crustal structures over time. The oldest stage of reactivation is testified by voluminous Pliocene-Quaternary anorogenic volcanic activity localized along the strike-slip faults in northern and central Sardinia. Farther to the south, strike-slip faults reactivated as normal faults during the Quaternary accommodating the deposition of more than 1000 m of continental deposits in the Campidano basin. Finally, in several sites strike-slip faults reactivated as normal or oblique faults offsetting upper Pleistocene to Holocene coastal deposits.

In spite of these evidence of recent deformation, the CSB is characterized by vertical aseismic movements in the order of few mm per year and weak seismicity, with earthquakes occurring usually at depth not higher than 10 km and along the main Cenozoic faults. These structures also control the topography of the Corsica and Sardinia islands, supporting a rugged morphology with peaks close to 2000 m in Sardinia and 3000 m in Corsica, deep river incisions and other geomorphic features typical of relief rejuvenation. To investigate the cause of this cryptic neotectonic activity we run a set of Finite Differences numerical models that simulate the CSB as thin elastic plate overlying an inviscid asthenosphere.

The structure of the model lithosphere is based on available geological and geophysical dataset and is divided into six compositionally homogeneous layers: air or water, sedimentary or volcanic cover, crystalline middle crust, lower crust, lithospheric mantle, and asthenosphere. In the experiments, we change the density and heat production rate of the crustal layers to fit the measured Bouguer gravity anomaly and surface heat flow.

The best fit experiment shows that the CSB crust consists of a relatively low-density lower crust composed by felsic granulites moderately enriched in heat-producing elements, and a standard-density middle crust composed of highly productive granites or migmatites. The results suggest that neotectonic activity can be related to regional uplift driven by a mass deficit localized in the lower crust. In our opinion, the Cenozoic faults accommodate differential vertical displacements of fault-bounded blocks, occasionally triggering low-magnitude earthquakes in the upper crust. This interpretation account also for the peculiar geomorphic features of Sardinia and Corsica, where the landscape is continuously rejuvenated according to the uplift movements.

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The structural evolution of the Rotondo granite (Gotthard nappe, Central Alps): constraints on the strength and timing of weakening of the European upper crust during Alpine collision

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Collisional dynamics, exhumation rates, and the large-scale geometry of orogenic belts are dependent on the relative strength contrast between colliding plates. In the Central Alps, the strong Adriatic lower crust indents into the thickened European upper crust, composed of stacked slices of weak, upper continental crust. The geological factors controlling this weak rheology and the timing of weakening are still debated.

To provide further constraints on what makes the European continental crust so weak, we have investigated the structural and tectonic evolution of the Rotondo granite through integrated field, microstructural, and in-situ (U-Pb on garnet, Rb-Sr on mica) petrochronological analyses. The Rotondo granite, an early Permian peraluminous granite (295 Ma, Rast et al., 2022), represents a strong inclusion in the polymetamorphic Gotthard nappe in the Swiss Central Alps. We have identified a sequence of four (D1-D4) main classes of deformation structures developed during the pre-Alpine, Alpine collisional, and exhumation history of the nappe.

D1 structures include brittle breccias, cataclasites and shear fractures, occurring pervasively throughout the pluton and pre-dating the Alpine peak metamorphic conditions. Garnet overgrew the brittle deformation fabric during Alpine peak metamorphic conditions at 580 ± 25 ºC and 0.9 ± 0.1 GPa at different times from 34 to 20 Ma (in-situ U-Pb dating on garnet). The following Alpine exhumation is recorded through the development of D2 reverse, ductile shear zones at 520 ± 40 ºC and 0.8 ± 0.1 GPa around 18-20 Ma (in-situ Rb-Sr on white mica). Exhumation perdured until 14 Ma, as inferred from in-situ Rb-Sr on synkinematic micas of D3 strike-slip brittle-ductile shear zones developed at 395 ± 25 ºC and 0.4 ± 0.1 GPa. The latest stages of upper crustal, brittle tectonics are shown by the development of D4 zeolite- and gouge-bearing fault zones at < 13 Ma (K-Ar illite dating).

This tectonic evolution is common to many other crystalline massifs of the External domains of the European Alps, and allow us to propose some large-scale implications on the rheological behavior of the continental (upper) crust during Alpine collision. The 34-20 Ma range of ages obtained from in-situ U-Pb dating on garnet suggests that the peak metamorphic conditions in the area likely persisted for more than 10 Myrs. After the peak, exhumation occurred at relatively fast rates (~3 mm/yr), and the internal deformation of the nappe was accommodated by weak ductile shear zones, localized on pre-existent (inherited) structural features. Indeed, meso- and microstructural considerations suggest that these shear zones were capable of sustaining differential stresses not larger than 10 MPa during collision and exhumation. The strength of the undeformed granite, limited by tensional veining, has been estimated to not exceed 60 MPa. This also demonstrates that the main weakening event of the crust occurred at retrograde conditions, during exhumation, after residing for a prolonged period of time at peak metamorphic conditions.

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Northern Apennines transpressive structuring result of Nubia Plate oblique subduction (Upper Oligocene – Early Miocene)

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The geodynamic role of Northern Appennines must be investigated in relation to geological data supporting a transpressive upper Oligocene-early Miocene evolution, rather than a compressive one.

Several sedimentological, stratigraphic and structural data suggest that Northern Appennines are the result of tectonic coupling of two stacks, the eastern emilian sector and the western ligurian-tuscan sector, originally contiguous along the axis of the chain.

It can be assumed that the eastern stacking must have originally occupied a more north eastern position, more closely connected to the Alps, than its current position.

The coupling of the two stratigraphic structural stacks on the same transversal would have been achieved in a right transpressive regime with a few hundreds of km displacement parallel to the axis of the chain.

The transpressive structure is typical of a fore- arc sliver in the geodynamic context of oblique subduction.

Northern Appennines would have being playing this tectonic role, during upper Oligocene and early Miocene, in the geodynamic context of the oblique westward subduction of the Nubia plate oceanic crust , at present represented by the Ionian Sea and Herodotus Ocean.

The subduction would therefore have occurred according to the anti-clockwise rotation trajectory of the upper plate, represented by the composite lithospheric unit (Corsican Sardinian block + deformed and undeformed Adria plate) limited to the north-west by the expanding back-arc basin (Algero-Provencal basin).

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The Apula plate's response to the interaction between Calabrian and Hellenic orogens: tectono-stratigraphic evolution and implications on intra-plate deformation (Northern Ionian Sea, Central Mediterranean)

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The Apula plate in the Northern Ionian Sea, is a sliver of continental crust covered by around 8 km of Mesozoic carbonates. It acts as the foreland of two opposite verging chains: the SE-verging Southern Apennine to the southwest, which merges with the Calabrian Arc wedge at the Taranto Gulf and the SW-verging External Hellenides to the northeast. In this work we use deep seismic reflection profiles to illuminate the structures and stratigraphic relationships between the frontal part of the orogenic belts and adjacent foreland, as well as to determine the key tectonic processes that have governed the onset of the region's existing structural architecture. A detailed seismo-stratigraphic study allows us to recognize three major regional unconformities: i) the Jurassic/Cretaceous unconformity which is marked by Cretaceous reflectors that clearly onlap the Jurassic carbonate platform; ii) the Messinian unconformity, related to a regional erosive event linked to the Messinian desiccation of the Mediterranean Sea; and iii) the middle Pliocene unconformity, an erosive and angular unconformity that truncates the Lower Pliocene reflectors. Although the Apula plate is typically thought to be a stable foreland zone, our study shows that it underwent extensive deformation strongly influenced by its interaction with the neighboring Southern Apennine/Calabrian Arc and Hellenic wedges. An active NW-SE-striking extensional fault system is possible due to the Apula plate bending under the stress of the two opposing orogens. Compressive and transpressive structures (e.g., smooth and open folds at the plate contact zone as well as active NE-SW striking positive flower structures) accommodate shortening processes and oblique plate convergence. Transpressive tectonic structures resulted from inherited Mesozoic normal faults that have been reactivated since the middle Pliocene and such compressive/transpressive regime promoted the mobilization and squeezing of Upper Triassic evaporites into teardrop diapirs. These findings make the regional geological setting and the pre-collisional grain of the Apula plate critical aspects in defining the tectonic evolution of the Northern Ionian Sea as well as the position and geometry of tectonic structures located in this area.

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The "Digital Structural Model of Italy", the new geological map of Italy, Alps and adjacent areas at a scale of 1:250,000.

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Currently, the most detailed geological map that completely covers the Italian territory and the entire Alps is the 'Structural Model of Italy' at a scale of 1:500,000, published in 1990-1992, which has never been updated. Since the publication of this map, there has been an increasingly production of geological cartography at different scales on a national and international level, together with the proliferation of spatial data management systems (GIS) and the development of technologies for the dissemination of such data, on various types of media and systems.
The project "Digital Structural Model of Italy - DiSMI", funded by Istituto Nazionale di Geofisica e Vulcanologia - INGV and coordinated by INGV and University of Siena (Italy), aims at producing a new geological map for the entire Italian territory, Alps and adjacent areas (over 700,500 km^2). This project will be characterised by: a) geological cartography at a scale of 1:250.000; b) full vector maps produced in a GIS environment; c) a single and continuous geological database and legend for the entire area; d) production of a new topography basemap for the entire area; e) production of PDFs with portions of the geological map with traditional print layout; f) production of Explanatory Notes.
All the results of this Project (geological database, maps in PDF format, topographic base, Explanatory Notes) will be made freely available. The geological cartography will also be made viewable through a WebGIS service. The WebGIS will also include the cartography of the "Structural Model of Italy" at a scale of 1:500,000 (1990-1992), both on land and at sea.

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Tectonometamorphic evolution of a long-lived crystalline basement: the northern Dora-Maira Massif in the Germanasca – Pellice Valleys (Western Alps)

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Recent investigations in the northwestern part of the Dora-Maira Massif (Nosenzo et al., 2024 and references therein) shed new light on the structural architecture and metamorphism of its tectonic units, with the discovery of a new UHP unit. Despite these efforts, many open questions remain regarding the structural architecture and tectono-metamorphic evolution of this basement. In this contribution, we present preliminary data from an area located between the Tredici Laghi and Conca Cialancia natural park (Germanasca - Pellice Valleys), a so far poorly explored mountainous region. This area consists of a polycyclic basement composed of micaschist, orthogneiss, paragneiss, marble and metabasite. The structural setting of the area has been reconstructed using a new structural map and geological cross-sections carried out in the framework of the CARG mapping project (Sheet 172 –"Pinerolo"). Microtectonics studies and preliminary P-T-t data have been integrated to tentatively provide a more complete picture of the tectono-metamorphic evolution of the studied area.

Geochronological analyses (U-Pb dating on zircon) allow the recognition of several generations of orthogneiss, with locally preserved overlapping relationships in the field, whose ages range from Early to Late Ordovician. The Alpine structural evolution of the area has been deduced from the correlation of the P-T path with the microstructures. The S_1 foliation, rarely preserved in microlithons, developed during prograde P-T conditions and is associated with the syn-kinematic recrystallization of phengite, paragonite, chloritoid, garnet, rutile and probably sodic amphibole (currently pseudomorphsed by albite and chlorite). A subsequent S_2 foliation (defined by a second generation of phengite, paragonite, chloritoid, garnet with epidote, ilmenite, albite and minor chlorite) developed along E-W trending lineation-parallel folds. D_2 deformation is very heterogeneous: a mylonitic fabric is present in high-strain domains, whereas local pre-Alpine features are preserved in low-strain domains (as already documented elsewhere by Nosenzo et al., 2022). The D_3 event is associated with the development of a local S_3 foliation, parallel to the axial planes of open NW-SE trending folds and deforms all the previous structures. The S_3 foliation is associated with metamorphic re-equilibration in greenschist facies. Several examples of superimposed D_2 and D_3 folds are documented at various scales. The axial planes of the D_3 folds are bended by the final doming of the Dora-Maira nappe stack (D_4), associated with late metamorphic conditions.

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Tectonic map and structural architecture of the "*Briançonnais Zone*" (Western Alps)

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In the Southwestern Alps, tectonic units derived from the Briançonnais passive margin are exposed in two domains (Michard et al., 2022 and references therein): (i) the "*Briançonnais Zone s.l.*", dominated by Mesozoic sequences either overlying Permo-Carboniferous deposits or Variscan basement, described by the early French authors (e.g., Termier, 1903), and (ii) the pre-Mesozoic basement-dominated "*Internal Crystalline Massifs*" (ICM). We present a new tectonic map covering a large portion of the diverse units of the "*Briançonnais Zone s.l.*" and immediately adjacent units. These comprise, from W to E: (1) Briançonnais, Subbriançonnais and Dauphiné units and far-travelled Ligurian Helminthoid units, structurally located in the footwall of the out-of sequence Penninic Frontal Thrust (PFT), (2) a stack of *Briançonnais s.str.* units in the immediate hangingwall of the PFT dominated by W-directed fore-thrusting (e.g., the classical "1.-4. écailles" of Termier, 1903), (3) a complex intermediate zone characterized by large-scale backfolds leading to (4) a pile of backthrusted units, comprising units referred to as "*Acceglio-type*" and "*Prepiemonte*" units, and (5) units derived from the Piemont-Liguria Ocean. Units (4) and (5) tectonically overlie ICM (Michard et al., 2022 and references therein; Dana et al., 2023). We use existing geological maps and literature combined with own fieldwork data to construct a tectonic map, and associated geological cross-sections, of the above-mentioned units between Modane (north of Briançon) and the Argentera-Mercantour Massif. Our compilation aims at revealing the structural architecture of the "*Briançonnais Zone s.l*", allowing for a classification of these units over longer distances along strike on the basis of structural and metamorphic criteria, avoiding as much as possible the traditional mixing of paleogeography and tectonics and preventing the use of a wealth of multiple names for one and the same unit. These units have been deformed by a polyphase structural evolution (from D1 up to D3) associated with Alpine metamorphic conditions ranging from greenschist to blueschist facies. Particularly, we highlight the frequently underestimated importance of backfolding and backthrusting (D3) and its effect on the structures associated with the previous deformation phases linked to subduction and fore-thrusting (D1-D2). A comprehensive review in the form of a map and profiles of the "*Briançonnais Zone s.l.*" tectonic units is essential for future and more detailed studies, on the one hand, and for better understanding of the highly non-cylindrical large-scale structure of the Western Alps arc and its transition into the E-W striking Central Alps.

Dana, D., Iaccarino, S., Schmid, S.M., Petroccia, A., & Michard, A. (2023). Structural and metamorphic evolution of a subducted passive margin: insights from the Briançonnais nappes of the Western Alps (Ubaye–Maira valleys, France–Italy). *Swiss Journal of Geosciences*, *116*, 18.

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Unveiling the Tectono-Metamorphic Framework of northern Dora-Maira Massif (Western Alps): new preliminary data from Pellice and Chisone valleys

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Dora-Maira (DM) Massif plays a crucial role in understanding the geodynamics that shaped the Alpine belt. Extensive studies have been mostly conducted in the southern portion of DM (e.g., Chopin et al., 1991). Recent investigations (Manzotti et al. 2022; Nosenzo et al., 2024) have renewed interest in the northern portion of the massif. These authors provided new structural and metamorphic data on the area, particularly with the discovery of a new ultra-high-pressure unit (the Chasteiran Unit). Despite these significant contributions, there are many open questions at the scale of the entire DM. In this contribution we present new data collected within the framework of the CARG mapping project (Foglio 172-Pinerolo). Our aim is to shed light on the structural and metamorphic architecture in the Val Pellice and Val Chisone areas. We present a geological map with geological cross-sections, at a scale of 1:10,000, covering the region between Colle Lazzarà and Colle Vaccera. Additionally, we conducted preliminary microtectonic, petrographic, and geochronological studies to reconstruct the structural and metamorphic evolution of the investigated area. In this relatively unexplored part of DM, three distinct tectono-metamorphic units are exposed, which are (from bottom to top): Pinerolo-Sanfront Unit; Chasteiran Unit, and the poly-cyclic basement unit of the DM massif. Particular attention has been paid to mapping the tectonic contact related to the Chasteiran Unit, which is sandwiched between the other two tectono-metamorphic units. This contact has been traced further southward, up to Colle Vaccera, compared to previous investigations. To reconstruct the metamorphic history, we present preliminary P-T data obtained from ongoing analysis of the micaschist in the Pinerolo-Sanfront Unit. At least four deformation phases have been recognized: (i) the D1 phase, associated with the development of an S1 foliation preserved only within the microlithons; (ii) a second deformation phase, associated with the development of the main foliation (S2) characterized by an E-W trending lineation, (iii) the D3 deformation phase overprinting D2 structures; (iv) a D4 deformation phase that developed during the doming of the Dora-Maira Massif; and finally, (iv) a D4 deformational phase that developed during the doming of the Dora-Maira Massif. In addition, we present preliminary geochronological data performed on Freidour-type orthogneiss in the Pinerolo-Sanfront Unit, refining the Permian age obtained from previous studies (Bussy & Cadoppi 1996).

This contribution has been performed whit the found of the CARG mapping project.

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Evolution of the Carpathian Foreland Basin and its link with collision and slab detachment

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The Carpathians are a typical Mediterranean-type orogen that resulted from slab roll-back, nappe accretion, collision and slab detachment. We will use basin-scale sedimentological and provenance analysis to reconstruct the Miocene to recent evolution of the Carpathian Foreland Basin. Paleontological observations will highlight the basin's biogeographic relations with the surrounding regions, demonstrating the creation and destruction of topographic barriers with the Pannonian Basin and the Black Sea. Results from inverse modelling of thermochronological data from the Carpathians with PECUBE will be used to understand the timing and volume of sediment supply from different parts of the mountain belt, which will then be compared to deposition over time in the foreland basin. Finally we will establish a link between the geodynamic events in the subduction system, particularly collision and slab-detachment, and the evolution of the foreland basin. Since there are many similarities between the Carpathians and other roll-back orogens, our results might be interesting for researchers studying other Mediterranean-type orogens.

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New geochronological data from mafic and felsic meta-intrusives of the Western Alpine Ophiolites: the missing magmatism of the Ligurian-Piedmont Ocean?

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The Ligurian-Piedmont Ocean (LPO) is inferred as a relatively narrow oceanic basin in palaeogeographic restorations, but the actual amount of oceanic lithosphere generated and the timing of magmatic accretion are still debated. Magmatic ages obtained from LPO intrusive rocks predominantly range between 165 and 160 Ma, supporting the interpretation of the LPO as a magma-poor ocean. However, this relatively short timespan of magmatic accretion may also suggest that the orogen sampled older sectors of the oceanic lithosphere, while younger (and more oceanward?) sectors could have been deeply subducted without returning.

We therefore focus on studying a poorly-known stack of oceanic lithosphere (i.e., the Susa and Lanzo Valley Ophiolites; SLVO), which is exposed in the inner-central sector of the Western Alps and tectonically juxtaposed with the Gran Paradiso and Dora-Maira massifs. The SLVO were metamorphosed under eclogite-facies peak conditions and consist of large volumes of serpentinite hosting up to kilometer-sized metagabbro bodies, with Fe-Ti-rich differentiated masses and rare metaplagiogranite dykes. The metaophiolite sequence also includes widespread metabasaltic rocks and a metasedimentary cover consisting of minor quartzite and marble levels overlain by calcschist.

Two pairs of Fe-Ti metagabbro and metaplagiogranite s.l. sampled close to the Avigliana (lower Susa Valley) and Mondrone (middle Ala Valley) localities have been selected for zircon U-Pb dating. In each sample, the dated zircons yield magmatic ages falling within the uppermost Jurassic Period (~150 Ma). The common age, along with similar major and trace element compositions, suggests a cogenetic origin within differentiation trends for the two pairs of metagabbro-metaplagiogranite (De Togni et al., 2024). Consequently, the SLVO were sampled from a sector of the LPO characterized by magmatic activity at ~150 Ma, significantly younger than most of previously reported ages for the LPO magmatism. We argue that the SLVO represent the youngest oceanic lithosphere accreted in the Western Alps and they may provide new constraints on the structural architecture of the LPO.

