

**Special Collection:**Alpine mountain belts in 4-  
dimensions**Key Points:**

- Review of studies on tectonic activity in the eastern part of the Alps
- Description of the overall pattern of tectonic deformation from 1 Ma to today
- Discussion of the role of crustal properties and mantle geometry on localization of crustal deformation

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## Active Tectonics of the Eastern and Southern Alps - Crustal Response to Deep Processes? A Review

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**Abstract** Owing to the low N-S convergence rates between Adria and Europe, crustal deformation rates in the Alps and its forelands are low. Active tectonics are, therefore, difficult to study, especially as non-tectonic landscape forming processes can erase or modify the tectonic surface imprint. Large-scale and dense seismological data recently offered insights into earthquakes and into the lithospheric structure beneath the Alps. Recent field studies added data on geological archives of active tectonics. In this review, we summarize the results from studies of seismic tomography, geodesy, seismology, historical seismology, archeoseismology, on-fault and off-fault paleoseismology, and fault gouge dating, focusing on the eastern part of the Alps during the last c. 1 Ma. We discuss the influence of the lithosphere on the localization of deformation, and we draw a generalized picture of active deformation. We show that deformation is primarily accommodated across the South Alpine Front (~2 mm/yr out of max 3 mm/yr total shortening) and NW-SE striking strike-slip faults in western Slovenia (~1.5 mm/yr shear). Large fault systems in the interior of the Eastern Alps are still actively accommodating extrusion of crustal material toward the east at very low rates (0.5–1.0 mm/yr). Diffuse deformation and clusters of seismicity are observed in the interior of the Alps. Minor shortening occurs at the North Alpine Front. Crustal strength controls the localization of deformation resulting in non-deforming blocks. Neogene slab break-off events do not control the present-day deformation. Instead, present-day uplift of 1.5–2 mm/yr correlates to areas glaciated during the Last Glacial Maximum.

**Plain Language Summary** The European Alps deform because Adria, a small tectonic plate comprising the northern Adriatic Sea and northern Italy, moves northward by about 3 mm/yr with respect to the Europe. Deformation rates here are very low and tectonic deformation in the Earth's uppermost layer, the crust, is hard to detect. Additional geological processes in the Alps make it difficult to detect the tectonic signal. New data now allow to better understand the structure of the crust and the hot, slowly deforming mantle beneath the Alps. We review published data on crustal deformation in the eastern part of the Alps over the last 1 million years. We describe the pattern of tectonic deformation, and we discuss how it is influenced by processes in the crust and in the mantle. Active tectonics are driven by the movements of the Adriatic Plate and not by deeper mantle processes. Most deformation happens at the southern edge of the Alps. To a lesser extent, large faults in the Alps that transport crustal material eastwards are also still active. Diffuse deformation occurs in the northern parts of the Alps. In some areas we observe increased seismicity that cannot be explained with the large-scale tectonic motions.