De Togni, M., Balestro, G., Rubatto, D., Castelli, D., Gattiglio, M., & Festa, A. (2024). Late Jurassic magmatism in the Ligurian-Piedmont Ocean constrained by zircon ages of mafic and felsic meta-intrusives. *Terra Nova*, 00, 1–11. doi.org/10.1111/ter.12723

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The European margin to and from the mantle depth: insights from the Lower Units (Alpine Corsica, France)

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In the late Eocene, the peripheral portion of the European margin was involved in the Alpine subduction/exhumation processes. Witnesses of this event are the polyphase deformation and the metamorphism registered by slices of continental crust which compose the Lower Units, i.e. a set of tectonic units placed at the lowest structural level of the Alpine Corsica (France). The pressure-temperature-deformation-time (*P-T-d-t*) path of one of them named Venaco Unit was traced by using an integrated set of data related to the phyllosilicates which dynamically recrystallized in the metagranitoids and metapelites. Different thermobarometric tools were applied to the chlorite and white mica crystals selected in the microdomains of the metapelites of the Venaco Unit. The ^{40}Ar/^{39}Ar dating was instead applied on syn-kinematic muscovite sampled from metagranitoids of the Venaco Unit. The results indicates that the Venaco Unit reached the baric peak at ≈ 33 km depth and was exhumed at shallower structural level (i.e., at ≈ 26 km depth) in the middle Priabonian. This retrograde path suggests that the Venaco Unit experienced fast exhumation through the activation of the top-to-W shear zones.

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Western alpine orogenic front geometry : new insight from the Digne nappe area by a 3D geometrical modelling approach

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The external parts of mountain belts, including their foreland basins, classically present a fold-and-thrust belt often detached on shallow decollement levels. These areas exhibit complex geometries with significant non-cylindrical components, necessitating a 3D approach to accurately determine the timing and style of deformation in the external zones.

The southwestern Alpine orogenic front is mainly characterized by the Digne Nappe, which thrusts over the deformed Mesozoic units. These Mesozoic units are unconformably overlain by the Cenozoic molasse deposits of the Valensole foreland basin, which are also deformed.

Despite the well-constrained sedimentary series of Barles and many of its structures, no study has yet fully explained the complex 3D geometries and processes that led to their formation. This region serves as an exceptional 3D example of a folded foreland, capturing much of the syn- and post-collisional history of the Alpine orogeny. The structural style, timing, and presence of salt structures remain challenging to specify, largely due to the non-cylindrical geometries that complicate simple 2D reconstruction. The Velodrome fold, formed by the initial deposits of the Valensole foreland basin, exemplifies a non-cylindrical structure whose understanding is still incomplete, leading to debates and various interpretations, including growth fold, post-sedimentary fold, and salt mini-basin.

To provide an accurate depiction and interpretation of the 3D geometries of the structures and to better characterize the style and timing of deformation in the Digne region, a combined approach of detailed structural field study and 3D geometric modeling using GeoModeller ©BRGM was undertaken. The 3D modeling was conducted at two scales: (i) regional, encompassing the Digne Nappe, the Robine unit, the Barles half-window, and the Valensole Basin, and (ii) more local, focusing on the Velodrome syncline. For the latter, GeoModeller was utilized to test hypotheses proposed in the literature. This approach enabled the reproduction of field-observed geometries in 3D, offering an interpretation of all formations consistent with surface observations. As a result, the contributions of regional tectonics and salt tectonics were assessed, and the timing of deformation was refined.

Elements of the geometry and timing of deformation in this frontal part of the Alps have been clarified. We show that south of the Barles half-window, the deformation of the Velodrome is early syn-depositional, starting earlier in the south of the basin (23 Ma) than in the north (18 Ma), requiring both regional tectonic control and halokinetic processes to account for the closure of the folded structures. The northern part of this half-window shows more cylindrical structures, but some faults appear localized and correlated with thickness variations of the Tithonian unit, indicating a role of inheritance in the localization of deformation. Finally, this study also demonstrated the power of GeoModeller as a 3D tool that is both predictive and useful for testing geological hypotheses in areas as complex as folded forelands.

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The heritage of Tethyan oceanic transform faults within Alpine orogens: The Shkoder-Peja transverse zone (SPTZ) of Northern Albania

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The Shkoder-Peja transverse zone (SPTZ) of Northern Albania marks the boundary between the Dinarides and the Albano-Hellenides chains and corresponds to a ~100 km SW-ward shift of the ophiolitic nappe front. Over the last sixty years, it has been variably interpreted as an inherited paleogeographic feature, a dextral strike-slip fault, the hinge of the clockwise (CW) rotating Albano-Hellenides system, and a Miocene-to-recent normal fault. Here we report on the paleomagnetism of 27 Triassic-Cretaceous sites from the Krasta-Cukali and the High Karst domain, both within and north of the SPTZ. Two sites yielded only a pre-tilting magnetization, 15 sites were found to be remagnetized after mid-Eocene-lower Miocene tilt, while 8 sites showed both pre- and post-tilt magnetizations. Both pre- and post-tilt paleomagnetic directions yielded a 60-70° clockwise (CW) rotation with respect to Adria/Africa, except 9 sites from the Koman zone at the ophiolitic nappe boundary showing a smaller 38°±15° CW rotation. Thus, the well-known regional CW rotation of the Albano-Hellenides extends northward in the southern Dinarides, and the SPTZ is not a rotation boundary as previously assumed. The ~70° CW rotation is consistent with available data from the nearby ophiolitic nappe complex, and is assumed to represent the sum of a 30° lower Miocene rotation during thrusting of the Kasta-Cukali over Kruja nappe plus the 40° Miocene-Pleistocene rotation well documented in the external zones of Albania. We suggest that the SPTZ is the heritage of a mid-Triassic transform fault of the Maliac Tethyan ocean, later overprinted by the lower Cretaceous obduction of the Vardar ocean, replacing Maliac since the middle-Jurassic.

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Control of pre-orogenic inherited faults on Alpine thrusting and fluid circulation: an example from transverse zones of the Central Southern Alps (Lombardy, Italy)

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Multiple rifting phases can strongly influence the structural architecture and stratigraphic evolution of a developing passive margin. Some stratigraphic intervals can be characterised by distinct changes in thickness, lithology and facies controlled by synsedimentary faults. These features profoundly modify and alter the classic "layer-cake" model. The Central Southern Alps, and the Lecco area in particular, are a first-class example of interaction between inherited and contractional structures (Gaetani & Jadoul, 1987). A Ladinian rifting phase caused the coexistence of both deep- and shallow-water successions of Middle Triassic age, as well as considerable changes in their thickness across the study area. During the Early Jurassic, another rifting phase caused the drowning of the Late Triassic to Hettangian carbonate platforms, leading to the formation of intra-basin structural highs and lows as well as extreme lateral thickness variations within the syn-rifting succession. The most striking evidence of the role of inherited structures during Alpine contraction are N-S trending transverse zones parallel to the main orogenic transport direction (Schönborn, 1992). During orogenic build-up, rift-related faults were passively transported along thrusts, preserving part of the post-rifting, pre-orogenic framework within the same tectonic unit or were reactivated as large displacement transfer faults separating tectonic sectors with different shortening. These transverse zones and the inherited, pre-orogenic structural architecture strongly influenced thrust development: lateral ramps, oblique thrusting, younger-on-older-relationships and lateral transfer of displacement occur throughout the entire study area. Geological mapping and structural analysis have been conducted to reconstruct kinematics and geometries of fault zones. Several geological cross-sections have been realized to constrain the fold-and-thrust belt geometry and reconstruct the structural evolution of Central Southern Alps. The complex pre- and syn-orogenic tectonic history of fault activity, particularly of the main thrusts and transverse zones, has been constrained from in-situ U-Pb dating of syn-tectonic carbonates. Inorganic thermal indicators were used to constrain the eroded overburden and the exhumation depth of the faulted succession. Another goal of our work is to reveal how fluid circulation may change from the high-angle dipping, inherited and misoriented transverse zones to the low-angle thrust faults, from the internal to the frontal sectors of the belt. C-O stable isotopes and clumped isotopes analyses on syn-tectonic carbonates collected along thrusts and transverse zones have been performed to assess fluid-host rock chemical and thermal (dis)equilibrium. We compare compressional mineralizations with those exposed in transverse zones where fluids might circulate in an open to semi-open system, with the ingress of cold (meteoric) and/or hot (deep) fluids.

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Discovering Earth's Challenge: Insights of Out-of-Sequence Thrusts in Alpine-Himalayan Orogenic Belt

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The Zagros orogenic belt is a component of the active Arabia-Eurasia collision zone in the Middle Eastern segment of the Alpine-Himalayan system, and it is one of the world's youngest seismically active continental collision zones. The Zagros region, which is one of the most seismically active continental collision zones in Zagros orogenic belt, provides an excellent case study for understanding tectonic processes and their consequences for geological development and seismic hazard assessment. This work presents an overview of the geological significance of the Zagros orogenic belt, with a focus on its function in larger context of the Arabia-Eurasia collision. It investigates the dynamic interaction of tectonic forces that have sculpted the landscape, from the first convergence of the Arabian and Eurasian plates to current deformation and seismic activity.

Furthermore, significance of continuing scientific efforts to understand the complexity of the Zagros orogenic region and its implications for seismic risk mitigation and natural resource exploration. Out-of-Sequence thrusts in the Eastern Alps' frontal zone (Levi et al., 2021). Out-of-Sequence thrusting in the Karwendel mountains of the western Northern Calcareous Alp (Kilian and Ortner, 2019). Besides, Out-of-sequence reactivation of older in-sequence thrusts is difficult to quantify. In Vienna Basin area, out of sequence Thrust adjusted to around 2 km at the Early Karpatian (approximately 16.5 Ma). The well Kirchdorf-1 drill explores that Molasse rocks that are exposed in tectonic windows caused by out-of-sequence thrusting at a depth of approximately 800 m above the basal thrust at the Alpine-Carpathian junction (Beidinger and Decker 2014). In-depth examination of the geological significance of the Zagros orogenic belt, focusing on its role within the broader context of the Arabia-Eurasia collision. Mukherjee (2015) docuemented OOS thrust displacement along the length Himalayan Arc.

Through a detailed analysis of tectonic processes and their consequences for geological development and seismic hazard assessment, this study offers insights into the dynamic evolution of the region. From the initial convergence of the Arabian and Eurasian plates to the ongoing deformation and seismic activity, the landscape of the Zagros orogenic belt bears the imprint of complex tectonic interactions. Furthermore, this study highlights understanding the complexity of the Zagros orogenic region and its implications for seismic risk mitigation and natural resource exploration in neighbouring mountain ranges such as the Eastern Alps and the Northern Calcareous Alps.

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Mantle rheology inferred from seismic tomography and foreland basin uplift around the Alps-Carpathian arc

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Positive P-wave velocity V_p anomalies beneath the Alps resolved with teleseismic tomography (TEL, Paffrath et al. 2021) and local earthqake tomography (LET, Jozi Najafabadi et al. 2022) from AlpArray have geometries that are reminiscent of drips rather than slabs. These slab drips are still attached to the European orogenic lithosphere in the Central Alps, but appear to be partly detached in the Eastern Alps (Handy et al. 2021). The amount of Neogene crustal shortening during north-directed Adriatic indentation of the latter corresponds to the length of the slab drip within the limits of vertical resolution (20-50 km) down to a depth of 300 km (McPhee & Handy, in press). This allows us to establish the ages of the drip (14-21 Ma) and of a horizontal negative V_p-anomaly (≤ 14 Ma) separating this drip from its orogenic lithosphere.

Using these ages, we estimate the sink rate of the hanging part of the European slab drip to be 6-11 mm/yr. A higher sink rate (32 mm/yr) is obtained by using the clockwise migration of depocenter uplift and thrusting in the foreland basin around the Carpathian arc as proxies for the timing of slab detachment from the European orogenic lithosphere (Meulenkamp et al. 1996). Accordingly, the slab drip detached between 19 and 11.5 Ma and is currently entrained in the Mantle Transition Zone, MTZ (Wortel & Spakman 2000). Taken together, these relations indicate that the sink rate of slab drips increased with depth and time. However, we are unable to ascertain whether these drips reached a terminal sink velocity.

The lack of Neogene magmatism in the Alpine orogen suggests that detachment and sinking of the slab drips occurred in the absence of melting of the mantle. Taking the sink rates above at face value, we apply a modified form of the Stoke's Law equation to obtain a dynamic viscosity of some 10^8 MPa-s for asthenosphere undergoing solid-state flow around the slab dripping beneath the Eastern Alps. This is several orders of magnitude greater than the generally cited range of asthenospheric viscosities in subduction settings (10^{12} – 10^{13} MPa-s) as well as viscosities obtained for polycrystalline dunite undergoing grainsize-insensitive creep (10^{11}-10^{13} MPa-s, grainsize = 1cm), but similar to viscosities for grainsize-sensitive creep (10^9 MPa-s, grainsize = 50 microns, Handy et al. 1989) in the temperature range (1270-1345 °C) of the aforementioned negative V_p-anomaly (≤ 14 Ma) under the Eastern Alps. While we can only speculate on the temperatures and syntectonic grainsize in the asthenospheric mantle beneath the Alps, our findings indicate that suborogenic asthenophere is anomolously weak, even in the absence of melting, and facilitates the rapid detachment and sinking of slabs at the end of convergence and indentation.

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P-T-t-d history of low-grade Permian metasediments in the Austroalpine Unit

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The Austroalpine Unit is a nappe stack that formed by accretion of Adria-derived material in Late Jurassic to middle Late Cretaceous times. Its history is mostly recorded by upper crustal non-metamorphic rocks and lower crustal upper greenschist to eclogite facies metamorphic rocks. Data from the ubiquitous mid-crustal, low-grade metamorphic units are, however, either missing or difficult to interpret, complicating the link between the shallow and deep orogenic levels. We present new pressure-temperature-time-deformation data for the Permian Präbichl Formation, sampled in the Tirolic-Noric Nappe System (TNNS) below the overlying Juvavic Nappe System (JNS) at two localities. This formation consists of lower greenschist facies clastic sediments and corresponds to the Permian cover of the pre-Variscan basement. The metamorphic assemblage of the Präbichl Formation contains chloritoid + muscovite ± pyrophyllite + hematite + rutile + quartz. Phase equilibrium calculations and Raman spectroscopy on carbonaceous material indicate peak P-T conditions of ~350°C and 0.4-0.5 GPa. In both samples, 10 to 30 µm xenotime show systematic chemical zoning with a heterogeneous core and a distinct MREEs-rich rim. We targeted each chemical domain by in-situ LA-ICP-MS U-Pb dating. The concordant U-Pb ages from cores range between 632 Ma and 250 Ma, and likely reflect an inherited component. Younger dates were measured in the xenotime rims. In the eastern sample (Noric Nappe), a concordant cluster yields a weighted mean age of 133.6 ± 2.8 Ma (MSWD: 1.7, n: 14). Host-inclusion relationships of chloritoid and xenotime suggest coeval growth of the xenotime rim and chloritoid porphyroblasts, linking the U-Pb age to the growth of the main metamorphic assemblage. An additional set of discordant analyses yield an anchored discordia age of 91.5 ± 3.6 Ma (MSWD: 1.2, n: 7). In the western sample (Staufen-Höllengebirge Nappe), a set of concordant and discordant analyses yield an anchored age of 90.1 ± 1.4 Ma (MSWD: 1.8, n: 16). Xenotime and chloritoid are not observed in direct contact, and this sample is characterized by a pervasive crenulation cleavage, which postdates chloritoid growth. From the distribution and morphology of xenotime we conclude that post-peak dissolution-precipitation related to crenulation cleavage formation facilitated growth of the rim. These results have two key implications. Firstly, the 133.6 ± 2.8 Ma date coincides with the age of the latest syn-orogenic sediments overthrusted by the Juvavic Dachstein Nappe. It is therefore interpreted as the age of peak metamorphism after thrusting of the JNS over the TNNS ceased. The peak pressure of 0.4-0.5 GPa at that time corresponds to an overburden of ~17 km, which cannot be solely explained by the thickness of the JNS, which has a present day thickness of 5-10 km, suggesting the existence of a missing unit. Secondly, the 90-92 Ma dates correspond to the timing of the onset of post-orogenic sedimentation in the Gosau basins overlying both the TNNS and JNS and the exhumation of the Austroalpine eclogites. This implies a major change of dynamics at all levels of the orogen at that time.

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Alpine (c. 96 Ma) metamorphism revealed by monazite dating in the Veporic unit, Western Carpathians

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The Central Western Carpathians represent a tectonic system that extends eastward from the Alps and may be well correlated with the Austroalpine units of the Alps. The pre-Tertiary complexes of the Central Western Carpathians originated during the Cretaceous collisional events following the closure of the Meliata ocean by Late Jurassic times. Alpine metamorphism, related to the development of a metamorphic core complex during Cretaceous orogenic events, has been recognised in the Veporic unit (Janák et al. 2001). Increasing *P-T* conditions from greenschist to middle amphibolite facies reflect a coherent metamorphic field gradient. The isograds are roughly parallel to the north-east dipping foliation related to extensional updoming along low-angle normal faults, $^{40}Ar/^{39}Ar$ data constrain the timing of cooling and exhumation in the Late Cretacous. To constrain the timing of prograde metamorphism we dated monazite using electron microprobe. One reason for that is a shortage of geochronological data on Alpine metamorphism from the polymetamorphosed rocks which include pre-Alpine, mostly Variscan relicts. The dated monazite occurs in semi-pelitic schists of the highest grade Alpine metamorphic zone, exposed from the deepest levels of the Veporic dome. The peak metamorphic assemblage consists of garnet + biotite + muscovite + paragonite + rutile + quartz. Garnet occurs as clusters involving the fragments of fractured (pre -Alpine) garnet, and newly-formed, idioblastic Alpine garnet. Alpine garnet is zoned with decreasing Ca (X_{Grs} = 0.23-0.16) and increasing Mg (X_{Prp} = 0.05-0.12) from the core to the rim. Thermodynamic modelling indicates that Alpine garnet was growing during the burial (up to 1.2-1.4 GPa; 580-600°C). The metamorphic *P-T-t* path is "clockwise", reflecting post-burial decompression (down to 0.8-0.1; 600-610°C) and cooling during Alpine orogenic cycle. Monazite (30-50 µm in size) occurs in the matrix occasionally associated with allanite (REE-epidote) and xenotime, suggesting monazite formation via allanite breakdown during the prograde P-T path. Chemical Th-U-Pb dating yielded Cretaceous age of 95.8 ± 2.7 Ma (MSWD = 1.13) with point ages ranging from 75 to 124 Ma. Similar age of 97 Ma was reported from the ICP-MS dating of monazite in a lower grade chloritoid-kyanite schists. This timing is in excellent agreement with metamorphism between c. 100 and 90 Ma in the Eo-Alpine HP/UHP belt in the Austroalpine Nappes of the Eastern Alps (Miladinova et al. 2022). We argue that the Veporic Unit represents direct continuation of the Eo-Alpine high-pressure belt into the West Carpathians.

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New constraints on the crustal structure and rifting processes of the Liguro-Provençal Basin, Western Mediterranean

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Geophysical data from the Liguro-Provençal Basin show prominent margin asymmetry but the nature of the crust, especially in the northeastern part of the basin, remains unclear. The basin formed at the junction of the northern Apennines and the western Alps due to the rollback of the Calabrian-Apennines subduction zone in the Oligo-Miocene. The opening of the basin was accompanied by counter-clockwise rotation of the Corsica-Sardinia block relative to Europe with the basin widening southwestwards. Recent weak compressional earthquakes offshore within the basin suggest possible basin inversion due to the ongoing Africa-Eurasia convergence. An insight into the crustal structure of the basin is therefore the key to understanding these recent processes. To this end, we compiled existing geological and geophysical data, including new data from the German project "Mountain Building Processes in Four Dimensions" (4DMB), to constrain the crustal and sedimentary thicknesses throughout the basin. Moreover, we derived kinematic parameters of extension using regional tectonic reconstructions and used the coupled ASPECT and FastScape geodynamic code to model the opening of the basin in its northeastern (Corsica – Provence) and southwestern (Sardinia – Gulf of Lion) parts. The comparison of the geodynamic models and geophysical data suggests: 1) the extent of oceanic crust in the Liguro-Provençal Basin did not reach as far north as previously presumed; 2) rift-related structures are possibly being reactivated offshore to the northwest of Corsica. We also present new constraints on the lateral extent of rifted continental crust and exhumed mantle and evolution of the basin through time.

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Palaeoceanographic significance of the Jurassic and Cretaceous phosphatic events in geotectonic history of the Pieniny Klippen Basin (Carpathians)

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The Pieniny Klippen Belt (PKB) represents a boundary zone between the Outer and Central Western Carpathians and is interpreted as a separate branch of the north-westernmost Tethyan Ocean (Pieniny Klippen Basin – PKBs). In whole PKBs history at least three phosphatic events took place: (**i**) Early Bajocian, (**ii**) Berriasian and (**iii**) Albian times. The several facies successions accumulated in subtidal/neritic shelf environments of the submarine swell (so-called Czorsztyn Ridge and its southeastern slope), while palaeogeographical orientation of this Czorsztyn Ridge was from NE to SW. These successions can be distinguished, from shallowest zone (Czorsztyn Succession) trough transitional zone (Niedzica and Czertezik successions) up to deepest one (Branisko and Pieniny successions) in the axial part of this basin.

In the **late Early Bajocian** time (**i**), just after Czorsztyn Ridge originated by tectonic uplift, sedimentary features recorded condensation episode during start of crinoidal limestones sedimentation (even up to 150m in thickness). The base of the crinoidal limestones are very sharp and directly overlying, with stratigraphical hiatus (ca. 2Ma), the oxygen-depleted dark/black *Fleckenkalk*/*Fleckenmergel*-type deposits of Toarcian-lowermost Bajocian in age. This part of crinoidal limestones consists of phosphatic concretions pavements, large phosphatic macrooncoids (up to 8-10cm), light-greenish clasts of micritic limestones, pyrite concretions, and fossils as ammonites, brachiopods and bivalves. Phosphatic concretions (up to 6cm) occur in almost all PKB successions exclusively within lowermost part (first 1.0m above base) of crinoidal beds, which is isochronous event. On the other hand, very rapid change of sedimentation from oxygen-depleted environments (during Toarcian-earliest Bajocian) to carbonate sedimentation is record of rapid vertical tectonic uplift of the Czorsztyn Ridge and adjacent areas and may be also reflect palaeoceanographical changes after this tectonic movements and origin of upwelling currents, for which such condensation and phosphatic structures are typical. The second (**ii**), **Berriasian** episode of phosphatisation within PKBs has been connected with post-Tithonian time tectonic uplifting of the Czorsztyn Ridge and surroundings, including Niedzica Succession. The presence of phosphate-rich deposits (phosphorites and microbial phosphate macrooncoids) in this succession, which should be localized in a palinspastic reconstruction near shelf-edge slope boundary, supported idea of upwelling currents as well. In the PKBs this idea is additionally supported by Berriasian brachiopods/crinoids-rich beds of the Czorsztyn Succession and their distribution probably have also been controlled by the upwelling currents, where nutrient-rich oceanic water formed such conditions which caused the proliferation of benthos. The third (**iii**), **Albian** episode of phosphatisation of marly deposits on sea-floor occupied by the Czorsztyn Succession zone are represented by phosphatic: stromatolites, lithoclasts and microbialite-coatted bioclasts within beds of different thickness (a few cm up to dozen ones). Usually, these are on the base of Albian marls/marly limestones which covered erosional surfaces of older limestones with several fossil-karst phenomena originated as effect of at least two episodes of tectonic uplift and emersions of the Czorsztyn Ridge/Czorsztyn Succession zone.

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Tracing the aborted Middle Triassic Neotethyan rift along the Dinarides

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Volcano-sedimentary successions of Middle Triassic age can be traced along the Dinaridic mountain chain from northern Croatia in the northwest to Montenegro in the southeast. Their deposition is related to a regionally well-marked rifting phase linked to the opening of the Neotethys Ocean. The successions locally vary in thickness and display great facies variability of sedimentary and volcanic/volcaniclastic rocks, reflecting complex geodynamic settings in which they were formed.

Sedimentary rocks in these successions range from the outer margin and upper slope deposits, characterized by coarse- and fine-grained resedimented shallow-marine carbonate material, to open-marine deposits including pelagic limestone and radiolarian chert. Locally, specific low-diversity fossil assemblages and the high proportion of organic matter in sediments indicate deposition in a restricted environment where primary production was limited to the upper part of the water column (Goričan et al. 2015).

Stratigraphically stacked, volcanic and volcaniclastic lithologies range in composition from basaltic to rhyolitic and are present as doleritic subvolcanic intrusions, basaltic effusions and several volcaniclastic facies. Autoclastic basaltic facies and resedimented autoclastic facies are formed by the fragmentation caused by the rapid cooling of lava in contact with cold seawater and subsequent redeposition of the newly formed clasts. Rhyolitic *pietra verde* tuffs are interpreted as products of explosive volcanic eruptions distributed in pelagic environments by gravitational mechanisms, including air-fall and pyroclastic density currents. Locally, medium- to fine-grained volcanogenic turbidites represent unconsolidated pyroclastic detritus redeposited during or shortly after eruptions. Geochemical data show that parental magmas responsible for generating these volcanics/volcaniclastics had a calc-alkaline to shoshonitic composition and are interpreted to have formed during continental rifting in ensialic and mature arc settings.

Biostratigraphic data indicate pelagic conditions generally lasted from the Middle Anisian to the Late Ladinian, with local variations. Late Anisian age (*Reitziites reitzi* Ammonoid Zone) is inferred for the oldest *pietra verde* tuffs with radiolarians from intercalated chert. Basaltic volcanic/volcaniclastic rocks yielded K-Ar and Ar-Ar ages of 241.1±5.2 and 244.5±2.8 Ma. These ages indicate the coeval existence of bimodal volcanism comparable to the modern East African Rift System.

Middle Triassic volcano-sedimentary successions of the Dinarides testify about an active rift in the Dinarides between the Middle Anisian and the Late Ladinian. Extensional movements of the lithospheric blocks created horst-and-graben topography with pelagic sediments and volcaniclastic detritus accumulating on the subsided blocks. Laterally still active carbonate platform areas supplied carbonate detritus to these pelagic environments. Deep-rooted normal faults served as conduits for the ascent of basaltic magma and the formation of associated volcaniclastic facies. However, with the main Neotethyan rift located further to the east, extension in this area of the Dinarides ceased in the Ladinian, resulting in the filling of pelagic areas and the reestablishment of shallow-marine carbonate sedimentation.

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

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A striking difference along the Alpine Orogen is the style of collisional tectonics during the Oligo-Miocene, with the onset of escape tectonics in the Eastern Alps. The indentation of the Adriatic Plate into the Eastern Alpine Orogen resulted in the formation of conjugate dextral and sinistral strike-slip faults in the vicinity of the Tauern Window. Moreover, major changes occurred in the foreland of the Eastern and Southern Alps in the Early Miocene, with the cessation of the northern Alpine front propagation and the onset of thrusting along the Southern Alpine Front. We present new results from structural, stratigraphic and subsidence analyses of the eastern North Alpine Foreland Basin (NAFB) to study the relationship between these Alpine tectonic events and basin dynamics.

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

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Polymetamorphic evolution of a micaschist from the ultrahigh-pressure terrane of the southern Dora Maira Massif, Western Alps

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For a better process understanding of the subduction of the Ligurian Ocean and the adherent European plate under microcontinent Adria including the exhumation of deeply subducted rocks, we have investigated a micaschist from the ultrahigh-pressure (UHP) terrane of the southern Dora Maira Massif. This micaschist crops out about 1 km north of the hamlet of Masueria and contains quartz (40-45 vol%), phengite (almost 30 vol%), garnet (17 vol%), which is strongly variable in size (diameter of 300 µm to almost 1 cm), kyanite (7 vol%), pseudomorphs after jadeite (4 vol%) and different accessory minerals. The compositions and textural relations of the minerals were carefully studied with an electron microprobe. After determination of the bulk-rock composition of the micaschist, which points to a pelitic protolith, thermodynamic modelling with PERPLE_X was undertaken to reconstruct the metamorphic evolution of this rock.

The early mineral assemblage found as inclusions in extended cores of large garnet grains being chemically fairly homogeneous consists of quartz, chloritoid, staurolite, paragonite and kyanite. This assemblage formed at pressure-temperature (P-T) around 12.5 kbar and 600 °C, before relatively large volumes of garnet, after significant overstepping of its P-T limits, overgrew these minerals under release of considerable amounts of water. A relatively narrow rim developed around the inclusion-rich garnet core as the result of early subduction of the rock to depths corresponding to pressures of 20 kbar accompanied by slight heating. Only paragonite reacted to jadeite + kyanite at pressures of 26 kbar before UHP conditions were reached. This reaction resulted in another pulse of water released. Nevertheless, the subsequent burial at UHP to P-T conditions of 34±2 kbar and 715±35 °C, at which phengite with Si contents of 3.47 per formula unit (pfu) equilibrated, occurred under water-absent conditions so that possibly no coesite formed from quartz as the result of overstepping the coesite-quartz transition. The retrograde path is only characterized by the formation of phengite with Si contents lower than 3.4 pfu around UHP phengite and the replacement of jadeite mainly by albite rods. The latter reaction occurred at pressures below 18 kbar, a retrograde path provided that is characterized by slight cooling down to pressures of about 15 kbar as suggested by previous researchers of the Dora Maira UHP terrane. The described retrogression occurred in absence of free H_2O, but defornation caused the partial recrystallization of UHP phengite by phengite with lower Si contents.

The studied polymetamorphic micaschist does not indicate a polycyclic metamorphism. A flat subduction to 45 km (~12.5 kbar) was followed by steep subduction to 110 km. During subduction, pulses of hydrous fluid changed the rock during prograde metamorphism in the pressure range of about 11 to 26 kbar clearly. At UHP and during early retrogression (down to ~15 kbar), changes took place only by deformation as virtually no hydrous fluids were released in the rock or infiltrated it.

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Geological interpretation of the CIFALPS2 seismic tomography data in the Ligurian Alps

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In the Western Alps, rocks belonging to the fossil subduction zone are exceptionally well exposed, and structures related to the (U)HP exhumation stage are still preserved. Some recent studies have analyzed the along-strike variations in the deep tectonic structure of the Western Alps, but analysis was not extended southward to the Ligurian Alps, where geodynamic reconstructions have predicted the strongest upper-plate divergent motion that may have favored exhumation of (U)HP metamorphic rocks and associated mantle-wedge rocks. Here we analyze the deep tectonic structure of the Ligurian Alps as revealed by the first receiver-function profile and a new local earthquake tomography model based on data collected during the passive seismic experiments CIFALPS and CIFALPS2. We provide evidence for an exhumed mantle wedge and a former subduction channel preserved at shallow levels beneath the Ligurian Alps, above a shallow-dipping lower-plate Moho. We found that the lower boundary of the exhumed subduction channel is the most evident seismic-velocity interface beneath the Ligurian Alps, which may be easily misinterpreted as a Moho. Similar Moho-like interfaces are found beneath the exhumed (U)HP domes of eastern Papua New Guinea and the Dabie Shan, which suggests that the results of the CIFALPS experiments may be used as a reference case to improve the interpretation of the deep tectonic structure of other (U)HP terranes worldwide.

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Petrochronology of the UHP Chasteiran Unit (northern Dora-Maira Massif)

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The Chasteiran Unit in the northern Dora-Maira Massif reached *UHP* conditions in the chloritoid-coesite stability field. The chemical and isotopic behaviour of zircon, garnet, and rutile was explored in a metapelite in order to reconstruct a timeline for the metamorphic evolution of this Unit.

Zircon crystals display detrital cores and thin (< 5 mm) undatable metamorphic rims. The dominant zircon population consists of Late Neoproterozoic (□600 Ma) magmatic grains whereas the youngest zircon cluster is Ordovician in age (□470 Ma).

Garnet records three main growth stages: initial growth during a prograde *P* and *T* increase in the quartz stability field (2.5–2.7 GPa at 470–500 °C, inner core – stage 1), peak growth in the coesite stability field (2.7–2.8 GPa at 510–530 °C, outer core – stage 2), and final growth of the garnet rim between 2.3 GPa 520 °C and 1.5 GPa 510 °C (stage 3), contemporaneously with lawsonite consumption coupled with fluid production. LA-ICP-MS U-Pb dating of garnet indicates two distinct stages of growth for garnet cores and rims at □61 Ma and □43 Ma, respectively. The time interval separating the growth of garnet core and rim is consistent with our thermodynamic modelling, which indicates the absence of garnet growth during the initial stage of exhumation, between 2.7. GPa and 2.3 GPa.

Rutile is found both as inclusions in garnet and in the matrix. Rare inclusions of jadeite and Si-rich muscovite constrain rutile growth during burial at a minimum *P* of 2.0 GPa. Inclusions of rutile in garnet are commonly surrounded by fracture and some crystals display ilmenite exsolution lamellae, suggesting that despite their mode of occurrence, they might have behaved as an open system during later events. Rutile consumption took place during exhumation, as suggested by the increase in Ti content in garnet and muscovite rims and thermodynamic modelling. Rutile in the matrix is partially replaced by ilmenite corona, which developed at *P* < 1.5 GPa, after garnet growth. SIMS U-Pb dating of rutile, irrespective of its petrographic mode of occurrence, yields a date of □37 Ma.

Our geochronological data puts new constraints on the metamorphic evolution of the Chasteiran Unit, which will be discussed in the context of published chronological data and *P*–*T* estimates from the Dora-Maira Massif.

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A crustal balanced-cross section across the central Apennines and the relationship between thick- and thin-skinned tectonics

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The Apennines form part of the Africa-Eurasia convergent plate boundary and are cored by two diachronous back-arc basins formed in response to slab retreat, separated by the Sardinia-Corsica continental ribbon. Subduction of oceanic lithosphere in the central Apennines lasted until the Oligocene - early Miocene, coevally with the opening of the Liguro-Provencal back-arc basin and led to the development of a thin-skinned thrust pile. The subsequent transition from subduction to collision occurred when the distal portion of the Adria passive margin became involved in the orogenic system. The arrival of a progressively thicker continental crust of the Adria rifted margin imposed a deceleration of trench retreat, arresting the opening of the first back-arc basin. This stage is evidenced by the almost stable position of the thrust front and of the peripheral bulge until the late Miocene. During Tortonian, the forelandward migration of the thrust front and of the peripheral bulge re-accelerated, coevally with the opening of the Tyrrhenian back-arc basin. In our view, this occurred as a consequence of the relocalization of the subduction interface in the basement.

In this contribution, via cross-section balancing, we focus on the crustal structure of the central Apennines to investigate the relationship between shortening in the basement and in the sedimentary cover. We employ well-constrained surface geological data from available public maps, as well as tomography and seismological data, supplemented by thermochronological, biostratigraphic, and radiometric dating. Furthermore, the data are integrated into a coherent geodynamic framework supported by a geometrically balanced kinematic model, giving insight on the coupled forward migration of compressional and extensional domains due to the slab pull/trench retreat system.

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West Mediterranean subductions, puppeteers of the Alps: lessons from analog models and paleomagnetic data

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We present analogue models simulating subductions that occurred in the Western Mediterranean region, in order to understand how it impacted the regional tectonics. Models suggest that the tectonic evolution is largely controlled by slab roll-backs, that may be much faster than the Africa-Eurasia convergence. They reproduce the opening of the Western Mediterranean Basins and the dispersion of continental fragments that accompany slab roll-back. They show that oceanic subduction in the Western Mediterranean region favors the counterclockwise rotation of Adria. Some models reproduce the break-off of the oceanic slab that followed the beginning of continental subduction both beneath Northern Africa and Italia. The influence of subduction on the kinematics of Adria largely decreases following slab break-off. In models, the total counterclockwise rotation of Adria varies between 7° and more than 30°, depending on the timing of slab break-off. Since the process of subduction modifies the displacement of Adria, it also impacts the tectonic evolution of the regions that bound this plate, especially in the Alpine belt: in the Western Alps, an older Late Cretaceous to Eocene "Pyrenean-Provençal" tectonic phase accommodating N-S shortening is classically described resulting from the convergence between Africa and Eurasia. It is followed by the Neogene "Alpine phase" accommodating E-W shortening. Since this major tectonic change is not explained by a modification of the global Africa-Eurasia convergence, it should be explained instead by more local causes. Our models show that during slab-roll back and before slab break-off, the azimuth of convergence between Adria and Europe shifts from ~N-S to ~NE-SW, and that the oceanic subduction in the Western Mediterranean may explain both the post-Oligocene E-W shortening in the Western Alps and part of the Periadriatic right-lateral shear zones in the Central Alps. We compare the rotations observed in experiments with the post-Eocene rotations registered by paleomagnetic data in the Western Alpine realm, that are deduced from a synthesis of more than 55 paleomagnetic studies. We compare the counterclockwise rotations affecting internal units of the Alps evidenced by paleomagnetic data with the rotations observed in analogue experiments. The change from N-S to E-W shortening enhanced left-lateral motions in the Southern border of the Western Alps, which may explain the particularly large rotations registered in this sector. We conclude that the western Mediterranean region is a spectacular example showing how the tectonics of mountain ranges and plate boundaries may be controlled by distant subduction processes.

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Metamorphic evolution of calcareous schists of the Margna Nappe at Valmalenco, Central Alps

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Metamorphic rocks cropping out north of the Periadriatic Line are objects of our study to better understand the Cenozoic subduction process during the collision of microcontinent Adria with the European plate forming the Central and Eastern Alps. For this purpose, we collected rocks along the Malenco valley that are suitable to allow us to decipher their pressure-temperature (P-T) evolution. About 1.5 km northwest of the village of San Giuseppe, calcareous schists rich in phengite were sampled. Their bulk-rock compositions were determined. The minerals in three samples were carefully chemically characterized with the electron microprobe. Thermodynamic modelling followed for two garnet-bearing samples using the program package PERPLE_X.

The protoliths of the samples were probably carbonate-bearing psammopelites. The two modelled rocks are characterized by alternating, a few mm thick layers either enriched in phengite or quartz representing the main foliation. The phengite-rich layers host most of the mafic minerals, whereas quartz-rich layers also contain plagioclase, which is nearly pure albite. The mafic minerals are hornblende, idiomorphic garnet with diameters between 50 to 200 µm, and minor biotite and chlorite. One sample also contains some epidote, the other one some titanite. Accessories are zircon, apatite, and opaque phases. Carbonate is lacking.

Modelling of the peak metamorphism is based on phengite with Si contents between 3.25 (rim) and 3.35 per formula unit (pfu) and zoned garnet. The zonation is characterized by significantly decreasing Mn, slightly decreasing Mg (0.05 to 0.04 Xpyrope), and clearly increasing Ca contents (e.g., 0.25 to 0.36 Xgrossular in one sample) from core to rim. The modelling yielded, consistently for both samples, a pressure decrease from 13.5 kbar at 570°C to 11.5 kbar at 550°C. In spite of the temperature decrease, a growth of garnet occurred because the modelling predicts 2-2.5 vol% garnet coexisting with about 20-25 vol% phengite and 30-35 vol% as well as significant quantities of omphacite (20-25 vol%), biotite (7-10 vol%), and paragonite (7-10 vol%) at the pressure peak, but 4.5 vol% garnet at 11.5 kbar due to breakdown of omphacite, biotite, and paragonite. The decomposition of these minerals also led to increasing contents of phengite with Si contents of 3.25 to 3.30 pfu as well as significant quantities of hornblende and albite during further pressure release. The observed chlorite seems to be a late retrogression product.