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## 1. Introduction

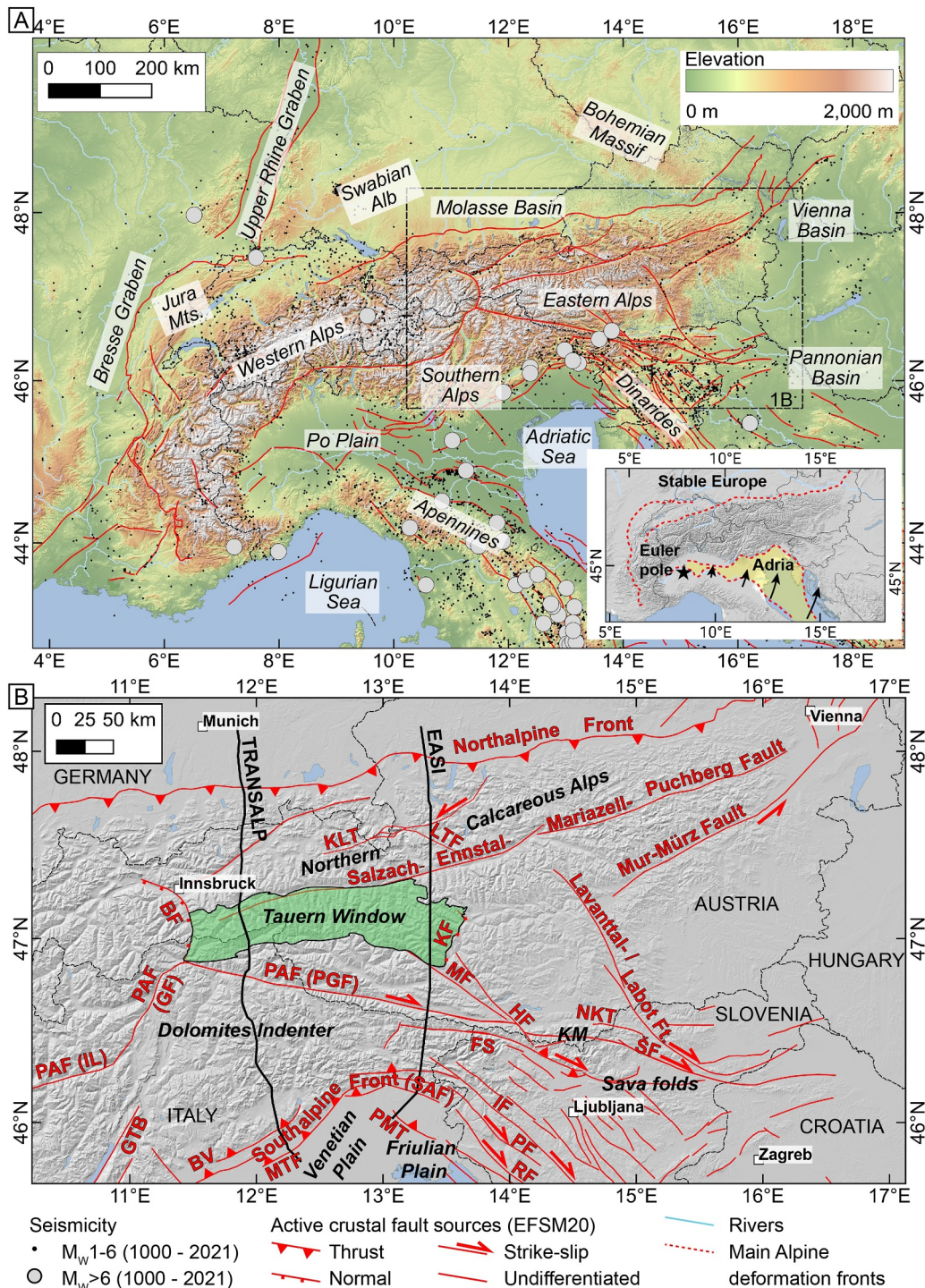
The arcuate European Alps (Figure 1) form a topographically continuous orogen with an along-strike distance of c. 1,500 km between the Ligurian Sea and the Vienna basin. They were formed by the collision of the European and Adriatic plates since the Late Eocene, following the prolonged subduction of the European plate below the Adriatic plate since c. 84 Ma (Agard & Handy, 2021; Handy et al., 2010, 2015). This orogen has accommodated between 90 and 260 km of collisional shortening since c. 35 Ma (i.e., regarding only the shortening that occurred since the arrival of European continental lithosphere in the subduction zone; Le Breton et al., 2021; Rosenberg et al., 2021; Schmid & Kissling, 2000; Schmid et al., 1996). The Adriatic promontory of the African plate is still moving northwards with respect to stable Europe, albeit at very low rates of less than 3–4 mm/yr (e.g., Serpelloni et al., 2022), possibly underthrusting the Alpine orogenic edifice (inset Figure 1a). Rock uplift peaks in the Central Alps at 2–3 mm/yr (Houlié et al., 2018; Pintori et al., 2022).

Most of the damaging magnitude  $M > 6$  earthquakes in our study area occurred at the foothills of the Southern Alps (Figure 1). Historical records list the 1976 moment magnitude  $M_W$  6.4 Friuli earthquake (e.g., Cipar, 1980; Pondrelli et al., 2001), the 1117 ( $M \sim 6.7$ ) Verona earthquake, the 1348 ( $M_W \sim 7$ ) Carinthia earthquake, and the 1511 ( $M_W \sim 6.9$ ) Slovenia earthquake (Rovida et al., 2020) as the largest in the region. The 1976 Friuli earthquake caused nearly 1000 casualties and severe damage to 85,000 buildings in the epicentral area (e.g., Slejko, 2018), illustrating the societal impact of these earthquakes. The exact location of pre-instrumental historical earthquakes is difficult to constrain; they might have occurred in currently aseismic areas. In large parts of the Eastern Alps, the low magnitude seismicity and limited spatial resolution of comparably sparse seismic networks impede interpretations of seismogenic fault structures and their geometry.