We suggest that the studied samples are monocyclic metamorphic rocks. They were located at (or near) the surface of the downgoing European plate and subducted to Earth's depths of about 50 km in the Cenozoic. Hydrous fluids were present during the subduction process and early exhumation evidenced by the aforementioned mineral reaction (paragonite breakdown). Major deformation occurred at the pressure peak and during early exhumation. The corresponding tectonic movements led to nappe stacking, so that the contact to the Malenco Unit, which represents Permian lowermost crust and underlying mantle, in the south was established.

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The reconstruction of middle Miocene-late Pleistocene Tuscan shelf evolution (Tyrrhenian Sea, Italy) through a re-interpretation and geometrical-kinematic validation of seismic profiles.

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The Middle Miocene- late Pliocene tectonic evolution of the Tuscan Shelf (northern Tyrrhenian Sea) between Elba Island and Monte Argentario Promontory is re-defined by the re-interpretation of vintage seismic profiles. The location and first evolution of Neogene sedimentary basins in those areas were controlled by structural inheritance since they developed on top of major thrusts before and during the Tyrrhenian Sea formation. Successive minor crustal extension contributed to today's structural setting and basin geometries. Using forward kinematic modeling, the geometrical validation of the seismic transects is presented here. The geometrical validation has been tied to the Martina-1 and Mimosa-1 wells, and the forward models have been successively compared with the geologic constraints derived from the available regional-scale geologic information (geological maps and literature data). Complete forward modeling from the Miocene to the late Pleistocene is forwarded along with an estimation of crustal shortening and extension that may account for the observed geometries of the seismic horizons and the modern basin geometries.

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Regional Strike-Slip Structures in the Internal Dinarides: Insights from the Zvornik Fault

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The Dinarides represent a part of a double-vergent Dinaric – Carpatho – Balkan orogenic chain that formed as a response to the closure of a branch of the Tethys ocean in the latest Jurassic and subsequent convergence between the Adriatic microplate and the European continent, which is still active in the recent times. Different in convergence rates, this driving force of tectonics in the Balkans produced different kinematics of the fault structures in the central part of the Balkan Peninsula. General opinion is that from the Cretaceous times up to the Oligocene the fault kinematics in the area acted in a compressional regime, which, after the extensional episode in the Miocene, continued as a strike-slip regime in the neotectonic time. However, some regional structures seem to show evidence of oblique-slip kinematics much earlier, already in the Late Cretaceous times. Some of these pieces of evidence are related to the existence of intracontinental basalts related to the fault structures, asymmetric pull-apart sedimentary basins, tectonic structures, etc.

In this contribution, we will present the most recent results of the study of one of the most prominent tectonic structures of the Internal Dinarides, the well-known Zvornik fault (suture), and its southward continuation in the area of the Jelica Mts. in western Serbia. We will show evidence of the Late Cretaceous activity of this regional fault and discuss its importance in the context of the formation of Late Cretaceous basaltic magmas and specific sedimentary basins in this area.

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Chaotic complexes of the Meliata Unit: biochronology, lithostratigraphy and geochemistry of a mélange near Čoltovo (Western Carpathians, Slovakia)

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The supposed Meliata suture divides the Austroalpine-related Central Western Carpathian (CWC) units from the Internal Western Carpathian (IWC) units of the Adria and/or Dinaridic affinity (Transdanubian and Bükk, respectively). The tightly imbricated and dismembered Triassic–Jurassic complexes of the Meliata Unit (Meliaticum) record the subduction/accretionary processes connected with the opening, expansion, subduction and closure of the Neotethyan Meliata Ocean in the southern Western Carpathian zones. The Meliaticum exhibits a lithologically variable composition. In general, three main partial units or complexes can be distinguished: i) the blueschist-facies Bôrka Nappe representing the distal continental margin exhumed from the subduction channel during the Late Jurassic and subsequently thrust over the foreland lower CWC plate; ii) variable chaotic, in part ophiolite-bearing mélange complexes; iii) relatively coherent Jurassic successions of deep-marine hemipelagic and distal flysch deposits with olistostrome bodies which include Triassic carbonate blocks revealing the late Mid-Anisian (Pelsonian) breakup of the Meliata Ocean. This study focuses on the examination of the chaotic complexes of the Meliata Unit at the crucial Čoltovo locality. Due to the poor outcrop conditions caused by soil and debris cover and tectonic reworking typical for the Meliaticum, heavy equipment was used to expose the bedrock and establish the relationships between various components. Based on lithological study and biostratigraphy of radiolarians, the Čoltovo locality represents a chaotic mélange structure of Lower Jurassic clastic pelagic deposits and Middle Jurassic olistostromes with cherty intercalations and blocks of Middle Triassic limestones, terrigenous siltstones and variegated radiolarites, Upper Triassic red radiolarites, siltstones and basic volcanics.

Geochemical analyses were undertaken on various types of sedimentary rocks. Majority of the samples fall within the fields of the pelagic environment affected by terrigenous input from the marginal continental area and a continental slope/rise environment, where they intercalate the radiolaritic shales. In the provenance discrimination diagram, most of the sample's plot fall in the fields of mature quartzose, i.e. continental terrigenous provenance. Basic volcanics plot in the border between the within-plate tholeiites with volcanic arc basalts and MORB. According to primitive mantle normalized REE patterns and other immobile trace elements, samples indicate a typical oceanic crust origin.

Čoltovo locality records gradual spreading and deepening of the Meliata Ocean which was the NW branch of the Neotethys. First phase of deep-water sedimentation is represented by distal terrigenous clastics and radiolarite sedimentation with significant volcanic and tectonic activity during the Middle–Upper Triassic. The second, Jurassic phase, points to the formation of olistostromes in connection to the subduction process. In its current form the Meliatic complexes are fragmented into allochthonous blocks/sheets, comprising the Meliatic Basin and the northern continental margin, together incorporated into subduction–accretion mélanges.

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The Santa Lucia Nappe (Alpine Corsica): paleotectonic heritage and deformation history

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The Santa Lucia Nappe is a continental-derived unit exposed East of Corte, in central Alpine Corsica (Durand Delga 1984; Rossi et al., 1996). The unit includes a peculiar lower- to mid-crustal section, exposing mafic and felsic granulites, with an overall structure, Permian age of tectono-metamorphic and magmatic history (Caby et al., 2002; Zibra et al, 2010, 2012), like that of the Ivrea Zone (northwestern Alps), and of the Sila-Stilo unit in the Calabria terrane (Molli et al., 2020). Moreover, the Santa Lucia Nappe includes a Cretaceous metasedimentary cover, with a basal conglomerate transitioning to a calcareous flysch, which shows affinities with calcareous-marly Ligurian Flysch (Amaudric Du Chaffaut 1972; Rieuf 1980). The Santa Lucia Nappe recorded a polyphase Alpine tectonic evolution, developed under greenschist-facies conditions (Zibra, 2006; Vitale-Brovarone et al., 2013)

Because of its unique lithological association, the structural position, significance, and paleotectonic attribution of the Santa Lucia Nappe are the subject of a long-standing debate. These topics are here re-discussed, based on our data collected in the last two decades of field work.

Our observations allow: (i) to document the Alpine deformation structures affecting both basement and cover sequence, their styles and distribution; (ii) to analyze the structural characters and kinematics of its basal tectonic contacts; (iii) to confirm its tectonic position with respect to the “Schistes Lustres”- composite Nappe system; and, finally, (iv) to propose an original interpretation of its internal architecture. The latter results from the tectonic inversion of pre-Cretaceous high-angle faults, which were originally arranged in an east-dipping, domino-like system, which affected the already exhumed and exposed basement, formerly part of a Permian regional-scale transtensional shear zone.

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Syn-collisional exhumation of the San Bernardino eclogites (Adula unit, central Alps)

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In the Central Alps, the Adula unit reveals (U)HP mafic and ultramafic rocks, offering insights into the subduction history of the distal European margin during the final phases of the Europe-Adria collision. The Adula unit, one of the highest basement units in the Lower Penninic nappe stack of the Lepontine Dome, is located between non-eclogitic Lower Penninic units, Simano and Lucomagno, derived from distal European margin below and non-eclogitic Middle Penninic units, Tambò and Suretta, above, composed of pre-Permian basement and Mesozoic covers of the Briançonnais terrane. The upper tectonic boundary of the Adula unit is a complex shear zone known as the Misox zone, which contains lenses of non-metamorphic sheared Mesozoic sediments and volcanics.

It is widely accepted that Suretta, Tambò and Adula units were thrusted over each other during extensive mylonitic shearing directed northward. However, the current structural arrangement and the metamorphic discontinuity between the (U)HP Adula unit and the eclogite-free Tambò-Suretta complex suggest the presence of a normal-sense shear zone. This shear zone, at some point during the tectonic evolution of the central Alps, facilitated the exhumation of the Adula unit.

We have documented this shear zone between the top of the Adula unit and the base of the Misox zone in the San Bernardino pass area (Switzerland). The shear zone primarily developed within Adula orthogneisses, containing lenses of paragneisses and eclogites at the top. These eclogites consistently display a mylonitic texture, with the mylonitic foliation rotated at various angles relative to the shear zone-related foliation.

The P-T equilibrium conditions of the eclogites have been determined to be approximately 2.0-2.1 GPa and 520-645 °C, which are considered coeval with the development of the mylonitic texture based on microstructural evidence. The $^{40}Ar/^{39}Ar$ dating of phengite in eclogites yielded ages of 37-39 Ma. The $^{40}Ar/^{39}Ar$ age distribution across the mylonitic orthogneiss of the shear zone indicates a younging trend from the bottom to the top (eclogite-bearing zone) of the shear zone, from approximately 37 to 29 Ma. This is consistent with top-to-the-east normal shearing that started just after the HP metamorphism.

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Integrating structural and seismotectonic data in a fault catalog for Seismic Hazard Assessment for South East France

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Identifying and studying active faults is crucial for assessing seismic hazards and implementing measures to mitigate earthquake risks in areas prone to seismic activity. The region of SE France is found in a continental active tectonic domain where seismic activity is low to moderate and crustal deformation is slow, nevertheless about 1 magnitude 5 earthquake is recorded every 5 years and 1 magnitude 6 per century (estimated from the historical seismic catalog EPICA). Social vulnerability to seismic hazard in SE France is noticeble due to the presence of urban agglomerations, chemical industries and nuclear facilities.

Today's seismic activity in this region is contrasted between the core of the Alps, where most of the activity is concentrated in transtensional behaviour, and the Alpine foreland, where activity is low and transpressional. The related geodynamics are dominated by the interaction of far-field plate tectonics and buoyancy forces. However, seismic hazard assessments for the region are challenging due to the relatively small time windows of seismic records (~ 100 years of instrumental period, ~ 1000 years of historical period) with respect to the small deformation rates as shown by 25 years of GNSS data acquisition. The 4.9 Mw Teil earthquake in 2019 illustrates the importance of characterising faults and their potential activity. This is a challenging task for this region as its structure is complex and derives from several tectonic phases. Moreover, the definition of active fault is still under debate and is here discussed.

This study aims to build an analytical and critical compilation of fault data, including geological maps, previous fault datasets, fault models, neotectonic evidences, seismic catalogs and seismotectonic analysis. To determine the uncertainties of the compiled data we propose a methodology of estimation of activity, importance and reliability for each fault. The resulting SEFPAF fault dataset (South East France Potentially Active Faults) will then be applied to build fault models and earthquake occurrence models, with a final goal of assessing probabilistic seismic hazard for South East France.

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Wedge-top basins of the Ukranian Outer Carpathians and the Northern Apennines as tracers of (almost) coeval evolution of accretionary-collisional orogens

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The northeast migration of the Oligocene-Pleistocene foreland basins system of the Northern Apennines brought the formation and younging, in the same direction, of wedge-top basins which were moving on top of the Ligurian prism; these basins allow to reconstruct the evolution and propagation of the accretionary prism and orogen growth. A first comparison of the structural and stratigraphic evolution of Northern Apennines and Ukrainian Outer Carpathians foreland basins system shows they are very similar and allow to reveal the occurrence of wedge top basins in the Ukrainian orogenic wedge. Ukrainian Carpathians, now NW-SE trending, are a thin-skinned thrust belt considered to be the Cretaceous-Neogene accretionary prism formed as a result of south-western subduction of the Carpathian basin, a portion of the Northern Penninic ocean. Neogene Carpathian Foredeep can be divided into the Inner zone, accreted to frontal Boryslav-Pokuttya nappe, and the Outer zone overlaying the European plate.

In 2023-2024, geological-structural and sedimentological field studies were carried out in this frontal part of Ukrainian Carpathians. In Boryslav-Pokuttya nappe frontal zone we identified Early Miocene (23-16 Ma) wedge top basins. They represent NW-SE trending narrow and steep synclines filled with synorogenic deposits grouped in Polyanytsa, Vorotyshcha and Stebnyk Fms. The Polyanytsa and Vorotyshcha Fms start with thick chaotic complex, which lies on the erosional surface above the Oligocene and Eocene turbidites. The chaotic complex consists of matrix-supported debris-flow deposits containing exotic Paleozoic and Riphean fragments of European platform and Carpathian flysch. Specifically, the Polyanytsa Fm is made of gray flysch-like deposits with olistostrome lenses in the inner zones of the studied wedge-top basins. The shallow-water Vorotyshcha Fm is made of gray clays and sandstones and locally conformably overlays the Polyanytsa Fm and, since 21 Ma, evaporitic lenses mark the inception of Inner Foredeep for the more external portion of the Boryslav-Pokuttya nappe. In both wedge-top and Inner Foredeep basins, the Vorotyshcha Fm is followed by shallow-water deposits of the Stebnyk Fm. At the Early-Middle Miocene transition, the sedimentation in the wedge-top basins above the Boryslav-Pokuttya nappe is completed and chaotic complex were deposited in the Inner Foredeep formed to the NE of the Boryslav-Pokuttya nappe. In fact, since 16 Ma, Boryslav-Pokuttya nappe was accreted to the Outer Carpathian prism and became part of the orogenic wedge while the detachments began to advance within the Inner Foredeep which corresponds to the second wedge-top basin identified. The latter is the Middle-Late Miocene wedge-top basin (16-10 Ma), a gently dipping syncline infilled with shallow-water salt-bearing sediments with a thick chaotic complex at the base. In this wedge-top basin the sedimentation ends by 10 Ma with a conglomerate sequence sourced by the Carpathian Flysch.
These newly revealed wedge-top basins in the Ukranian Carpathians and related major tectonic events are (almost) coeval to the lower Miocene, middle Miocene and late Miocene nappe advancement of the Northern Apennines posing the bases for a better comparison between the two orogens.

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Swiss Alps 3D: building a large-scale 3D underground model of the Central European Alps

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The Swiss Geological Survey (SGS) is the competence centre for the investigation of the subsurface and georesources of the Swiss Confederation. It provides up-to-date, high-quality spatial reference data for the entire country in the form of nationwide geological 2D datasets and 3D geological models. Between 2024 and 2030, the SGS is funding the Swiss Alps 3D (SA3D) project, which consists of eight research projects involving multiple universities and aims to develop a consistent large-scale underground 3D geological model of the main contacts and structures of the Central Alps.

In this presentation we show the workflow that will be used to build the SA3D model and the project plan until 2030. The main challenge for 3D modelling in Alpine regions is the lack of subsurface data (seismic data, borehole data, etc.). However, the high relief, the sparse vegetation and the large number of scientific studies make these regions an excellent site for advanced surface-based 3D geological modelling. In addition, researchers from several universities in Switzerland and Europe, as well as the SGS, have a wide range of expertise in regional geology and 3D geological modelling. SA3D aims to bring all this know-how together in teams of people with diverse expertise. The result will be a large-scale 3D geological model validated by scientific arguments.

Based on the new Tectonic Map of Switzerland 1:500'000 (swisstopo, 2024), the target area is divided into eight 3D modelling projects according to their paleogeographic origin and structural evolution. The resulting models will be then compiled into a single large-scale 3D model. Within each project, the target structural and lithostratigraphic contacts are modelled at the equivalent scale of 1:25’000. A network of regularly spaced (1000 m) geological cross sections and scientific concepts, discussed and reviewed by the different modelling teams, are then developed to strengthen the modelling interpolation. The workflow developed for the SA3D project offers the chance to gain validation approaches for domains only weakly constrained by/ or with no subsurface data available, by generating a 3D model that integrates multiscale geological data unified by a common dataset provided by the Tectonic Map.

SA3D will generate key knowledge by establishing an experienced modelling community and 3D visualization of the main geological structures and lithostratigraphic boundaries of the Central European Alps. The development of such a project will provide a framework model of the area as a basis for higher resolution 3D geological models to be used for infrastructure planning, groundwater studies, natural hazard assessment, education and research purposes. In addition, the models will facilitate access to strategic subsurface knowledge, which is essential for the management and exploration of geo-resources and geo-energy.

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A Method for Recovering Fault Kinematics and Long-Wavelength Surface Uplift from the Inversion of Landscape Features and its Application in the Eastern European Alps

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A large body of geomorphological research has shown that topography records the history of both uplift and horizontal motions. Numerical landscape evolution models can be used to test the effects of various kinematic scenarios on landscape development. This enables the possibility of using landscape evolution models to solve an inverse problem and quantify tectonic motions based on observed features of a landscape. Various approaches of inverse landscape evolution modelling have been employed in recent years, with most previous work focusing on purely vertical motions, and/or the inversion of longitudinal stream channels in 1D rather than 2D landscapes. In this study, we introduce an approach using Ensemble Kalman Inversion – an efficient, ensemble-based data inversion method – to recover both vertical and horizontal kinematics from the present-day topography. Our approach is capable of handling large numbers of free parameters and quantifying uncertainty in the result. We use the average elevation and average normalised river steepness index (K_{sn}) calculated in a moving window along a profile across-strike of the orogen, to which we fit a large number of landscape evolution models. In this way, the models target first-order geomorphological features avoiding second-order variations characteristic in natural settings. Given the high data density and knowledge of the upper crustal structural evolution in the European Alps, we first demonstrate our method using a synthetic model set-up that emulates the structural geometry beneath the Tauern Window along the TRANSALP transect. We specifically include the possibility of long-wavelength surface uplift in our models, which may be derived from various mantle processes or isostatic responses. Our novel inversion approach can recover magnitudes and changes in surface uplift and horizontal advection rates in space and time. Not surprisingly, the ability of the method to determine past rates of deformation decreases the farther back in time they occur. However, initial results suggest that this effect is less pronounced for horizontal advection rates than for surface uplift rates, indicating potential limitations in modelling studies that do not consider horizontal advection. Our novel approach is now being applied to the topography along TRANSALP. We will use our inversion results to assess to what extent orogen-scale geomorphological features are able to record the tectonic and geodynamic evolution of Cenozoic mountain ranges.

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Jurassic-Cretaceous transform faults control the present-day shape of the Eastern Alps

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Paleogeographic reconstructions of the Alps for the Jurassic suggest an important role of transform faults during rifting and drifting of the Piemont-Liguria and Valais oceans. A common characteristic of such reconstructions is a roughly S- to SW-trending southern segment of the ocean where rifting and drifting was orthogonal to its margins, and an E- to ESE-trending eastern part controlled by transform faults. In the N or NE, Adria (or Apulia) would be delimited by a transform margin against the ocean. According to published sequential reconstructions, these transform faults were active from the Jurassic to the early Late Cretaceous (Cenomanian). Here we investigate the impact of such transform faults on the tectonics of the Eastern Alps.

The Northern Calcareous Alps (NCA) are the Cretaceous external thin-skinned foreland fold-and-thrust belt of the Cretaceous Alpine orogenic wedge. The NCA were detached from their basement at an salt-bearing evaporitic décollement. Thrust sheets in typical foreland settings form salients if salt-floored (e.g., Subalpine Chains of southern France, Jura fold-and-thrust belt, South-Central Pyrenees).

In contrast, the northern margin of the externmost NCA is straight. Folds tend to be tight and symmetric, and local thrusts verge both to the N and the S and are upward concave. Such a structural style has been observed in wrench zones, suggesting that the northern margin of the NCA is a wrench fault. Kinematics of this wrench zone is sinistral. This wrench zone duplicates the hanging wall cutoff of one of the NCA thrust sheets. Therefore, the wrench zone postdates initial nappe stacking in the NCA. Based on overthrust sediments, local stacking has an Early Albian age. The age of the wrench zone can be dated by Albian basanitic dykes intruded into wrench faults within the NCA which are parallel to the NCA northern margin.

At several places within the NCA, sinistral shearing across roughly E-W trending faults has been observed. We list three faults here, but there are probably more: The **Stanzertal fault** delimits the Austroalpine basement (Silvretta nappe) against the southern margin of the NCA. Quartz fibres on outcrop-scale faults probably formed during peak metamorphic conditions in the Lower Cretaceous. The sinistral **Puitental fault** S of Zugspitze is intruded by Albian basanitic dykes (as the Stanzertal fault). The **Trattberg fault** S of Salzburg is a transpressive sinistral fault, associated with Late Jurassic folding and transpressive thrusting, and Upper Jurassic growth strata are observed in the synclines. During the early Cretaceous, kinematics changed to sinistral transtension.

In summary, there is evidence for sinistral shearing across E-W faults at the northern and southern boundaries of the NCA, and within. These faults have a Late Jurassic to Early Cretaceous age, and were active intermittent with Alpine shortening. Locally, they channelized basaltic melts from the subcontinental mantle to the surface, as in present-day transform zones (e.g., Dead Sea transform, Atlas system). Such faults pre-determined the shape of NCA. According to previous studies also Cretaceous subduction initiated along such a transform fault.

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Relationship between Olivine Fabrics and Seismic Anisotropy in the Yugu Peridotites, Gyeonggi Massif, South Korea

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Olivine, a major mineral in the upper mantle with strong intrinsic elastic anisotropy, plays a crucial role in seismic anisotropy in the mantle, primarily through its lattice preferred orientation (LPO). Despite this, the influence of the microstructure of mylonitic rocks on seismic anisotropy remains inadequately understood. Notably, there is a current research gap concerning seismic anisotropy directly inferred from mylonitic peridotite massifs in Korea. In this study, we introduce the deformation microstructure and LPO of olivine in the mantle shear zone. We calculate the characteristics of seismic anisotropy based on the degree of deformation (proto-mylonite, mylonite, ultra-mylonite) and establish correlations between these characteristics. Our findings reveal that the seismic anisotropy resulting from the olivine LPO in the ultra-mylonitic rock appears to be the weakest, whereas the seismic anisotropy resulting from the olivine LPO in the proto-mylonitic rock appears to be the strongest. The results demonstrate a gradual decrease in seismic anisotropy as the fabric strength of olivine LPO diminishes, irrespective of the specific pattern of olivine's LPO. Moreover, all samples exhibit a polarization direction of the fast S-wave aligned subparallel to the lineation. This suggests that seismic anisotropy originating from olivine in mylonitic peridotites is primarily influenced by fabric strength rather than LPO type. Considering these distinctive characteristics of seismic anisotropy is expected to facilitate comparisons and interpretations of the internal mantle structure and seismic data in the Yugu area, Gyeonggi Massif.

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A 3-D geological model of the Western Alps and Ligurian basin from joint interpretation of geological data and seismic imaging models

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The Western Alps exhibit a non-cylindrical lithospheric structure that cannot be understood using 2-D sections. To improve our understanding of the dynamics of the W-Alps and their peripheral basins, we have synthesised the latest geological and geophysical knowledge into a lithospheric-scale 3-D numerical geomodel. This work has been conducted by a team of geologists and geophysicists in the framework of the French Geological Reference Platform (RGF, http://rgf.brgm.fr), worksite “Alps and peripheral basins” (RGF-Abp). Our 3-D crustal-scale geological model covers the area [41.5°N - 48°N; 4°E - 10°E], from the Jura and Subalpine chains to the Ligurian-Provence basin and Corsica, and from the South-East basin of France to the western Po basin. We have modelled the crust-mantle boundary and the 2 boundaries of the highly metamorphosed subduction complex of the internal Alps, i.e. the Penninic front and the Insubric line.

The high-quality 3-D S-wave velocity models computed from ambient-noise tomography using data of the AlpArray, Cifalps and Cifalps-2 temporary seismic networks were key elements in our geomodelling (Nouibat et al. 2022, 2023). We have also used the receiver-function profiles along the Cifalps and Cifalps-2 transects (Paul et al. 2022), and the recent active seismic reflection-refraction and wide-angle profiles SEFASILS (Dessa et al. 2020) and LOBSTER-P02 (Dannowski et al., 2020) in the Ligurian-Provence basin. All previous models or data have been taken into account, including 3-D P-wave velocity models (Diehl et al. 2009; Solarino et al. 2018), the ECORS-CROP deep seismic reflection profile, Moho depth models from active and passive seismic imaging (e.g. Spada et al. 2013), a Moho depth model of the Ligurian basin from gravity inversion (Chamot-Rooke et al. 1999) and results of active seismic profiles in the Ligurian basin (e.g. Rollet et al. 2002). The digital terrain model, geological map, and geophysical models have been input in the GeoModeller software to share data in the same reference frame, and model the geological boundaries in 3-D (Calcagno et al. 2008). All available models have been carefully cross-checked along reference 2-D cross-sections to determine which Moho proxy should be picked in the 3-D Vs model. The Penninic Front and the Insubric line were picked by geologists based on their surface trace and extended to depth based on velocity heterogeneities. The geological boundaries, Moho and boundaries of the subduction complex, have then been interpolated from interpreted 2-D cross-sections to 3-D surfaces by GeoModeller.

Unlike previously published Moho models in the W-Alps, our 3-D geomodel highlights the downthrusting of the European Moho in the subduction of Europe beneath Adria, and it emphasizes its strong shape changes along the arc. The 3-D shape of the Adriatic Moho on top of the Ivrea geophysical body is also clearly highlighted. This first version of the crustal-scale geomodel of the W-Alps will be later augmented by the addition of earthquake hypocentres and focal mechanisms. It will also be used as initial model in the inversion of gravity data. Within the RGF-Abp programme, the geomodel will help to integrate results of local studies in a crustal reference frame.

RGF-Abp geomodel working group: M-O. Beslier, A. Canva, S. Guillot, L. Jolivet, C. Larroque, M. Malusà, D. Marquer, A. Nouibat, A. Plunder, C. Rosenberg, D. Thieblemont, I. Thinon

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The basins of the Calabria Arc, important constraints for the dynamics of the Tyrrhenian opening.

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The Calabrian Arc is the only segment of the Apennine chain that has recorded the entire history of the geological evolution of the Mediterranean. In addition to the first Mesozoic rifts, it recorded Alpine subduction and the subsequent formation of the present Mediterranean basin. The oldest successions, attributable to the opening of the Tyrrhenian Sea, start from the Serravallian stage and fill increasingly recent basins which, in addition to the timing, well record the direction of Tyrrhenian extensions. These data provide the essential elements to outline the dynamics of the opening of the Tyrrhenian Sea and the contemporary formation of the Apennine chain. The main stratigraphic records, regional scale structural maps and the kinematic extension model will be shown to outline the constraints for the dynamics of the Tyrrhenian opening and its correlation with the Calabrian Arc, with the main objective of achieving a more complete knowledge of this portion of the Mediterranean area.

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Pre-Variscan evolution and high temperature metamorphism of the Oetztal-Stübai Complex (Eastern Alps)

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The Oetztal-Stübai Complex (OSC) of the Eastern Austroalpine domain is a polymetamorphic unit extending between western Austria (Tyrol) and northern Italy (Autonomous Province of Bozen/Bolzano). The OSC is made of crystalline basement consisting of metasedimentary rocks (paragneisses and micaschists) hosting numerous bodies of metagranitoids and metabasic rocks, along with subordinate metacarbonates and ultramafics of igneous origin. The Alpine metamorphism in the OSC increases from the north-west to the south-east (Purtscheller & Rammlmair, 1982).

Pre-Alpine evolution of the OSC is testified by the crystallization of Cambrian mafic-to-ultramafic cumulates with MORB-like signatures preserved in pods and layers within the Central Metabasite Zone (CMZ) (Miller & Thöni, 1995; Konzett et al., 2005); an Ordovician high temperature event resulting in intrusions of granitoids and metapelites anatexis (*e.g.* Winnebach migmatites); occurrence of Variscan eclogites within the CMZ and subsequent pervasive re-equilibration under amphibolite facies conditions. However, structural relationships in the field do not rule out the possibility of a pre-Variscan HP event.

Extensive field work, microstructural and petrological analyses, and radiometric dating are being carried out in two key areas, Längenfeld and Reschenpass/Passo Resia. The two areas are similar in the occurrence of two Ordovician intrusions, the Sulztal type-S granite (Längenfeld) and the Klopaier Tonalite (Reschenpass), for which we obtained by U-Pb LA-ICP-MS dating of zircons ages of 482.4 ± 1.5 Ma and 460 ± 0.83 Ma, respectively.

In the Längenfeld area, rocks belonging to the CMZ show various degrees of metamorphic reactions progress often resulting in symplectitic relationships. Mafic-to-ultramafic rocks, with exceptionally well preserved cumulitic textures, display the destabilization at high pressure conditions of anorthite-rich plagioclase to omphacite+corundum intergrowths bordered by garnet, replacing plagioclase as confirmed by REE patterns determined by in-situ LA-ICP-MS. Within these cumulates, newly discovered troctolitic layers show corundum-bearing coronas around olivine and granoblastic textures with increased anorthite content in plagioclase rims, implying a static phase of high temperature recrystallization. Associated metacarbonates are characterized by olivine (Mg/(Mg+Fe)=0.95) and Fe-spinel.

Additionally, we found evidence of partial melting involving metapelites and eclogites of the CMZ, resulting in corundum-bearing migmatitic gneisses and eclogite-derived melts. The Variscan age of CMZ eclogites has been assessed by Sm-Nd mineral and WR isochrons in Miller & Thöni (1995), but unpublished U-Pb zircon data (Sollner & Gebauer in Hoinkes & Thöni, 1993) points to an age of 497 Ma for this high pressure event. This hypothesis deserves further investigations on account of our field work and newly discovered field relationships, suggesting the existence of a pre-Variscan high temperature event post-dating an older eclogite facies metamorphism.

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The complex thermotectonic history of the eastern Southern Alps

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Neogene to ongoing N(W)-directed continental indentation of the Adriatic microplate into Europe controls the evolution of the European eastern Southern Alps (ESA). Despite the Adriatic plate acting as a rigid indenter, it has undergone internal deformation, with predominantly Miocene shortening being accommodated within a WSW-ENE striking, S-vergent fold-and-thrust belt. This deformation overprints a compositionally heterogeneous upper crust affected by several magmatic and tectonic events. We present new (Apatite (U-Th)/He (AHe) and Fission Track (AFT) data along a N-S profile in the western ESA to better understand the thermotectonic evolution of this complex area.

Time-temperature path modelling confirms the Valsugana phase as the most significant period of tectonic exhumation within the western ESA. AFT data in the research area tend to cluster within consistent distinguishable tectonic blocks, however, they are quite scattered especially in the central part of the ESA, warranting further investigation. The geodynamic history of the ESA is characterised by multiple heat pulses, which must be considered when interpreting the AFT data especially as the temperature of this pulses likely did not significantly exceed the partial annealing zone of AFT. Potential heating events are the (1) Permian magmatism, (2) Ladinian magmatism, (3) Jurassic crustal extension, (4) sedimentary superimposition (maximum thickness in Cretaceous), Middle Eocene to Lower Oligocene (5) Periadriatic intrusions and (6) Veneto Volcanic Province magmatic event.

Modelled cooling paths indicate that nearly all samples experienced heating just above the AFT partial annealing zone during the Middle Triassic, preceding the Jurassic extension and Cretaceous maximum burial indicated by the stratigraphic record. Detailed analysis of AFT data reveals that only a small, single-digit percentage of analysed grains give a single grain age older than Middle Triassic. Accounting for the σ1 error, all single grain ages can be interpreted as post-Middle Triassic. This suggests that the Ladinian magmatic event caused a geothermal anomaly affecting the entire research area, not just the well-known magmatic centres (e.g. Predazzo area). During and after the subsequent relaxation of the geothermal gradient the aforementioned events (3) – (6) overprinted the geothermal field locally. Based on the modelled cooling paths, it can be assumed that most of the samples remained in the temperature range of the AFT partial annealing zone or at slightly cooler temperatures during this period. Finally, during Miocene, the entire area was affected by fast tectonic exhumation on thrusts related to the Valsugana phase. This sequence of regional and local, magmatic and tectonic events results in very complex cooling histories that can vary significantly even for closely situated samples, explaining the scattered AFT ages.

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Step-by-step microstructural characteristics of coesite-quartz phase transition during exhumation of UHP white-schists from Dora Maira Massif, Western Alps

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Ultra-high pressure (UHP) complexes are crucial in comprehending dynamic orogenic processes. One of the most representative UHP mineral in such rocks is coesite, which is on the other hand unstable in lower (near-surface) conditions and undergoes a rapid transformation to quartz. The objective of this study is to gain insight into the retrogressive development of quartz microstructures and the phase transition of coesite to quartz. New analyses of quartz surrounding a relict coesite inclusion in garnet and pseudomorphs in the rock matrix from the Dora Maira white schist (pyrope quartzite) are presented. The analyses include electron backscatter diffraction (EBSD), scanning acoustic microscopy (SAM), cathodoluminescence (CL), and misorientation analysis. The white schist contains quartz in a variety of forms, including single grain inclusions, fringes of palisade quartz surrounding coesite inclusions, and palisade/polygonal textures in the matrix. The microstructures were characterized using EBSD. In quartz grains, EBSD orientation maps can reveal intracrystalline deformation features in addition to grain reconstruction. Quartz grains form multiple microstructurally distinct domains. I) A thin rim of perpendicularly growing palisade quartz surrounds primary coesite single crystal – PQ1 (Fig. 1); II) Large grains (0.2-1.5mm) of palisade-type quartz, in direct contact and often sharp boundary with the rim of the first-type microstructure – PQ2 (Fig. 1); III) Fully recrystallized polygonal texture matrix – MQ (Fig. 1). Two distinct positions are observed in the PQ1 microstructure. In the first position, PQ1 typically forms a thin rim around the coesite inclusion in direct contact with the surrounding pyrope garnet. In the latter position, it forms thin boundary between porphyroblasts of garnet and the PQ2 microstructure (Fig. 1). The shape of the 0.005 to 0.1 mm wide PQ1 grains is generally perpendicular to the boundaries with coesite and garnet. The PQ2 microstructure is observed in the location of second-generation palisade quartz, which has undergone grain boundary migration recrystallization mechanism. The final type of microstructure exhibits a typical polygonal texture, with sharp grain boundaries and uniform grain size (Fig. 1), indicative of fully recrystallized matrix. A prerequisite for the study of CL was the assumed zonation and a discernible difference in microstructures. However, this was not confirmed, and the differences in microstructures are not clearly discernible in CL. On the other hand, CL can be used as a quick and simple tool to find or confirm coesite that is significantly brighter and distinguishable from its surroundings (including quartz). The study of quartz using SAM also reveals differences in microstructure. However, this method is still in the preparation and calibration stage and may yet prove useful in the study of decompression in UHP rocks.

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Reconstruction of the Tethys' Waning in the Balkans

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The complex geodynamic evolution of the northernmost Neotethys is the subject of ongoing controversy. Key issues revolve around the waning stages of the Tethyan ocean(s) in the Balkans and the timing of the Europe-Adria collision. Some researchers propose that this collision occurred in the Late Jurassic, while others argue it happened at the end of the Cretaceous along the Sava Zone. The latter hypothesis suggests that the Cretaceous Sava Ocean is a remnant of the youngest Tethyan oceanic realm, left behind after a major convergence in the Jurassic.

In this study, we present recent findings from magmatic, sedimentary, and basement formations within the Sava Zone. Our goal is to constrain the timing, origin, geodynamic environment, and lifespan of the purported Cretaceous Sava Ocean. The central scientific question we address is whether the Sava Zone represents: (i) a relic of the Neo-Tethyan Ocean that closed in the late Cretaceous, or (ii) a diffuse tectonic boundary between earlier collided Gondwana-related blocks and Europe, characterized by a system of pull-apart basins and transtensional tectonics.

Cretaceous igneous formations are found on both sides of the Sava-Vardar suture Zone, in the Dinarides (Gondwana) and Serbian-Macedonian Mass (Europe). These formations predominantly consist of basalts, with subordinate occurrences of lamprophyres, trachybasalts, and andesites, none of which exhibit ophiolitic geochemical characteristics. They show heterogeneous geochemical affinities, primarily derived from (metasomatized) continental lithospheric mantle. Notably, there are clear geochemical differences between the lavas in the Dinarides (depleted) and those in Europe (enriched due to metasomatism).

Our recent zircon provenance data from Cretaceous sediments in the Sava Zone offer new insights into the closure of the Tethys in the Balkans. We first analysed numerous zircon grains from various basement units. Our results indicate that zircons from both the Dinarides and Europe contain ubiquitous Neoproterozoic (Cadomian) and well-defined Silurian-Ordovician (±Devonian) populations. Carboniferous (Hercynian) zircons (>300 Ma) are predominant on the European side, whereas they are somewhat younger (~300 Ma) in the Dinarides. Permotriassic zircons constitute the strongest geochronological signal in all examined Dinarides samples (Africa) likely representing a ubiquitous signal in all Gondwana-affinity units in the Balkans, but are absent on the European side.

Our zircon provenance data from Cretaceous formations in the Sava-Vardar suture Zone show the ubiquitous presence of Permotriassic zircons, constituting the strongest geochronological signal in all samples. If our findings are correct, the basin on the European margin was partially filled from the Adriatic side during the Lower Cretaceous, which suggests the non-existence of a vast (>350 km) Sava (Tethys) Ocean.

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Strain Partitioning in Front of the Dolomites Indenter: Field Observations in the Austroalpine Nappe Stack

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Shortening in highly oblique convergent settings often causes strain partitioning into components parallel and orthogonal to the block boundary. Field data collected as part of the 'Progetto CARG della Provincia Autonoma di Bolzano - Foglio Vipiteno scala 1:25.000' provide insight into the structural evolution of the area around Sterzing/Vipiteno (Autonomous Province of South Tyrol, Italy), which is located at a key position in front of the Dolomites Indenter. The southeastern margin of the Ötztal Nappe, with its Permomesozoic cover (Brenner Mesozoic), has been overthrust by garnet mica schist of the Schneeberg Complex. Initially, however, the contact between the Ötztal Nappe and the Schneeberg Complex formed as a thrust during the Eoalpine nappe stacking, with the latter unit being in a footwall position. The garnet mica schist of the Schneeberg Complex shows predominantly E-W trending, subhorizontal fold axes with a subvertical axial plane in the western parts of the study area. These folds are correlated with N-S directed shortening that presumably led to the (?Eocene-Oligocene?) emplacement of the Schneeberg Complex on top of the Ötztal Nappe. Progressive counterclockwise rotation of the fold axes towards the east is interpreted as the result of ongoing shortening combined with left lateral displacement. Brittle-ductile, SE-dipping shear zones and NNE-SSW trending strike-slip faults, comparable to the Passeier or Jaufen faults, accommodate sinistral slip in the study area. Interestingly, a thin layer of garnet mica schist (often misinterpreted as schist of the Raibl Group) is wedged into a cataclastically overprinted dolomitic marble of the Brenner Mesozoic below the Monte Velo. The contact shows top-to-the-W kinematics and N-S trending, subhorizontal fold axes with E-dipping axial planes. The geometry of the Dolomites Indenter results in a highly oblique convergent setting in the study area, therefore, this Monte Velo Thrust is interpreted to accommodate shortening orthogonal to the indenter boundary. NW-SE striking normal faults with top-NE-down kinematics dissect the top-W-thrust plane. These normal faults are considered antithetic faults in the hanging wall of the Brenner Normal Fault and represent the final stage of deformation in the study area. Altogether, the observed structures show good agreement with published results from analogue modeling of highly oblique convergent settings and are consistent with the scenario of strain partitioning in a sinistral transpressional regime. Furthermore, the advance of the Dolomites Indenter had a significant impact on the southeasternmost part of the Ötztal Nappe and its contact with the Schneeberg Complex.