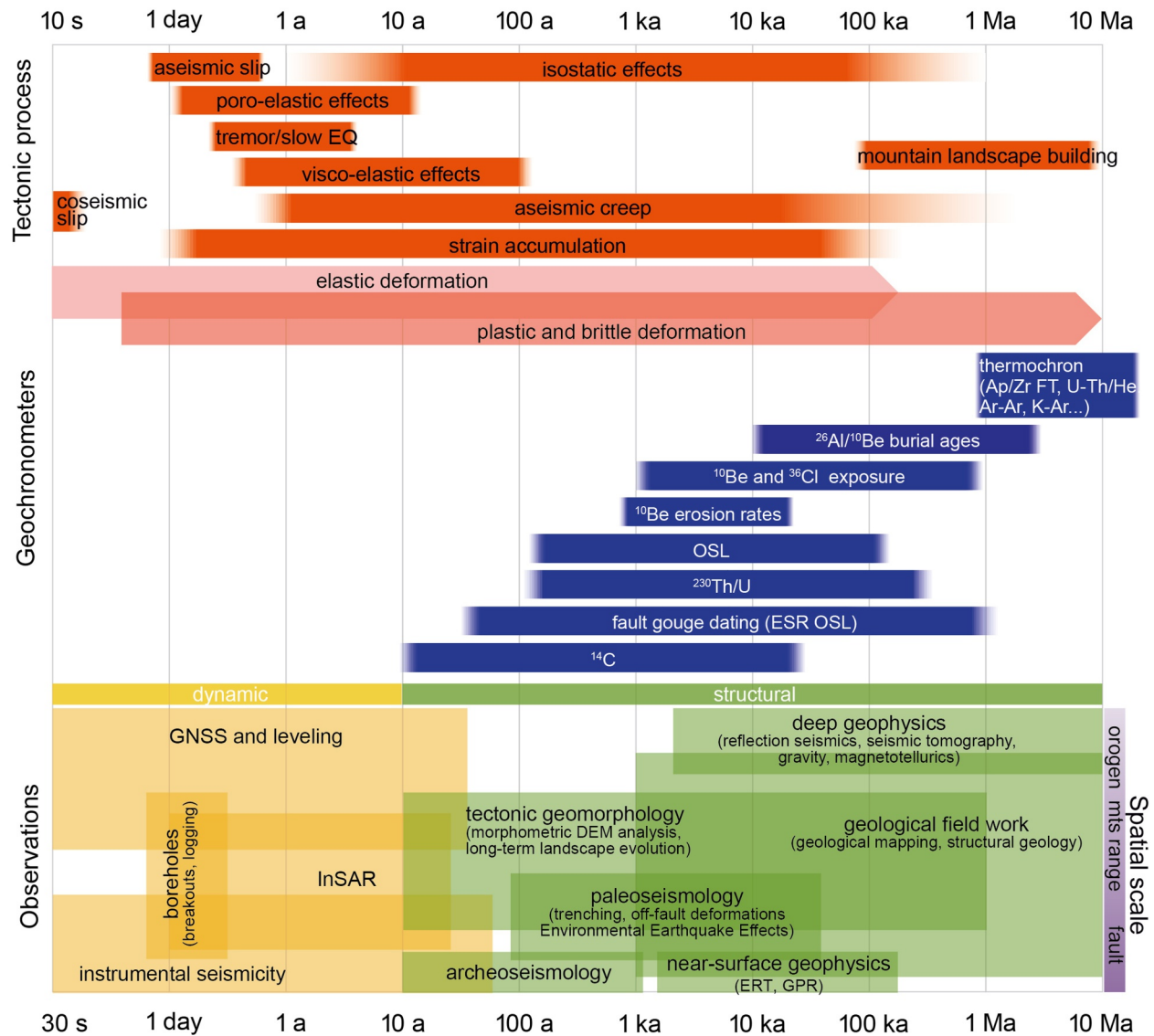
The low deformation rates and diffuse seismicity (Figure 1) pose a challenge for research on active tectonics for several reasons. First, within the observation period of space-based geodetic techniques, the accumulated strain and the resultant deformation signal are close to the detection threshold. Second, low-magnitude and sparse seismicity provide no clear insights into fault activity and geometry (e.g., Anselmi et al., 2011; Diehl et al., 2021; Mathey et al., 2021; Pondrelli et al., 2006). Third, the Alps are subject to significant non-tectonic surface modification through mass movements, karst, glacial and fluvial processes, and, recently, anthropogenic surface processes, often obliterating possible signals of tectonics in the landscape (e.g., Diercks et al., 2023; Jamšek Rupnik et al., 2022). Fourth, the low crustal deformation rates may compete with other sources of deformation, such as deep-seated processes related to broken mantle slabs or uplift driven by post-glacial rebound and/or erosion (e.g., Champagnac et al., 2007, 2009; Fox et al., 2015; Mey et al., 2016; Meyer et al., 2011; Norton & Hampel, 2010; Sternai et al., 2019).

Research on active tectonics of the Alps started long before the breakthrough of the theory of plate tectonics. Catastrophic earthquakes caught the attention of scholars early on (e.g., Baratta, 1892; vom Rath, 1873a, 1873b; Suess, 1896), and Winkler-Hermaden (1957) devoted an entire book to the relationship between tectonic forces and the most recent phase of orogeny. In the following decades, active tectonics studies used the increasing data set from seismology to constrain the location and geometry of active faults, and new methods emerged to analyze the data. In the 1990s and early 2000s, the collection of accurate positioning time-series facilitated the quantification of surface deformation rates at mm-scale (e.g., Feigl et al., 1993). At the same time, the crustal structure was imaged along several active and passive seismic profiles in the Eastern Alps: TRANSALP (TRANSALP Working Group, 2002), ALP 2002 (Brückl et al., 2007), and EASI (Hetényi et al., 2018a). Between 2016 and 2019 the AlpArray initiative, an orogen-scale passive seismic experiment, provided unprecedentedly dense subsurface data using a station spacing of  $\sim 50$  km (Hetényi et al., 2018b). As part of this initiative, the further refined SWATH-D subnetwork with a spacing of  $\sim 15$  km (Heit et al., 2021) provided detailed insights into the Tauern Window, a  $\sim 40$  km-thick fault-bounded antiformal gneiss dome consisting of thrust imbricates of European-derived distal continental margin and oceanic crust surrounded by Adria-derived units (e.g., Lammerer et al., 2008; Ratschbacher et al., 1991a; Schmid et al., 2013). Complemented by simultaneous geologic efforts, these data facilitated and improved seismicity studies (e.g., Bagagli et al., 2022; Hofman et al., 2023; Mader et al., 2021; Petersen et al., 2021, 2025) and large-scale investigations on the lithospheric structure of the Alps, leading to a much more detailed picture of the crust and the mantle, including information on Moho depth and slab geometries attached to, or detached from, the Eurasian and Adriatic plates (e.g., Handy, 2025; Handy et al., 2021; McPhee & Handy, 2024; Mroczek et al., 2023; Paffrath et al., 2021).