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From orogenic range to orogenic plateau, what evolution along the Tethys subduction zone from the Alps to Tibet?

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For long, the continental lithosphere considered less dense than the mantle, was not supposed to be able to subduct. Nevertheless, continental subduction has been proposed for decades as a key process occurring during the long-lasting collision between India and Asia since ~50 Ma, allowing the subduction of the continental lower crust attached to the lithospheric mantle while the upper crust thickens and forms the Tibetan plateau (e.g. Mattauer, 1986; Tapponnier et al., 2001). In this talk, I will present the available data and models of this key process for the India/Asia collision, which requires to go beyond the paradigm of slab pull as a unique driver of plate tectonics, then I will compare to the Alps.

First, the deep intracontinental seismicity of the Pamir and Hindu Kush at the western extremity of the collision system reveals two subduction zones of opposite vergence. Global P-waves tomography shows the maximum depth extent of the two distinct slabs and the maximum depth of seismicity has been modeled, compatible with continental lithosphere subduction (Negredo et al., 2007). Further regional seismic studies reveal the continental nature of the slab beneath Pamir (Schneider et al., 2013) and the underplating of the Indian lithosphere below Pamir (Mechie et al., 2012). Beneath the Himalaya, the Indian lower crust, attached to its lithospheric mantle, is bent and is underplated below southern Tibet (Nabelek et al., 2008), with eclogitization of the Indian lower crust during the bending, which density could be close to mantle density (Hetenyi et al., 2007). The Asian lithosphere in central Tibet is inferred to subduct southward down to 300 km, with no related seismicity (Kind et al., 2002; Replumaz et al., 2013). During the early Tibetan collision stage, a first episode of subduction of the Asian lithosphere likely occurred, recorded by Cenozoic volcanics (Roger et al., 2000).

However, a dynamic explanation of continental subduction is still lacking. A low-density contrast between the continental lithosphere and the mantle, as inferred during the Indian plate bending, facilitates the subduction of the continental lithosphere attached to a dense oceanic slab (Capitanio et al., 2010). At the mantle scale, analogue models show that the continental subduction could occur in a context of convergence, due to far field forces instead of subduction related forces (Replumaz et al., 2016; Pitard et al., 2018), which could be due to the long lasting oceanic subduction on both sides of the Indian continent (Bose et al., 2022).

Bose et al., 2023, doi:10.1016/j.tecto.2023.229727

Capitanio et al., 2010, doi:10.1038/NGEO725

Hetenyi et al., 2007, doi:10.1016/j.epst.2007.09.036

Kind et al., 2002, doi:10.1126/science.1078115

Kufner et al., 2016, doi:10.1016/j.epsl.2015.11.046

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Basement-cover tectonostratigraphic relationships in the northern Dora-Maira Massif (Western Alps)

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The internal sector of the Western Alpine axial belt consists of Paleozoic basement units and minor Mesozoic cover successions, which are more widespread in the frontal part of the accretionary wedge. The Europa-derived Internal Crystalline Massifs, in their present-day dome-shaped exposure, consist of pre-Variscan basements hosting Permian intrusive bodies, while remnants of the Mesozoic cover occur discontinuously only along the flanks of the domes. This is also the case of the Dora-Maira Massif (DMM), a stack of different tectonic units metamorphosed under different peak pressure-temperature (P-T) conditions during the Alpine metamorphic cycle. The Triassic to Jurassic cover successions of the DMM basement are detached in the southernmost sector (Balestro et al., 2022) and tectonically sliced along the western flank of the dome in the central sector. In the northern sector of the massif, the basement-cover relationships are more ambiguous, having been represented either as tectonic or as stratigraphic in different geological maps.

We investigated the tectonostratigraphic relationships in the northernmost sector of the DMM in the Susa Valley, by analysing two detailed lithostratigraphic and structural sections across the basement-cover interface. The basement consists of polycyclic garnet- and chloritoid-bearing micaschist with bodies of metabasite and monocyclic orthogneiss, whereas the cover succession mainly consists of Middle Triassic dolomitic marble with minor calcschist of supposed Jurassic age. Both the Paleozoic and Mesozoic rocks were deformed during four main Alpine deformation phases corresponding to the subduction-related D1 phase and the early (i.e., D2) to late (i.e., D3 and D4) exhumation-related phases.

The investigated basement-cover interface is currently represented by a tectonic mélange, varying in thickness from a few meters to tens of meters, mixing tectonic slices of different sizes and lithologies (i.e., monocyclic carbonate-bearing micaschist, vacuolar dolomitic marble and carbonate tectonic breccia, marble, quartzite and quartz-rich schist, gneiss and garnet- and chloritoid-bearing micaschist). The occurrence of this mélange highlights the tectonic nature of the basement-cover interface, which (i) involved lithologies sourced from the Paleozoic basement and the Mesozoic carbonate cover and (ii) is localized along relatively weak metasediments similar to those occurring in the adjoining Briançonnais successions, which are considered Late Permian to Early Triassic in age. The tectonic mélange is deformed by late exhumation-related D3 and D4 folds. Ongoing investigations are focused on better defining when (t) and under which metamorphic conditions (P-T) the mélange was formed.

Balestro G., Festa A., Cadoppi, P., Groppo, C. & Roà M. (2022) - Pre-Orogenic Tectonostratigraphic Evolution of the European Distal Margin-Alpine Tethys Transition Zone in High-Pressure Units of the Southwestern Alps. Geosciences 2022, 12, 358.

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Gravitational sliding at the southern end of the western Alpine arc

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The southernmost segment of the western Alpine arc, strikes E-W along the Mediterranean coast between Nice and Menton (F), and it is bounded by N-S structures on both sides. These abrupt changes in orientation, and the E-W strike as such in an area located southwest of the Adriatic indenter is difficult to reconcile with alpine collisional displacements. Indeed the latter are inferred to be governed by NW-ward movement of the Adriatic Indenter, which is located NE of our study area. E-W -oriented structures in this area are commonly attributed to the Pyrenean (Pyreneo-Provençal) orogeny, which however does not explain their young, Miocene age. As a consequence this E-W Alpine (?) arc segment has been variously interpreted in the past literature (Brunsmann et al., 2024, for review), as the result of Alpine indentation, Pyrenean-Provençal shortening re-activated in post-Burdigalian times, or gravitational sliding (Gèze, 1956).

A 40 km long, NNE-SSW cross-section between the latter localities shows that the tectonic style varies from N to S. The northern sector shows that the Permian and Triassic cover are gently folded above the Argentera crystalline basement. Further south, in the areas of Breil-sur-Roya and Sospel, the Jurassic, Cretaceous and Eocene cover is more tightly folded, showing broadly E-W, steeply-dipping axial planes. However, this entire folded sequence tectonically overlies the very gently-dipping upper Triassic gypsum, forming a subtractive contact, thus a normal-type of displacement. Further south, from Castillon to Cap d'Ail, the entire Triassic to Eocene cover forms a stack of 10 distinct north-dipping thrusts, most of which lying directly above Triassic gypsum.

As shown in map view between Sospel and Gorbio, the same gypsum layer can be continuously followed from its normal-fault position in the north to thrust planes in the south, via a thin strike slip fault located between them. We suggest that not only the thrust faults of Gorbio, but even all the others further south are rooted in the gypsum of the normal fault further north.

This spatial distribution of normal faults at higher topographic altitude, kinematically linked with thrusts at a deeper topographic level, and all localized along gypsum layers, is analogous to what is frequently observed in the sedimentary sequences of passive margins. Cooling of the oceanic lithosphere causes differential subsidence (e.g., Brun and Fort, 2012), hence tilting of the sedimentary sequence, which initiates downward gliding of the post-Triassic beds. In our case study, the contemporaneous Miocene uplift of the Argentera crystalline massif (Bigot-Cormier et al., 2006) and extensional thinning of the Liguro-Provençal domain (Rollet et al., 2004) tilts the entire Mesozoic sequence allowing for a gradient that induces gliding along the low-viscosity upper triassic gypsum. If this interpretation is correct, a large part of this arc segment does not directly result from Alpine collisional convergence.

Bigot-Cormier et al. (2006). Geodinamica Acta, 19, 455-473.
Brun, J.-P. and Fort, X. (2011). Marine and Petroleum Geology, 28, 1123-1145.
Brunsmann et al. (2024). Comptes Rendus. Géoscience, 356, 231-263.
Gèze, B. (1956). Comptes Rendus Académie Sciences, 2733-2735.
Rollet et al. (2002). Tectonics, 21, 6-23.

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Centennial of « *Tectonics of Asia* », by Emile Argand : a milestone for Alpine and Mediterranean tectonics

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As stated by Argand's mentor, Maurice Lugeon, the title of Argand's publication is misleading, because it is a book about the general processes of the solid Earth, and by no means restricted to Asia. In fact large part of this book is about the Alps and the Mediterranean region, and its conclusions about the latter area precede by 50 years what scientists of the early « Plate Tectonics generation » will eventually assess and consider applying new methods of study, not yet available in the 1920'.

Argand's last significant publication before « La tectonique de l'Asie » is that of 1916, in which he presents a cross section of the northwestern Alps, covering a vertical depth of more than 20 km and revealing the complete nappe structure of the orogen. Whereas the most important Alpine geologists of that time promptly react by constructing Argand-type cross sections in all parts of the orogen, Argand himself does not apply his concepts and approach to any other area of the Alps. He steps back from refining the architecture of specific Alpine regions and eight years later he presents in « La tectonique de l'Asie » with eight orogen-scale sections including the Alps, the Apennines, the Betic Cordillera, Carpathians, Anatolia, and the Himalayas, all simplified to the very essential elements that allow Argand and his readers to understand the 1st-order orogenic processes that mould mountain chains.

Just like Wegener, and at the same time, Argand cogitates about continental displacements. Each of these scientists builds his arguments upon the ones of the other. Wegener bases his interpretations on the synthesis of most diverse data sets, Argand upon the deep and detailed understanding of how horizontal movements are accommodatedand and recorded in the structure of mountain chains.

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Building the Albanides by deep underplating: insights from low-temperature thermochronology and 3D thermokinematic modeling

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Located in the central-eastern Mediterranean, the Albanides are a subduction orogen formed by the accretion of slices of continental lithosphere scraped off the upper plate during the eastward subduction of Adria. This subduction has promoted NE-SW shortening that started in the Late Cretaceous and continues to the present. Despite advancements in geophysical studies, aimed at understanding and illuminating the deep structures, the dynamics of crustal accretion within the subduction zone remain challenging. We investigate the recent crustal thickening of the Albanides and explore the relationship between deep-seated structures and surface deformation by employing low-temperature thermochronology and 3D thermokinematic modeling of a seismically constrained crustal section. Our results reveal a latest Miocene-Pliocene rejuvenation of the orogenic system marked by pulses of 3-4 km of exhumation, likely driven by a deep-seated thrust system. These findings provide important insights into the timing and kinematics of orogenic building processes, highlighting the interaction between deep underplating and surface geology in the Albanides, and contributing to our understanding of Mediterranean plate kinematics.

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Detailed stratigraphic studies encourage geostructural reinterpretation of the eastern Southern Alps

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The general geological structure of the eastern Southern Alps and the transition to the Dinarides is generally well understood. The main structural boundaries run in a west-east direction and coincide with the margins of the main Mesozoic paleogeographic units. The eastern Southern Alps are divided into two large-scale composite thrust units. The lower ones are the Tolmin nappes, which consist of deep-marine Slovenian Basin successions. They are further subdivided into the lowermost Podmelec, the middle Rud and the uppermost Kobla Nappe. Above these are the Julian nappes composed of the Julian Carbonate Platform successions. They are traditionally divided into the Krn Nappe and the Slatna thrust sheet. However, detailed stratigraphic investigations within the Bohinj range of the Julian Alps in the NW Slovenia, provide an alternative solution. In the Kobla Nappe, significant lateral variations can be observed throughout the basinal succession, especially within the best-studied Rhaetian Slatnik Formation. In the west, this formation shows a distal development dominated by hemipelagic limestone. Towards the east, the resedimented limestones become progressively abundant. Near the Soriška planina ski resort, they already dominate the sequence and the formation is characteristic of the lower slope sedimentary environment. According to the existing geological maps, further east the successions of the Slovenian Basin of the Kobla Nappe suddenly disappear and the area is dominated by Norian-Rhaetian platform carbonates, which often contain marginal reef limestones. This entire area (Jelovica Plateau) was traditionally considered part of the Krn Nappe. The described geological situation was the reason for a detailed geological mapping of the Soriška planina ski resort area. Preliminary results indicate that the Kobla Nappe does not wedge to the east. Instead, the succession of the Slovenian Basin (including the Slatnik Formation) passes laterally into the succession of the Julian Carbonate Platform within the same overthrust unit, namely within the Kobla Nappe. This is also supported by a thin, newly mapped Mačji potok thrust sheet composed of Jurassic basinal rocks that lies beneath the basinal successions in the west, but can be traced all the way to the platform limestones to the east. In such a structural reinterpretation, large part of the southeastern Julian Alps, previously considered part of the Krn Nappe, actually belongs to the Kobla Nappe. Therefore, the Krn Nappe is located exclusively in the western and central Julian Alps. The contact between the two nappes is clear in the west, where the nappes consist of successions belonging to a different paleogeographic unit. In the east, the structure was probably overlooked because it runs between the platform limestones. We emphasise that the structure is further complicated by post-thrusting stike-slip displacements. The proposed reinterpretation also opens new perspectives for some other regional problems, such as the occurrence of isolated Oligocene deposits in the central Julian Alps and the emplacement of the Bled Basin (paleogeographically distal Adria margin) in the northwestern Julian Alps.

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Subduction imprint in the Internal Ligurian Units (Northern Apennines, Italy): evidence from multi-equilibrium thermobarometry

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Internal Ligurian Units exposed in the Northern Apennines are regarded as fragments of the Ligure Piemontese oceanic lithosphere, which was interposed between the Europe and Adria Plates in the Middle to Upper Jurassic age. Starting from the Late Cretaceous, the convergence between the two plates led to the progressive closure of the Ligure-Piemontese Ocean and subsequently to the Europe margin continental subduction, until the collision in the Oligocene. The succession of the Internal Ligurian Units consists of an ophiolitic basement topped by pelagic deposits characterized by cherts, limestones, and shales (i.e., Chert, Calpionella Limestone, and Palombini Shale Fms.), and a thick turbidite sequence (Val Lavagna Shale Group and Gottero Sandstone Fm.) capped by chaotic deposits (Bocco Shale). Since the Palombini Shale Fm. occur in many of the Internal Ligurian Units, they are sampled to perform thermobaric estimates. Although the deformation history of the Internal Ligurian Units has been largely documented and regarded as reflecting their involvement in the alpine subduction zone, thermobaric estimates are poorly constrained, and the only available data come from semi-quantitative methods. Therefore, we use a multiequilibrium thermobarometry approach on 8 samples of metapelites. X-ray quantitative compositional maps were used for a detailed investigation of the sin-kinematic chlorite-white mica mineral chemistry to accurately apply classic low-grade metamorphic thermometers and barometers. The temperature values estimated with this approach are coherent both with the Raman results and the semi-quantitative white mica crystallinity index available in literature which, together with the estimated pressure strongly suggest a lower blueschist facies metamorphic conditions. Results yielded interesting and surprising pressure and temperature estimates associated with the metamorphic peak conditions of the Internal Ligurian Units and reflected their subduction signature. The calculated geothermic gradient is coherent with those proposed by previous authors for other oceanic units exposed in the Alps-Apennine orogenic system.

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Dinaric thrust sheet over the Slovenian Basin. Where is the contact of Southern-Alps and Dinarides? Structural and stratigraphical constraints.

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The transition from the Dinarides to the S-Alps and the position of the S-Alpine Trust-front east of Ljubljana is debated. Previous research agrees that the contact runs in the central Slovenian Sava Folds, they follow the analogy of western Slovenia, where the S-Alpine Thrust front (SATF) has been determined as the base of the Tolmin Thrust sheet (Placer 2008, Schmid et al. 2020). This tectonic unit incorporates the deep-water Middle Triassic to Cretaceous sedimentary succession of the Slovenian Basin (SB) which has been thrust over the Dinaric Platform. The presence of SB sediments east from Ljubljana, in the Sava Folds was suggested before (Buser 1989), but the presence of Jurassic deep-water sediments have only been proved recently (Rožič et al. 2022, Scherman et al. 2023). However, the area lying north of the discontinuous occurrence of the SB rocks was postulated to be of SB origin (Buser 2010, Placer 2008).
Detailed stratigraphic and structural observations confirmed the following succession: Ladinian siliciclastic sediments with volcanites (Pseudozilian Formation) are followed by Ladinian to Carnian Platform limestone (Schlern Formation). With a large gap Late Jurassic to Early Cretaceous pelagic limestone layers follow, containing resedimented limestone beds (Biancone Formation sl.). Covered by Early Cretaceous marlstone, with occasional calcarenitic interlayers (Lower Flyschoid Formation). The succession ends with pelagic limestones (Volčе Limestone Formation).
The succession resembles the External Dinaric succession considered by Placer (2008) as the “Transitional zone” between the External and Internal Dinarides originally lying east from the Dinaric Carbonate Platform. With this discovery there is evidence for units of Dinaric origin north of the SATF, along the northern margin of the Sava Folds region, near the Sava Fault.
Tectonically this newly identified unit of External Dinaric origin is thrust over the SB succession in a south-vergent direction, which occurred likely during the Early Miocene, prior to the folding of the Sava Folds in a N-S contractional phase. The emplacement of the SB over the Dinaric units of the Sava folds is the oldest of the three events. Indirect evidence suggest that this thrusting was Palaeocene-Eocene, in SW direction (pre Oligocene post “mid” Cretaceous). The pre-Oligocene formations are folded. Over the erosional contact following Oligo-Miocene formations are folded in a following phase.
It is evident that the structural and the older palaeogeographical-stratigraphical boundaries have to deviate from each other east of Ljubljana. This also suggests that the SATF should be defined on structural basis (Schmid et al. 2020) and could represent a Miocene south-vergent thrust front. Emplacement of the deep-water Mesozoic basin over the platform seems to be a different deformation east of Ljubljana.
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The partitioning of present-day deformation in the W-Alps controlled by mantle indentation

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Recent ambient noise Vs tomography data at the scale of the Western Alps (Nouibat et al., 2022) highlight the deep structure of the chain. In the European foreland, the seismological model shows a crust of normal thickness, with slow velocities (<3.6 km.s^{-1}) in the lower part of the crust and the presence of Moho jumps localized below the External Crystalline Massifs (ECMs). In the inner zones to the east of the Pennine Front, crustal geometry is more complex, with the presence of a European continental slab that subducts locally more than 80 km beneath the Adria plate in the SW part of the Alpine arc, and detached beneath the Swiss Alps. This slab is surmounted by a metamorphic orogenic wedge whose lower part shows serpentinized mantle seismic signatures (Vs between 3.8 and 4.3 km.s^{-1}). Its roof is located at a depth of 10 km below the Dora Maira massif. These data allow to understand the role of crustal geometry in the development of the observed deformation field. Moho morphology is controlled by numerous pre-existing major faults reactivated during the Alpine orogeny. Two mantle indenters located above the subducted European plate at different depths appear to control the locus of active deformation. The rigid nature of Adria mantle explains the localization of brittle deformation that is transferred towards the upper crust. In this context, the strain-field partitioning results in a combination of strike-slip with either shortening or extension controlled by the the displacements imposed by the current NW/SE convergence associated with the anticlockwise rotation of Adria.

REF: Nouibat, A. et al. (2022) Lithospheric transdimensional ambient-noise tomography of W-Europe: implications for crustal-scale geometry of the W-Alps. Geophys. J. Intern. 229(2), 862–879.

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Relation between inherited basin size and fold-and-thrust belt deformation style in crustal-scale analogue models: implications for the evolution of the European eastern Southern Alps

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During the Cenozoic evolution of the Alps, the Adriatic plate is traditionally considered as a rigid indenter. However, in the eastern Southern Alps (ESA) of Italy and Slovenia, significant internal deformation is observed within the northernmost part of the Adriatic plate. Predominantly Miocene shortening is accommodated within a WSW-ENE striking, SSE-vergent fold-and-thrust belt, which overprints a pre-existing platform-basin geometry formed during Jurassic extension. Jurassic basins show a remarkable bend in eastern Italy and western Slovenia (i.e., Carnic and Julian Alps, respectively), where the N-S striking Belluno basin transitions into the E-W striking Slovenian basin north of the Friuli platform. The influence of this inherited basin geometry on Miocene shortening kinematics and geometries remains a topic of ongoing debate and is the focus of this study.

In this contribution we present a new series of 12 crustal-scale analogue models designed to investigate how inherited lateral crustal heterogeneities and basin geometries affect internal deformation within the ESA. The brittle and brittle-ductile analogue experiments for inversion parallel to the axes of pre-defined basins (areas of lower mechanical strength compared to accompanied platforms) particularly focus on the northeastern basin connected orthogonally to the eastern basin. Key parameters studied include the width of the northeastern basin (5 cm vs. 10 cm). For the case of oblique inversion experiments, contraction angles of 20° and 110° to the strike of the main basins and the northeastern basin, respectively, were applied. This approach allows us to test the influence of inherited basin widths and geometries on the style and timing of deformation within the evolving fold-and-thrust belt.

Our preliminary experimental results indicate that narrow northeastern basins primarily undergo inversion and are transported piggyback, leading to the formation of numerous faults in eastern model areas. The eastern platform south of the northeastern basin tends to be incorporated into the thrust belt. Increasing the width of the northeastern basin results in the eastern platform acting more as a barrier, thereby restricting the resulting fold-and-thrust belt to a smaller N-S extent. The latter is especially pronounced in oblique inversion experiments with large northeastern basins.

To compare analogue modelling results with deformation in the ESA, structural fieldwork was conducted along major fault systems within the eastern part of the ESA, specifically east of Lozzo di Cadore. The Dof-Auda-, Pinedo-Uccea- and Barcis-Staro Selo faults are overall SSE-vergent but show variations in strike direction across platform-basin boundaries. Comparative analysis of map-view observations from the ESA and oblique analogue experiments, particularly those including large northeastern basins, emphasises the significant influence of the eastern (i.e., Friuli) platform on the deformation style of the fold-and-thrust belt.

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Evolution of a post-Variscan mid-crustal shear zone in relation to the Tethyan rifting (Ivrea-Verbano Zone, Southern Alps)

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In the last decade, studies of rifted margins have benefited from an increasing quantity of high-quality data from several disciplines. The Ivrea-Verbano Zone (IVZ), in the Italian Southern Alps, represents a complete section of middle to lower continental crust, which records both the Variscan and subsequent Alpine Tethys rift-related tectonics (Beltrando et al., 2015; Simonetti et al., 2023).

One of the most important structures is the Forno-Rosarolo shear zone (Siegesmund et al., 2008). It is a NE-SW-oriented, subvertical shear zone made of metapelites, amphibolites, calc-silicates and granulites involved in anastomosed proto- to ultra-mylonite layers enveloping weakly deformed lenses. Mylonites formation postdate Variscan metamorphism and deformation and predate Jurassic brittle fracturing and faulting.

In present day orientation, the kinematic indicators point to a sinistral sense of shear. Removing the Alpine tilt at high angle of the IVZ, this kinematic points to a former extensional shear zone. Investigations on the mylonitic flow kinematic reveal a non-coaxial deformation characterized by dominant pure shear (between 70 % and 50 %) and minor simple shear. Metamorphic conditions of the wall rocks vary from the upper amphibolite (SE, footwall) to the granulite facies (NW, hanging wall). Within the mylonites, PT estimate from mineral assemblage points to amphibolite facies conditions during deformation (~650 °C and ~5.5 kbar).

Such kinematic data and metamorphic conditions allow to constrain the development of the Forno-Rosarolo shear zone mylonitic deformation, together with other similar structures of the IVZ, during the intermediate phase of the Tethyan rift (Beltrando et al., 2015; Simonetti et al., 2023) known as "thinning mode" (Manatschal et al., 2007). This stage was characterized by general shear conditions (pure shear between 70 % and 50 %) suggesting a phase of transition from a symmetric to an asymmetric configuration of rift.

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Paleomagnetic rotations and microplate-terrane dispersal during back-arc basin opening: from Greater Iberia rotation and fragmentation to Calabria and Peloritan terrane drift

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The Oligocene-to-present tectonic history of the western Mediterranean region is characterized by the ESE-ward roll-back of Alpine and Neo Tethys oceanic slab fragments that determined the diachronous spreading of two back-arc basins: the Liguro-Provencal Basin between 30 and 15 Ma and the Tyrrhenian Sea between 10 and 2 Ma. Such geodynamic events induced the fragmentation and dispersal of the Alpine chain through the formation and migration of microplates and terranes, making the debate on the nature, origin, and evolution of such crustal blocks vivid since the 1970s. For instance, it is commonly accepted that the Corsica-Sardinia microplate rotated counterclockwise (CCW) by at least 50° during Oligo-Miocene and that the Calabro-Peloritan, Kabylies and Alboran blocks drifted hundreds of kms on top of nappe piles ESE-ward, SE-ward and SW-ward, respectively. These blocks, know all together as AlKaPeCa, presently form isolated and enigmatic igneous/metamorphic terranes stacked over the Meso-Cenozoic sedimentary successions of the Apennines and Maghrebides. Besides back-arc basins widths and ages, no other kinds of geologic/geophysical data from Corsica-Sardinia microplate or AlKaPeCa terranes constraining their drift magnitudes exist. On the other hand, drift timing may be properly documented by paleomagnetic vertical-axis rotations obtained from different age rocks, and such data usefully complement ages derived from back-arc basins.

Here we show the synthesis of paleomagnetic investigations carried out during the last few years on the Calabro-Peloritan terrane, and Sardinia, where a different pre-21 Ma rotation history is proposed. We paleomagnetically sampled the Meso-Cenozoic sedimentary cover of the Calabrian (Longobucco succession) and Peloritan (Longi-Taormina succession) terranes and the mid-late Eocene continental Cixerri Formation of SW Sardinia. In addition, we re-evaluated previous paleomagnetic results from the whole Corsica-Sardinia microplate and considered the robust Serravallian-Pleistocene dataset from the Calabrian block. Such data indicate a novel rotation and drift history in the western Mediterranean region (Siravo et al., 2022; 2023). The South Sardinia, Peloritan and Calabrian blocks belonged to the "Greater Iberia plate" before mid-Oligocene (<30 Ma) dispersal, as they all show its characteristic paleomagnetic fingerprint (middle Cretaceous 30°-40° CCW rotation). Rifting of the Liguro-Provencal between 30 and 21 Ma induced 30° CCW rotation of both South Sardinia and Calabria blocks, whereas the Peloritan block, located further south, was passively drifted SE ward at the non-rotation apex of a Paleo Appennine-Maghrebides orogenic salient. South Sardinia plus the adjacent Calabrian block and North Sardinia-Corsica blocks assembled in the early Miocene and rotated 60° CCW as a whole between 21 and 15 Ma. After 10 Ma the Calabrian block detached from south Sardinia following the opening of the Tyrrhenian Sea and rotated 20° clockwise (CW), at the apex of a Neo Appennine-Maghrebides Arc. On the other hand, the Peloritan terrane rotated 130° CW on top of the Sicilian Maghrebides, along the southern limb of the orogenic salient.

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Rift-related differentiation of sedimentary environments: a case study from the Middle Triassic of NW Croatia

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The opening of the Neotethys Ocean had a major influence on the sedimentary processes of the wider Greater Adria promontory. A stable Early Triassic shallow marine environment was disrupted by coeval tectonic and volcanic activity, peaking during the Late Anisian – Early Ladinian. Consequently, Middle Triassic volcano-sedimentary successions were deposited on top of Lower Triassic shallow-marine carbonates. These successions, recorded in the Southern Alps, the Dinarides, and the Transdanubian range, are interpreted as deposited in grabens/half grabens created by extensional tectonics and filled with products of volcanic activity intercalated with hemipelagic and pelagic sediments. Although the newly formed Middle Triassic rift-related basins were spatially limited, investigated successions from NW Croatia indicate their complex depositional environments with multiple factors controlling sedimentation.

The investigated Middle Triassic successions of NW Croatia are composed of both shallow-marine and pelagic carbonates and radiolarian chert intercalated with volcanic and several types of volcaniclastic lithologies. Shallow-marine carbonates are characterized by dolostone and limestone with algae, foraminifera, sponges, and in places reefal biota. In dolostone, a faint lamination resembling stromatolite can be observed.

Pelagic limestone contains abundant thin-shelled bivalves, calcified radiolarians, rare sponge spicules, and scarce ammonoids of Pelsonian to Illyrian age. In places, medium- to coarse-grained resedimented shallow-water material is present. Well-bedded, red, and often horizontally laminated radiolarian chert yielded radiolarians of late Illyrian-early Fassanian age. Volcanic rocks are geochemically determined as trachy-basalt and andesite-basalt, while several volcaniclastic lithologies are determined in the studied successions. *Pietra verde* deposits, composed of vitroclastic and crystalloclastic tuffs, represent the dominant volcaniclastic facies. These deposits show normal grading and horizontal lamination. Occasionally, volcaniclastic particles are mixed with pelagic deposits. Trachy-basaltic autoclastites, the second volcaniclastic facies, are found intercalated with pelagic biomicrite and *pietra verde* deposits. Volcanogenic sandstone and siltstone are found on top of other lithologies. These deposits exhibit a coarsening-upwards sequence and horizontal lamination. The mixing of volcanic and pelagic material is recorded in coarser intervals.

The described successions add to the existence of a coeval carbonate platform area and adjacent deeper basins. Resedimented carbonates indicate erosion, shedding, and gravitational redeposition of an active carbonate platform bordered by the steep normal faults. These same faults could have served as conduits for basaltic magma to reach the surface. Once in the cold marine environment, lava quenched and autofragmented serving as a source for autoclastic deposits. Newly formed clasts were subsequently reworked and redeposited into deeper parts of the basin. Pelagic limestone and radiolarian chert were deposited in a deeper environment by suspension settling in episodes of volcanic standstill. *Pietra verde* type tuffs were generated by explosive eruptions and deposited in the pelagic environment by gravitational mechanisms and syn-eruptive redeposition. Volcanogenic sandstone and siltstone are interpreted as deposited by turbiditic currents with the material sourced from the reworking of unconsolidated volcanic detritus.

The Middle Triassic differentiation of sedimentary environments in the limited area of the NW Croatia is inferred from specific sedimentary conditions controlled by multiple factors: basinal topography, gravitational processes, reworking and redeposition, availability of source material, and active tectonic/volcanic processes.

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The role of petrophysics in interpreting geophysical images: the effect of rock chemistry and texture on seismic velocities

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The diversity and resolution of current geophysical models in the Alps make it possible to interpret changes in rock properties in terms of deformation or metamorphic reactions.

However, there are only a small number of rocks for which the seismic properties at different PT are known, and eclogitisation is the only metamorphic reaction whose effect on the seismic velocities of rocks is known. Yet there are other metamorphic reactions that can modify seismic velocities, particularly those involving micas and amphiboles. For example, by studying the effect of rock chemistry on seismic velocities using field analogues from the European lower crust, we show that amphibole-to-granulite transformation is a strong alternative to eclogitisation in the European lower crust.

On the other hand, by modifying velocity contrasts according to wave propagation directions, rock anisotropy is likely to produce or erase some conversions in receiver function models, depending on the seismic events considered. In order to constrain interpretations, a better understanding of the evolution of rock anisotropy as a function of P and T is therefore required, as well as the way this property is transferred to the higher scale, i.e. seismic. Within a sample, the bedding, the shape of the anisotropic minerals and the presence of cracks (shape, orientation and filling) are factors that greatly influence the anisotropy of rocks. By comparing the results of direct measurements on a macroscopic scale with those calculated from crystallographic measurements on a thin-section scale, we show that bedding increases anisotropy on a larger scale and discuss the effects of the shape of crystals or cracks.

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Diamonds formation revealed by their internal structure: a case study from Pohorje, Eastern Alps, Slovenia

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The metasedimentary rocks from the Pohorje Mountains (Slovenia) are predominantly gneisses, which represent parts of the Austroalpine metamorphic units of the Eastern Alps. The peak P-T conditions experienced during subduction in the Cretaceous orogeny reached UHPM in the diamond stability field [1, 2 and references therein]. The garnet porphyroblasts contain numerous fluid, solid and polyphase inclusions, among which diamonds have also been found. To better understand the conditions of diamonds formation, their internal structure was investigated. Advanced high-resolution (scanning) transmission electron microscopy (HR(S)TEM) techniques were applied, including high-angle annular dark-field (HAADF-STEM), combined with EDS and electron energy loss spectroscopy (EELS). The TEM lamella was prepared with FIB/SEM technique. Atomic scale resolution was achieved, allowing thorough analysis of diamond.

The investigated lamella contained three diamond grains, which was also confirmed by EELS and EDS analysis. Contacts between the diamond grains and the host garnet are closely intergrown but show no crystallographic relations. Selected area electron diffraction patterns (SAED) of individual diamond grains show that one of the grains is monocrystalline, while the others are polycrystalline. The latter exhibit some preferential orientation of the crystallites. The high-resolution imaging allowed to recognise the structures of the polycrystalline grains at the atomic scale. They consist of numerous nanocrystallites ranging in size from a few to several tens of nanometres in size. Some of them exhibit an undisturbed internal structure, while the others show some imperfections in the form of stacking faults, twins, and lattice dislocations. In addition, a detailed HRTEM study of the polycrystalline diamonds revealed the presence of carbon domains in the form of graphite, which was confirmed with the SAED. Furthermore, in certain areas between the nanocrystalline grains and host garnet, an amorphous layer with a composition close to garnet was identified. Monocrystalline diamond appears without internal defects or graphitic domains and is completely crystalline.

The presence of both monocrystalline and polycrystalline grains in a single inclusion is puzzling in terms of their crystallisation conditions. A change in physical (pressure, temperature) and/or chemical parameters (interaction of the trapped COH fluid with garnet) in the inclusions during metamorphism might induce the precipitation of diamonds with different structures. We hypothesise that the diamonds precipitated in response to changing P-T conditions during the prograde phase of metamorphism, when the solubility of C in COH fluids decreases. Absence of standalone prograde graphitic grains indicates that the C saturation was achieved in the diamond stability field. At first, before reaching peak metamorphism, monocrystalline diamond was formed. After reaching peak metamorphism, though still in the diamond stability field, the COH fluid began to interact with the walls of the garnet enabling precipitation of the amorphous phase, after which polycrystalline diamonds formed. The graphitic domains within the diamond nanocrystallites were formed due to transition from the diamond to the graphite stability field during exhumation of the rock. To draw more precise conclusions, further investigations need to be carried out.

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Can the dynamics of a subducted slab account for the Upper Cretaceous magmatism in the Sava-Vardar Zone and Timok Magmatic Complex? A Numerical Modelling Approach.

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Many questions regarding the geodynamics of the Vardar Tethys have mostly been settled, including the timing of the ophiolite obduction in the Balkans and the configuration of oceanic domains during the Jurassic period. However, the terminal stages of the evolution of Vardar branch of the last Tethyan ocean in the Balkans, specifically the time of its final closure, remains controversial. Current consensus favors a late ocean closure during the Late Cretaceous [1]. Although the timing of the obduction of the Balkan ophiolites indicate a closure in the latest Jurassic/earliest Cretaceous, the discovery of Upper Cretaceous magmatic rocks in the Sava-Vardar suture, interpreted as ophiolites, lead some authors to extend the life of the last Tethyan ocean to the latest Cretaceous. However, more recent findings call into question the oceanic character of these rocks [2], and propose a possible intra-continental environment for their origin. Another strong argument for the existence of an active subduction during the Cretaceous is the presence of the Timok Magmatic Complex (TMC) as part of the larger Apuseni-Banat-Timok-Srednogorje metallogenic belt. In this communication, we present our preliminary results of numerical modelling of Cretaceous geodynamics in the Balkans. We adopt the perspective that the magmatic rocks in the Sava-Vardar Zone do not represent ophiolites, and argue for ocean closure by the earliest Cretaceous, consistent with our previous models of Jurassic ophiolite obduction in the Balkans [3]. We try to account for the Cretaceous magmatism in the Sava-Vardar Zone and TMC in the context of an already closed ocean at the surface. To this end, we model the dynamics of the already subducted slab that is still attached, whereas the ocean lithosphere is completely consumed. The slab consists of the subducted oceanic lithosphere and a smaller portion of the basement of Adria. This slab undergoes detachment which is followed by the rise of its shallower parts and delivery of subducted rock material into favorable conditions for partial melting. The models are based on both an idealized configuration as well as the spontaneous continuation of our previous models of the Tethys closure.

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A multidisciplinary study of the Barrovian metamorphism in the Lepontine dome gives new insights into the heating history of the Central Alps

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This contribution aims to present to the Alpine scientific community some of the latest studies we performed in the Central Alps, with a focus on the origin of the Barrovian metamorphism in the Lepontine dome.

The Lepontine dome is a metamorphic and structural dome formed by crystalline basement nappes of the Penninic domain. The area is characterized by a Barrovian metamorphic imprint, which is testified by peak-temperature mineral isograds and by a pervasive mineral and stretching lineation in amphibolite-facies. Isograds locally intersect the tectonic nappe boundaries, an observation that was frequently considered as evidence of post-nappe emplacement heating. Nonetheless, the NW-SE directed lineation suggests that peak metamorphic conditions developed coeval to the emplacement of Lepontine nappes.

We addressed this inconsistency through a multidisciplinary approach. We combined extensive geological and structural mapping with U-Pb zircon dating, which permitted to identify a belt of syn-kinematic migmatites dated at 31-33 Ma. The discovery of these Alpine migmatites defines a major crustal-scale shear zone which we named “Maggia-Adula shear zone”. This thrust divides the Adula and Maggia nappes on top from the Simano below, with the Cima Lunga unit pinched and sheared between them.

We modelled nappe emplacement along this main shear zone with a simple thermo-kinematic numerical model, which revealed that heat was mainly advected from depth during overthrusting. Heat conduction also contributed to the final configuration of the peak-temperature isotherms and shear heating played a role in shaping the inverted metamorphism observed around the thrust.

Finally we investigated the cooling history of Lepontine garnet-paragneisses sampled at different tectonic levels within the nappe pile. We applied multicomponent diffusion modelling to Alpine garnet rims which experienced re-equilibration at close-to-peak conditions. The rocks within the main shear zone experienced post-peak conditions of ca. 635 °C and 0.8 GPa, with a subsequent very fast cooling of 100-400 °C/Myr. These high cooling rates can’t be explained with regional exhumation, and confirm the hypothesis of shear heating acting within the shear zone.