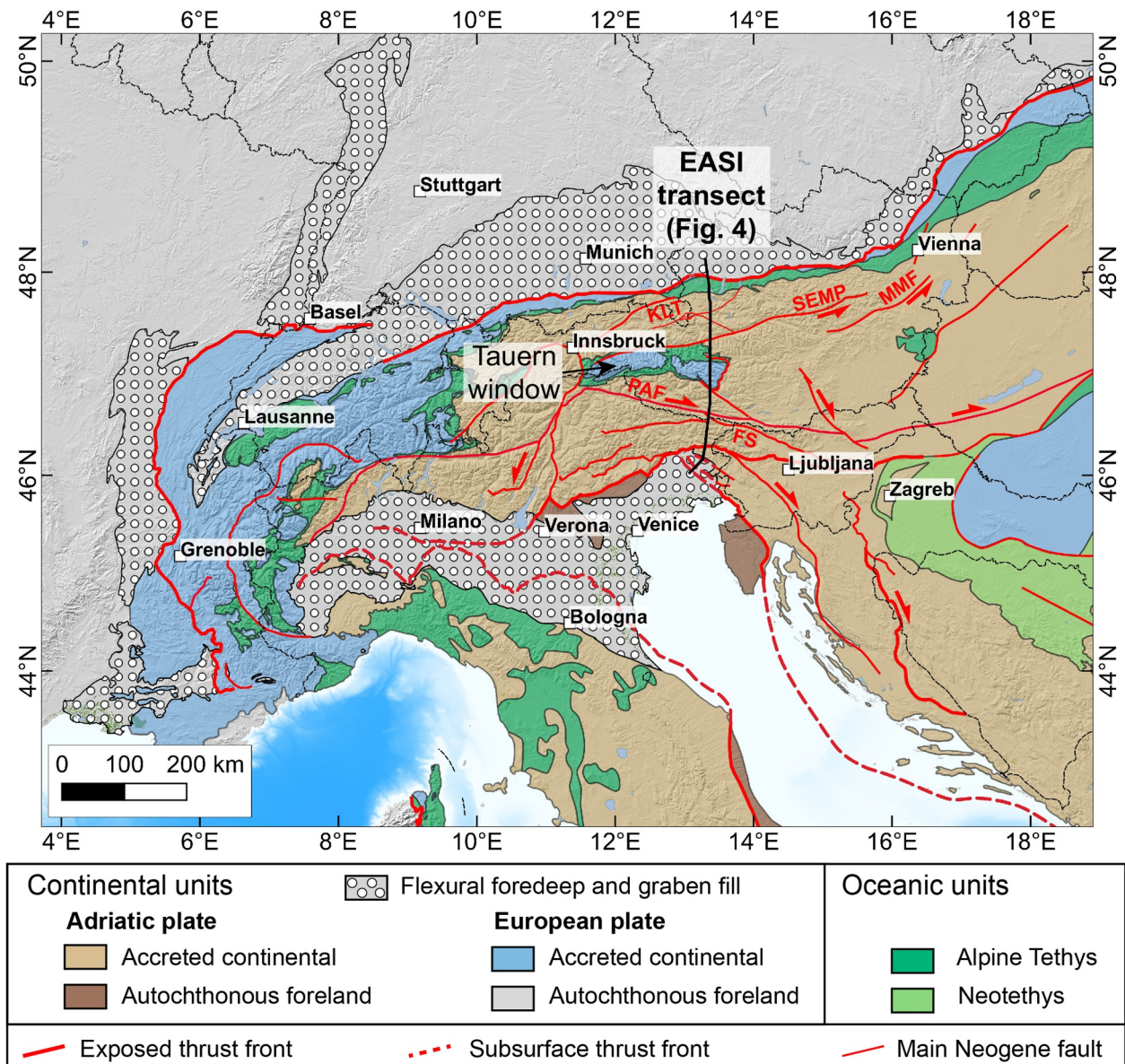
**Figure 1.** (a) Topographic overview of the Alps with active faults in red. Seismicity is from the EMEC catalog (1000–2021; Grünthal et al., 2013; Lammers et al., 2023; Stucchi et al., 2013). Active crustal fault sources are from the European Fault-Source Model EFSM2020 (Basili et al., 2022, 2024), the Northalpine Front and Periadriatic Fault are modified after Schmid et al. (2004, 2008). Inset: The Adriatic Plate rotates counterclockwise around an Euler pole in the Western Alps (schematic, after Nocquet & Calais, 2003; Serpelloni et al., 2022; Weber et al., 2010). Topography is based on SRTM1 data (NASA Shuttle Radar Topography Mission, 2013). (b) Hillshade map of the focus area, data as in (a), except KLT and LTF from Levi et al. (2022). BF, Brenner Fault; BV, Bassano-Valdobbiadene thrust system; FS, Fella-Sava Fault; GTB, Giudicarie Thrust Belt; HF, Hochstuhl Fault; IF, Idrija Fault; KF, Katschberg Fault; KLT, Königsee-Lammertal-Traunsee Fault; KM, Karawanke Mountains; LTF, Lammertal Fault; MF, Mölltal Fault; MTF, Montello Thrust Fault; NKT, Northern Karawanke Thrust; PF, Predjama Fault; PMT, Pozzuolo-Medea-Thrust; RF, Raša Fault; SF, Šoštanj Fault. The Periadriatic Fault System (PAF) is divided into IL, Insubric Line, GF, Giudicarie Fault, PGF, Pustertal-Gailtal Fault.