In conclusion, our results indicate that the origin of Barrovian metamorphism in the Lepontine dome can be ascribed to the emplacement of a hot Alpine nappe, which we refer to as the “Maggia-Adula nappe”. This event produced Barrovian isograds, amphibolite-facies lineation and migmatites at ca. 31 Ma. In specific locations within the Lepontine dome, our results also suggest that we should re-consider the distribution of peak-temperature isotherms. The subsequent cooling of the Lepontine area was spatially and temporally heterogeneous and could have determined a later re-heating in the northern units.
Assessing the extent of Barrovian metamorphism and its finite imprint in the field at different tectonic levels is challenging and requires an interdisciplinary study. Geometrical interpretation alone is insufficient to understand the origin of Barrovian metamorphism without considering the physical forces leading to deformation and metamorphism in mountain-building processes.

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Alboran Sea igneous intrusions revealed by magnetic anomalies and related to extensional opening constrain the ongoing continental collision

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The Alboran Sea is a Neogene basin formed by the extension of a continental crustal domain (Alboran Domain) during its westwards displacement. This process involved the collision of its margins with the African and Iberian palaeomargins, which led to the formation of the Betic and Rif cordilleras. The Alboran Sea is characterized by the presence of several highs that correspond to volcanic edifices and/or submarine ranges. The distribution of the magnetic anomalies on this basin shows some dipoles centered in these volcanic edifices. The most intense dipoles are aligned in two groups in the center of the basin: a NE-SW elongated group starts in the Ibn-Batouta bank, runs eastwards centered in the Alboran Channel along the northern boundary of the Alboran Ridge and continues eastwards, changing to a NW-SE group of aligned dipoles, along the Yusuf fault. Since these anomalies are not related to surface volcanic highs, several profiles have been modeled across these dipoles. The models show that the sources are probably crustal scale, basic igneous intrusions located at depths from 8 to 14 km. It is remarkable that these intrusions are northwards displaced with respect to the Alboran Ridge, which seems to be the main volcanic high of the Alboran Sea. The orientation of these groups of magnetic dipoles and the absence of a clear relation with the Neogene calc-alkaline volcanism of the main highs support the idea that these intrusions may be related to the rifting of meso-Mediterranean terrains that formed the Alboran Domain (like the AlKaPeCa Domain) during Oligocene-Early Miocene. This rifting process led to the spreading of the Algerian basin and the individualization of the Alboran Domain from other domains. Furthermore, that orientation shows a similar trend to the rift axis proposed for that period, so the intrusions could represent the western tip of that rift. Later, these intrusions could be affected by the STEP fault (Subduction Tear Edge Propagator fault) that accommodated the westward displacement of the Alboran Domain along its southern limit and that is related with the formation of the Yusuf fault. Since Tortonian, the tectonic inversion of the Alboran basin was characterized by the prevalence of the NNW-SSE compression over the ESE-WSW extension, which continues today. During Pliocene and Quaternary, this stress led to the formation of a tectonic indentation, whose front, the Alboran Ridge, is located next to the main intrusions. Thus, it is likely that the intrusions act as a backstop that have favored the folding and uplift of the Alboran Ridge in the front of the indenter. This constitutes an excellent example of how intrusions originated during the extensional, initial stages of a basin can condition and control the style of the later tectonic inversion of this basin in the context of the peri-Mediterranean chains.

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Single or double subduction? New constraints from structural analysis and magnetic fabric from the Vardar suture zone, Serbia

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The NNW–SSE-trending Vardar suture zone was formed as a result of the Late Triassic to Early Jurassic opening of the Vardar Ocean as a branch of Neotethys, followed by subduction and collision of the Adria- and Europe-derived continental microplates during Early Cretaceous. The paleogeography and kinematics of the closure of the Vardar Ocean are still a matter of debate, and two main models exist based on the differences between Eastern and Western Vardar ophiolites. A simpler, one-ocean model invokes one oceanic domain subducted beneath the European plate, with a slab-rollback generating Eastern Vardar ophiolite in a back-arc basin. In contrast, a two-ocean model assumes the existence of two separate oceanic basins (relict Paleotethys and Vardar) consumed by doubly-vergent subduction. To test these two contrasting models, we present new tectonic, kinematic, and anisotropy of magnetic susceptibility (AMS) data from the Vardar zone in southern Serbia, where a complete section from one continental margin to another is superbly exposed. From east to west, the main lithotectonic elements across the suture are: (1) the Serbo-Macedonian Massif, composed of medium- to high-grade orthogneisses and paragneisses with lenses of marble, quartzite, and amphibolite, representing the European margin; (2) the Cretaceous flysch, younging westward; (3) the Goč–Kopaonik and Radočelo metamorphic complexes, composed of Early Paleozoic volcano-sedimentary successions (phyllites, marbles, and metabasites), that crop out within the suture; (4) obducted ophiolites dominated by serpentinized peridotite (Ibar being the largest) and their metamorphic soles; (5) deep-marine, pelagic successions (shales, cherts, limestones); and (6) Drina–Ivanjica belt, dominated by low-grade albite–sericite slates, representing the Adria-derived microplate. The flysch successions have been strongly shortened and folded into upright, tight to isoclinal folds and thrust over the ophiolites in some places with top-to-the-WSW kinematics. The ophiolites are frequently cross-cut by a dense network of brittle-ductile shear zones anastomosing around rigid (less serpentinized) peridotite blocks. The sense of shear locally varies, but generally is top-to-the-WSW(SW). The AMS data in the Ibar ophiolite indicate simple-shear-dominated strain along the eastern ophiolite–flysch contact with magnetic foliations moderately dipping to the NE to SW and bearing down-dip magnetic lineations, whereas magnetic fabric of the inner part of the ophiolite indicates pure-shear-dominated strain with more variable orientation of the principal susceptibilities. The easterly sub-ophiolitic Goč–Kopaonik and Radočelo complexes preserve an older fabric predating ophiolite emplacement, except near-contact zones that are strongly sheared. In contrast, the westerly metamorphic sole and pelagic successions dip uniformly beneath the ophiolite. Finally, the Drina–Ivanjica belt is dominated by a pre-collisional flat fabric. Taken together, the obtained data suggest regionally consistent top-to-the-WSW(SW) kinematics of thrusting and ophiolite emplacement across the Vardar suture zone and along with westward-younging of deformation and flysch deposition support the one-ocean model.

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Active faulting in the Alps as seen by GNSS: comparative case-studies from the Belledonne and High-Durance fault systems

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In the W-Alpine context, where active deformation is slow and seismicity is moderate, the question of determining and characterizing active faulting remains a scientific challenge. However, previous studies have shown that reliable geodetic strain rates can be assigned to the High-Durance fault (HDF) system, in accordance with the regional seismicity. In this paper, we propose a comparative analysis of two major faults recognized in the W-Alps: the HDF in the Briançon vicinity and the Belledonne fault (BDF) close to Grenoble. The aim is to investigate the constrains that can be brought by GNSS, in slow deformation ranges of 0.1-1 mm/yr, to decipher active faulting, both in terms of localization at the regional scale and quantitative strain rates. We also aim to compare the seismotectonic framework with the geodetic results. Last but not least, these two major faults bear witness of the main kinematics found within the realm of the W-Alps, that is to say extensional mechanism in the internal zone (along the HDF) and strike-slip in the external zone (along the BDF). They can thus be considered as two major fault systems representative of the overall W-Alpine current deformation. From a quantitative viewpoint, the BDF extends over about 50 km along the western side of the Belledonne External Crystalline Massif. Using up to 20 years of data from 22 permanent GNSS stations, approaches exploiting the redundancy between the individual station velocity estimates provide dextral strike-slip kinematics with a rate of 0.2 ± 0.2 mm/yr. This rate is coherent with a unique strain tensor calculated over the 50 km wide local network, evaluating a NNE-SSW extensional axe of 2.0 ± 0.8 nanostrain/yr, with a WNW-ESE shortening axe of 4.7 ± 1.2 nanostrain/yr. Strain calculations by alternative methods on regular grids evaluate a lower total amplitude of strain rate close to the BDF trace, in particular less compression. Comparatively, the HDF is investigated thanks to a dense network of 30 GPS stations covering the Brianc☐on area, which was surveyed during 5 temporary campaigns in 1996, 2006, 2011, 2016, and 2021. The redundancy of the dense network and the long observation interval after the addition of the fifth campaign in 2021 allow to increase the accuracy of the velocity fields. The average horizontal strain rate over the entire network located in the center of the Brianc☐on Seismic Arc has been evaluated at 20 ± 2 nanostrain/yr of E-W extension across the 50 km network, yielding about 0.5 mm/yr of extension across the NS trending HDF. From a seismotectonic viewpoint, the comparison with seismicity highlight the coherency between seismotectonic and geodetic deformation fields, both for the HDF and BDF systems, in terms of style, direction, and amplitude of deformation.

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The long-lasting exhumation history of the Ötztal-Stubai Complex (Eastern European Alps): New constraints from zircon (U-Th)/He age-elevation profiles and thermo-kinematic modeling

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The Eastern European Alps formed during two orogenic cycles, which took place in the Cretaceous and Cenozoic, respectively. In the Ötztal-Stubai Complex – a thrust sheet of Variscan basement and Permo-Mesozoic cover rocks – the record of the first (Eoalpine) orogeny is well preserved, because during the second (Alpine) orogeny the complex remained largely undeformed. We use new zircon (U-Th)/He (ZHe) ages and thermo-kinematic modeling to constrain the cooling and exhumation history of the central part of the Ötztal-Stubai Complex since the Late Cretaceous. The ZHe ages from two elevation profiles increase over a vertical distance of 1500 m from 56±3 to 69±3 Ma (Stubaital) and from 50±2 to 71±4 Ma (Kaunertal), respectively (Hölzer et al., accepted by *Lithosphere*). These ZHe ages and few published zircon and apatite fission track ages were used for inverse thermo-kinematic modeling. The modeling results show that the age data are well reproduced with a three-phase exhumation history. A first phase with relatively fast exhumation (~250 m/Myr) during the Late Cretaceous ended at ~70 Ma and is interpreted to reflect the erosion of the Eoalpine mountain belt. As Late Cretaceous normal faults occur at the margins of the Ötztal-Stubai Complex, normal faulting may have also contributed to the exhumation of the study area. Subsequently, a long period with slow exhumation (<10 m/Myr) prevailed until ~16 Ma. This long-lasting phase of slow exhumation suggests a rather low topography with little relief in the Ötztal-Stubai Complex until the mid-Miocene, even though the Alpine orogeny had already begun in the Eocene with the subduction of the European continental margin. Accelerated exhumation since the mid-Miocene (~230 m/Myr) is interpreted to reflect the erosion of the mountain belt, due to the development of high topography in front of the Adriatic indenter and repeated glaciations during the Quaternary.

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Late-orogenic extension ceases with waning plate convergence:The case of the Simplon normal fault (Swiss Alps)

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The Simplon normal fault in the Western Alps caused tens of kilometers of orogen-parallel extension during convergence of the European and Adriatic plates, but the slip rate of the fault and the time when normal faulting ended are still debated. Here, we constrain the slip history of the Simplon fault with low-T thermochronology and thermo-kinematic modeling (Wolff et al. 2024). Closely spaced samples from an elevation profile in the center of the fault yield zircon (U-Th)/He ages (ZHe) that are nearly invariant over an altitude of 1.4 km and cluster around ~6 Ma. In contrast, apatite (U-Th)/He ages (AHe) increase with altitude from 3.4±0.3 to 4.6±0.7 Ma, while the AFT ages range from 4.4±0.7 to 5.8±1.5 Ma. In addition, recently published $^{40}Ar/^{39}Ar$ ages constrain that our samples moved through the brittle-ductile transition (i.e., ~300°C) at 8–10 Ma. Our thermo-kinematic inverse modeling shows that these age data can be explained by a single phase of normal faulting, which lasted from 19.8±1.8 to 5.3±0.3 Ma and caused 45±10 km of extension. The slip rate of the 30°-dipping model fault is 3.5±0.3 km/Myr and equivalent to an exhumation rate of ~1.8 km/Myr. Our modeling reveals that the altitude-dependent difference between ZHe and AHe ages reflects the thermal relaxation after faulting stopped at ~5.3 Ma. Since then, exhumation by erosion continued at a rate of ~0.5 km/Myr. Remarkably, the end of slip on the Simplon fault coincides with the cessation of reverse faulting at 6±2 Ma in the external crystalline massifs of the Alps (Aar, Mont Blanc, Aiguilles Rouges) and with a decrease in strain rate by one order of magnitude at 5-4 Ma in the Swiss molasse basin and the Jura mountains. This temporal coincidence suggests that normal faulting in the internal part of the Alps ceased when plate convergence waned and the under-thrusting of European continental lithosphere beneath the Adriatic plate came to an end.

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Updated gravity and geophysical model for the crust and upper mantle transectfrom the Ligurian Sea to the Po Basin

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A new gravity model was constructed for the composite line, 465 km long, crossing from the Ligurian Sea through the Northern Apennines to the Po Basin as far as Verona province and derived from published cross-sections. Gravity field along the transect varies strongly from high positive values of Bouguer anomalies (160 mGal) offshore to the low-amplitude gravity minima (-160 mGal) above the Po Basin. The structure of the sedimentary succession, basement, and the crystalline crust of the density model were constrained by offshore-onshore WARR (wide-angle reflection and refraction) and reflection seismic profiles. In addition, the European Moho compilation was used as well. We also constrained the upper mantle structure by the S-wave tomography model of Italy. Using the known velocity-density conversion functions for different velocity values and rock types, the velocity model of the crust was transferred into density one, from which the gravity effect was calculated by the GRAV3D software. A stable solution of the modelling was obtained for an oceanic crustal segment, a continental crust, and a transition zone from a thin (18 km) oceanic crust of the Ligurian Sea to ≤ 40 km-thick continental crust with a deep (up to 18 km) meta-sedimentary succession of the Po Basin, which causes the mentioned gravity minimum.

The ocean-continent transition zone, ~100-km wide, including much of the accretionary wedge, is a thinned crust (up to 25 km) with a thick basement (Tuscan metamorphic unit) overlain by Mz carbonate rocks, Oligocene-Miocene foredeep siliciclastic sediments and Ligurian units. A spectacular feature of the transition zone is a underplated sub-Moho high-velocity/density body, which is ~7 km thick and deepens northeastwards, below the Po Basin. This transition zone is separated from the oceanic crust by a block, ~40 km wide, with subvertical flanks, marked by local magnetic anomaly which we associate to exhumed HP/LT metamorphic rocks. This could be indicative of the complex nature of the transition zone, which was affected by various geodynamic processes during the long-lived history of the Europe and Africa plates and the closure of the Tethys ocean between them since the Late Cretaceous. These processes included the compressional deformation event of the crust (in Eocene times) during the closure of the Piedmont-Ligurian Ocean, between Europe and Adria/Apulia paleocontinent, and the Apenninic subduction. Later (since middle Miocene, ~20-15 Ma), rifting occurred in the area of the modern Ligurian Sea, and it led to formation of the modern Western Mediterranean Basin and southwards opening of the Tyrrhenian Sea which began under the influence of asthenospheric flows. The latters, in the offshore part of our transect, are recorded as low-velocity layers (from S-wave tomography) in the subcrustal region, at a depth of about 30 km, and in the upper mantle. Corresponding zones of low density (up to 3.20-3.25 g/cm^3) are present in the upper mantle of the Liguria-Verona density model. The distribution of the high heat flow zones strictly corresponds to the subcrustal astenospheric heterogeneities confirming that these heterogeneities are formed recently in the evolution of the Northern Apennines.

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New geochronologic constraints on the timing and geodynamic setting of Ordovician plutonism in the Ötztal nappe of the Eastern Alps

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The supercontinent Gondwana, assembled during late Neoproterozoic, was delineated by peripheral accretionary orogens and associated magmatic belts. The timing and geodynamic setting of the peri-Gondwana magmatism remain debated, especially in case of the Avalonian–Cadomian belt that straddled Gondwana´s northern margin. A great deal of this magmatism can be attributed to the Cadomian orogeny, however, the magmatic activity continued into the Ordovician. It has been well established that the Ordovician magmatism was widespread as abundant volcano-plutonic complexes are now found in almost all Cadomian terranes in the Variscan and Alpine orogens. Two different models have been proposed to explain the Ordovician magmatism in Western and Central Europe. One model, mainly based on observations in the Alps, invokes subduction and slab-rollback underneath north Gondwana (the Cenerian orogeny). The other model, based on work in the Bohemian Massif, assumes a hyperextended passive margin and rifting generated by a mantle plume or far-field slab pull. Whereas a large body of data exists for the latter, the Ordovician magmatism in the Alps remains worth of further investigation. In this study, we present new U–Pb zircon ages from the Ötztal nappe, composed of a metasedimentary complex which encloses bodies of metagranitoid rocks. The U–Pb detrital zircon age spectra obtained from paragneisses suggest deposition during the latest Ediacaran to Cambrian and were sourced from basement characterized by minor Archean and Paleoproterozoic, more abundant Tonian–Stenian, and dominant Ediacaran (Cadomian) ages, presumably the Arabian–Nubian shield. The metagranitoids, ranging in composition from tonalite through granodiorite to granite, were previously categorized into 5 groups and their intrusion ages (U–Pb on zircon) could now be constrained as follows: Group 1 (M-, I-, and A-type granitoids associated with metabasites) at ca. 500 Ma, Group 2 (Winnebach S-type granodiorite/tonalite) at ca. 640 Ma, Group 3 (Sulztal S-type granite suite) at ca. 470 Ma, Group 4 (Alpeiner I-type granitoids) at ca. 470 Ma, and Group 5 (Bassler S-type granite suite) at ca. 470 Ma. In addition, a mafic eclogite yielded zircon ages at ca. 480–450 Ma and a Variscan overprint at ca. 340 Ma. Although the timing of Ordovician magmatism is apparently similar in the Bohemian Massif and the Alps, we highlight the possibility of different geodynamic causes: in particular, we envisage a curved geometry of the north Gondwana margin, where rifting in its western segment (Bohemian Massif) was broadly coeval with subduction along its eastern segment which included also the present-day Ötztal nappe.

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Late Cretaceous S-verging thrusting in the central Southern Alps (N Italy) proved by U-Pb syn-tectonic calcite geochronology

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The central Southern Alps (cSA) form a complex S-verging polyphase fold-and-thrust belt formed in response to the Alpine convergence to the S of the Periadriatic Fault System. Despite the onset of the final continent-continent collision in the Alps is constrained in the Late Eocene, evidence of Late Cretaceous deformation occur in the northern part of the belt, along the Orobic Thrust stacking the Variscan basement onto the Permo-Triassic cover. Here, pseudotachylytes associated to faulting close to the brittle-ductile transition display radiometric ages that trace back to 80 Ma.

No radiometric ages on structures in the central and southern part of the belt are until now available, with only indirect constrains (andesitic dikes and stocks cross-cutting tectonic structures) providing a pre-Late Eocene age of deformation related to the Alpine crustal shortening.

We present here new U-Pb radiometric ages of calcite tectonites located along the main structures of the central and southern sectors of the cSA that consist here of a thick pile of thrust sheets deforming the Lower to Middle Triassic carbonate successions. Our new U-Pb calcite ages obtained on growth fibers along fault planes, veins and calc-mylonites sampled along some of the most important regional thrust planes mainly result in Late Cretaceous ages, suggesting that N-S to NW-SE directed compression already affected the central part of the cSA at those times. Similar ages also occur within the southern portion of the belt, where the Norian "Dolomia Principale" thrust sheets, override the Rhaetian Riva di Solto Shale immediately to the north of the frontal portion of the belt. Younger ages resulted from the Paleogene units which are involved in the exposed frontal part of the belt, which is mostly buried under the recent infilling of the Po Plain forming the Milan Belt.

These data confirm that S- to SE-directed thrusting and folding affected the central Southern Alps since the Late Cretaceous, well before the onset of the Alpine collision.

List of Authors

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