**Figure 2.** Overview of the temporal coverage of deformation processes and methods discussed in this paper and beyond. Upper panel shows the duration of elastic and permanent deformation in the lithosphere; middle panel shows the time coverage of most commonly used geochronological methods; lower panel shows spatial range (vertical scale) for the observations of structures and progressive processes with regard to temporal resolution of different methodological approaches.

These latest data sets and methodological developments call for a review of the active tectonics of the Eastern and Southern Alps in the upper crust. In this review paper, we discuss results from a variety of methods and observation time windows (Figure 2) to synthesize the present-day deformation of the crust. We achieve this by integration, cross-comparison, and evaluation of competing models using multiple evidence streams. The methods and data sets include space-based geodesy, recent seismicity, seismotectonics, seismic tomographic imaging, historical seismology and archeoseismology, on-fault and off-fault paleoseismology, and fault gouge dating. We explore whether the crustal deformation is linked to deep-seated processes, using the latest seismological results on the Alpine lithospheric and upper-mantle structure. We focus on the Eastern and eastern Southern Alps with two overarching questions: (i) Do current crustal deformation patterns reflect a mature orogen (in terms of tectonic strain rates becoming negligible) or a re-organization of convergence and orogenesis after slab break-off? (ii) How can we relate recent (1 Ma) deformation and ongoing uplift to long-term kinematics?



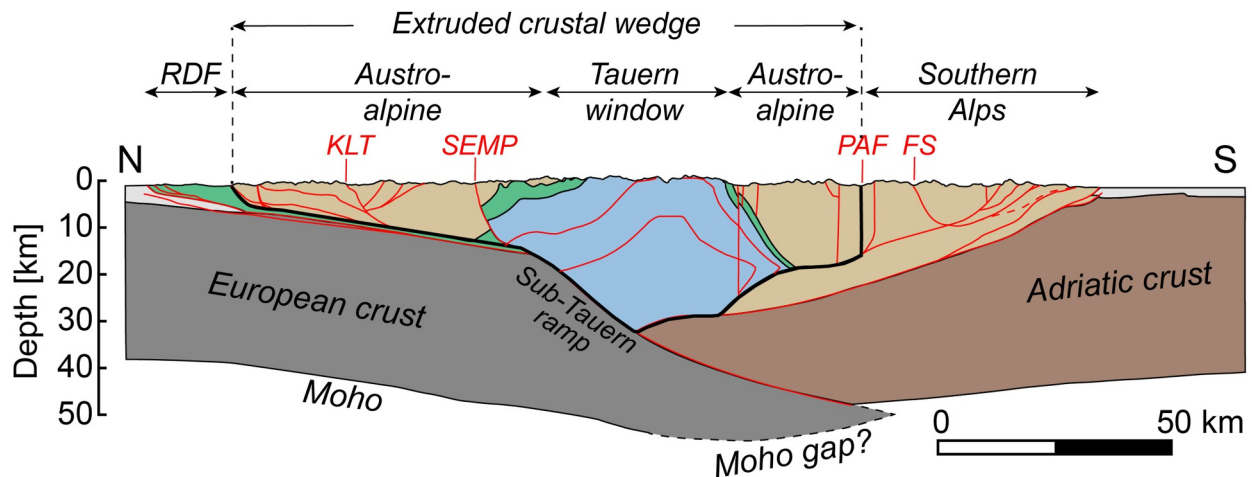


**Figure 3.** Tectonic map of the Alps, modified after the compilation by M.R. Handy with geological units and major faults simplified from Schmid et al. (2004, 2008), Handy et al. (2010, 2015), Bigi et al. (1990), Froitzheim et al. (1996), and Bousquet et al. (2012a). Black line marks the EASI Transect (Hetényi et al., 2018a). Faults and data as in Figure 1. Bathymetry is from GEBCO (2024). FS, Fella-Sava Fault; KLT, Königsee-Lammertal-Traunsee Fault; MMF, Mur-Mürz Fault; PAF, Periadriatic Fault System; SEMP, Salzach-Ennstal-Mariazell-Puchberg Fault.

## 2. Tectonic and Geologic Setting

### 2.1. Pre-Collisional Evolution of the Study Area

The European Alps are a topographically continuous orogen with an along-strike extent of c. 1,500 km (Figure 3) and formed due to the southward subduction and subsequent collision of the European plate and the Adriatic microplate, with the latter in an upper plate configuration. Subduction of European lithosphere commenced at c. 84 Ma and was initiated by a change in the plate motion of the Adriatic microplate with respect to Europe (e.g., Handy et al., 2010; Le Breton et al., 2021; Van Hinsbergen et al., 2020). Before that, the Adriatic microplate moved coherently with Africa toward the E with respect to Europe in conjunction with the opening of the Penninic Ocean (also called Alpine Tethys). Strictly speaking, back then the Adriatic microplate formed a northern promontory of the African Plate rather than an independently moving microplate (Channell et al., 1979; Le Breton



**Figure 4.** N-S-trending cross-section along the EASI transect at c. 13°E (see Figure 3), simplified after McPhee and Handy (2024). Faults and colors as in Figure 3. RDF, Rheno-Danubian Flysch.

et al., 2017). These E-ward plate motions of Africa and its Adriatic promontory before 84 Ma, linked to the opening of the Alpine Tethys, were coeval with the progressive closure of the Neotethys Ocean farther SE (Dercourt et al., 1986). The latter oceanic closure commenced already in the Middle to Late Jurassic and triggered shortening and orogenic processes in the NE part of the Adriatic Promontory that was to form the Austroalpine nappe stack (e.g., Gawlick & Missoni, 2019; Figure 4). However, these pre-Late Cretaceous plate tectonic events related to the closure of the Neotethys were limited to the Austroalpine realm but did affect neither the Alpine Tethys nor the European passive margin. For more details on this evolution, we refer to for example, Neubauer et al. (2000), Stüwe and Schuster (2010), and Kurz et al. (2024).

The Alpine Tethys formed a narrow and slowly spreading oceanic seaway connecting the later Alpine realm with the Iberian and Carpathian areas toward W and E, respectively (Frisch, 1979; Le Breton et al., 2021). Its opening was kinematically related to spreading of the Central Atlantic (Müller et al., 2019; Van Hinsbergen et al., 2020) and may be regarded as a failed rift of the Atlantic Ocean (N.B. hence the alternative name “Alpine Atlantic” coined by Gawlick and Missoni (2019) to denote the genetic link between the Alpine Tethys and the Atlantic). The Alpine Tethys comprised the domains of the paleogeographically more southerly Piemont-Liguria Ocean and the northerly Valais Basin, separated by the Briançonnais continental domain. An oceanic spreading stage was only reached in the Piemont-Liguria Ocean. By contrast, the Valais Basin very likely represented a hyper-extended rifted continental margin between the European and Adriatic plates (e.g., Beltrando et al., 2012). For a prolonged time between c. 84 and 47 Ma, the southward subduction of the Alpine Tethys below the northward advancing Adriatic Plate involved subsequently the subduction of the Piemont-Liguria Ocean, the Briançonnais continental domain, and eventually also the Valais Basin. This subduction gave rise to numerous occurrences of blueschist- and eclogite-facies rocks along-strike the entire Alps (e.g., Agard & Handy, 2021; Bousquet et al., 2012b; Manzotti & Ballèvre, 2024).

## 2.2. Collisional Evolution of the Study Area

The distal European passive margin began entering subduction below Adria-derived units by about 47 Ma, that is, in the Middle Eocene. This is documented by the stratigraphic minimum ages of turbiditic deposits in the structurally uppermost Europe-derived (Ultrahelvetetic) units both in the Engadine Window (Oberhauser, 1983) and in the easternmost Eastern Alps (Gresten Nappe, e.g., Decker & Peresson, 1996; Prey, 1980). Subduction of the European distal margin is also documented by its eclogite-facies overprint in the SE Tauern Window between about 45 and 33 Ma (e.g., Kurz et al., 1999; Nagel et al., 2013; Ratschbacher et al., 2004). The estimates for the overall (post)-collisional shortening accommodated due to the Europe-Adria convergence on the scale of the entire Alps since about the Middle Eocene amount to between 90 and 260 km (Le Breton et al., 2021; Rosenberg et al., 2021; Schmid & Kissling, 2000; Schmid et al., 1996). In the Western and Central Alps this shortening was responsible for the accretion of the External Massifs, the Dauphinois/Helvetic domain and, as a latest stage, the

accretion of the externalmost Jura fold-and-thrust belt between c. 12 and 5 Ma (Becker, 2000). Its frontal thrust straddles the margins of the eastern Bresse Graben and southern Upper Rhine Graben, hosting evidence for post-Late Pliocene tectonics (e.g., Giamboni et al., 2004; Madritsch et al., 2008; Ustaszewski & Schmid, 2007). In the Eastern Alps, collisional shortening was mainly accommodated between about 55 and c. 15 Ma (Beidinger & Decker, 2014). Part of this shortening led to N-directed thrusting of the Austroalpine units first onto the Penninic units derived from the Alpine Tethys, subsequently onto the extended European passive margin, and finally onto the northern flexural foreland basin (Molasse Basin) until about 17 Ma (Linzer et al., 2002). A major part of shortening, however, was accommodated within the Tauern Window (rather than by continued frontal accretion of European foreland crust, such as in the Central and Western Alps; see above; McPhee & Handy, 2024).

The Tauern Window presently forms an E-W-trending antiformal dome exposing European basement and cover, rimmed by Penninic units that are in turn overlain by Austroalpine units (Figures 3 and 4). Its formation first involved basal accretion of distal European margin units below the Austroalpine units and their stacking into several basement-cover nappes forming a crustal-scale duplex structure during the Oligocene (Lammerer & Weger, 1998; Figures 3 and 4). This was followed by antiformal doming of the duplex into a crustal-scale antiform during the Early to Middle Miocene. Unroofing of the antiform dome was facilitated by temporally coeval E-W extension along two N-S striking low-angle shear zones along the western and eastern end of the Tauern Window, respectively, the Brenner and Katschberg Faults (e.g., Fügenschuh et al., 1997; Genser & Neubauer, 1989; Rosenberg & Garcia, 2011; Scharf et al., 2013; Wolff et al., 2024). The orogen-internal shortening leading to the Tauern Window updoming (Figure 4; Frisch et al., 1998, 2000) was also coeval with late-stage frontal accretion in the easternmost Austroalpine units (Beidinger & Decker, 2014). Overall, the Tauern Window updoming was triggered by the E-ward extrusion of the orogenic crust into the simultaneously opening Pannonian Basin, facilitated by E-ward retreating subduction of European lithosphere in the Carpathians (Decker & Peresson, 1996; Ratschbacher et al., 1991a). Within the Eastern Alps, this E-ward lateral extrusion was largely accommodated by an array of c. NE-SW-striking sinistral and NW-SE-to W-E striking strike-slip faults (Figure 3). These faults (such as the sinistral Salzach-Ennstal-Mariazell-Puchberg Fault [SEMP] or the dextral Lavanttal (Labot) Fault) took up an estimated 160 km of E-W extension between about 22 and 12 Ma (Frisch et al., 1998; Linzer et al., 2002; Ustaszewski et al., 2008). The E-ward extruding Austroalpine units were confined southwards by the Periadriatic Fault System (PAF). An overall length of about 700 km along-strike with dominantly dextral displacement amounting to at least 150 km renders the PAF one of the largest fault systems of the Alps (e.g., Handy et al., 2015), which formed in response to the NW motion and counterclockwise rotation of the Adriatic plate with respect to Europe (inset in Figure 1).

Finally, next to foreland-directed thrusting and E-ward directed lateral extrusion, another part of collisional shortening due to N-S convergence of Europe and Adria was partitioned into S-directed thrusting in the Southern Alps. Tectonically, the Southern Alps constitute the deformed Adriatic crust south of the PAF (Figures 1 and 3). The onset of S-directed thrusting in the Southern Alps was not contemporaneous along their strike. West of the NNE-SSW-trending sinistral Giudicarie Fault (separating the otherwise E-W-trending dextral Insubric and Pustertal-Gaital segments of the PAF by about 70 km; e.g., Pomella et al., 2012), for instance in the Orobic Alps, Late Cretaceous contraction was reported (e.g., Zanchetta et al., 2015). East of the Giudicarie Fault, however (and more in the area focused on in this study), shortening in the Southern Alps was mostly accommodated by S-directed thrusting since about 28 Ma (Schönborn, 1992, 1999; Verwater et al., 2021). Within the eastern Southern Alps, the domain of the so-called “Dolomite Indenter” (a colloquial term referring to the basement carrying the Upper Permian to Mesozoic, dominantly carbonatic succession of the Dolomites) remained internally rather weakly deformed (e.g., Sieberer et al., 2023) in comparison to the offset along the adjacent Insubric Line and the Giudicarie Fault (Ratschbacher et al., 1991a, 1991b; Rosenberg et al., 2007) as well as the northerly and westerly adjacent Austroalpine units. A possible explanation for the weak internal deformation of the “Dolomite Indenter” since c. 28 Ma and its relatively “stiff” behavior compared with the strongly deformed Austroalpine and Penninic units farther north is the presence of a voluminous Lower Permian magmatic suite underlying the Permo-Mesozoic sedimentary succession and (just like the pre-Permian basement itself) lack of Alpine metamorphism (Bousquet et al., 2012b). This magmatic suite consists of both shallowly emplaced plutonic rocks (e.g., the Brixen/Bressanone pluton; e.g., Visoná et al., 2022) and an at least 2.5 km thick volcanic/volcaniclastic succession (“Athesian Volcanic Group,” Marocchi et al., 2008; Morelli et al., 2007, 2012).

The arrival of increasing amounts of positively buoyant continental lithosphere in the subduction zone since c. 35 Ma was critical for the further overall evolution of the Alps in terms of their topographic expression. An



important proxy hinting at the topographic evolution of the Alps is its erosional sedimentary record found in both the northern and southern Alpine flexural foredeeps (Figure 3). Paleobathymetry and sedimentological studies from the northern Alpine flexural foredeep, the Molasse Basin, suggest a gradual topographic development of the orogen since 35 Ma (Kuhlemann et al., 2002; Schlunegger & Kissling, 2015). However, as will be shown in the next section, an increasing number of seismic tomographic studies, aimed at imaging the configurations of subducted slabs underneath the Alps, suggest that postcollisional reorganizations of the slabs might also have exerted an important control on the topographic evolution of the Alps.

### 2.3. Slab Configuration Beneath the Alps

A long-standing debate concerns the configuration of the subducted slabs beneath the Alps and touches upon the question if recent tectonic activity is (partly) governed by mantle processes. The lack of abundant earthquakes at mantle depths in the Alps does not allow delineating slab geometries based on seismicity (e.g., Bagagli et al., 2022). While local earthquake tomography studies have greatly profited from the AlpArray initiative in terms of refined 3D velocity structures within the orogenic and foreland crust, the lack of mantle earthquakes renders those studies challenging for imaging deeper structures (e.g., Bagagli et al., 2025). Instead, tomographic methods using teleseismic arrivals were mainly used to image slab geometry. These methods measure seismic wave velocities, allowing to distinguish downgoing oceanic and continental crust and mantle from the surrounding mantle. Different methods lead to tomographic models with varying resolution at depth, among other constraints, and therefore, give room to different interpretations. The major debates concern the subduction direction (Europe under Adria, Adria under Europe, or a combination of both) and if the slabs are continuous or at least partly detached.

#### 2.3.1. Subduction Polarity

Lippitsch et al. (2003) proposed a south-dipping European slab in the Western Alps and in the center of the orogen, and a northward-dipping Adriatic slab in the Eastern Alps based on teleseismic tomography. This configuration would require a change in present-day subduction polarity between the Western and the Eastern Alps and, consequently, a slab break-off event in the eastern part of the orogen to allow for the subduction of Adriatic crust. Luth et al. (2013) used analogue modeling to point out that the present-day topography of the Alps could be explained with a switch in subduction polarity. Most other studies, however, showed no Adriatic slab in the Eastern Alps (e.g., Mitterbauer et al., 2011). Brückl et al. (2010) used elastic plate modeling, seismicity, geodesy, and the results from controlled seismic source experiments to propose a geometry for the Adria-Europe-Pannonian triple junction, arguing that their data imply a subduction of European lithosphere instead of a subduction polarity switch. Similarly, no evidence for a reversal of subduction direction was found along the N-S trending TRANSALP profile at about 12°E longitude (Castellarin et al., 2006; TRANSALP Working Group, 2002), where the Moho topography imaged by wide-angle seismic tomography (Bleibinhaus & Gebrande, 2006) and by receiver functions (Kummerow et al., 2004) suggests a south-dipping subduction. Handy et al. (2021) propose that the slight northward dip of the European slab in the Eastern Alps is a result of partial overturning (also see the discussion in Paul, 2024).

#### 2.3.2. Slab Continuity

Lippitsch et al. (2003) suggested a slab break-off beneath the Western Alps because of a gap in the P-wave fast velocity anomaly delineating the European slab. A slab break-off in the Western Alps could explain the rock exhumation history there (e.g., Fox et al., 2015) and the occurrence of magmatic intrusions, for example, along the PAF in the Eo-Oligocene (von Blanckenburg & Davies, 1995; Rosenberg, 2004). Subsequent studies did not confirm the slab gap beneath the Western Alps (e.g., Koulakov et al., 2009; Zhao et al., 2016), but Kästle et al. (2018) also interpret a slab break-off there at depths greater than 100 km based on surface-wave tomography models. Paffrath et al. (2021) imaged a fully detached slab beneath the Eastern Alps not necessarily of Adriatic origin. Based on tomography data and geological arguments on the amount of total post-collisional shortening, Handy et al. (2021) conclude that the European slab is partially detached in the Western Alps and in the central part of the orogen and fully detached in the Eastern Alps. Slab detachment in the Eastern Alps at around 20 Ma explains both Miocene and later uplift of the Eastern Alps and the filling and inversion of the Molasse Basin (Handy, 2025; Handy et al., 2021; Schlunegger & Kissling, 2022). The lack of a complete slab break-off in the central part of the Alps necessitates another mechanism for the Oligocene magmatism there, perhaps due to the

ascent of fluids from the downgoing slab through a relatively colder and heterogeneous mantle wedge (Handy, 2025; Müntener et al., 2021).

We refer to the comprehensive reviews by Kissling (1993) and Paul (2024) for details on the history of slab research in the Alps and the peculiarities of the employed methods.

### 3. Recent Deformation of the Alpine Crust

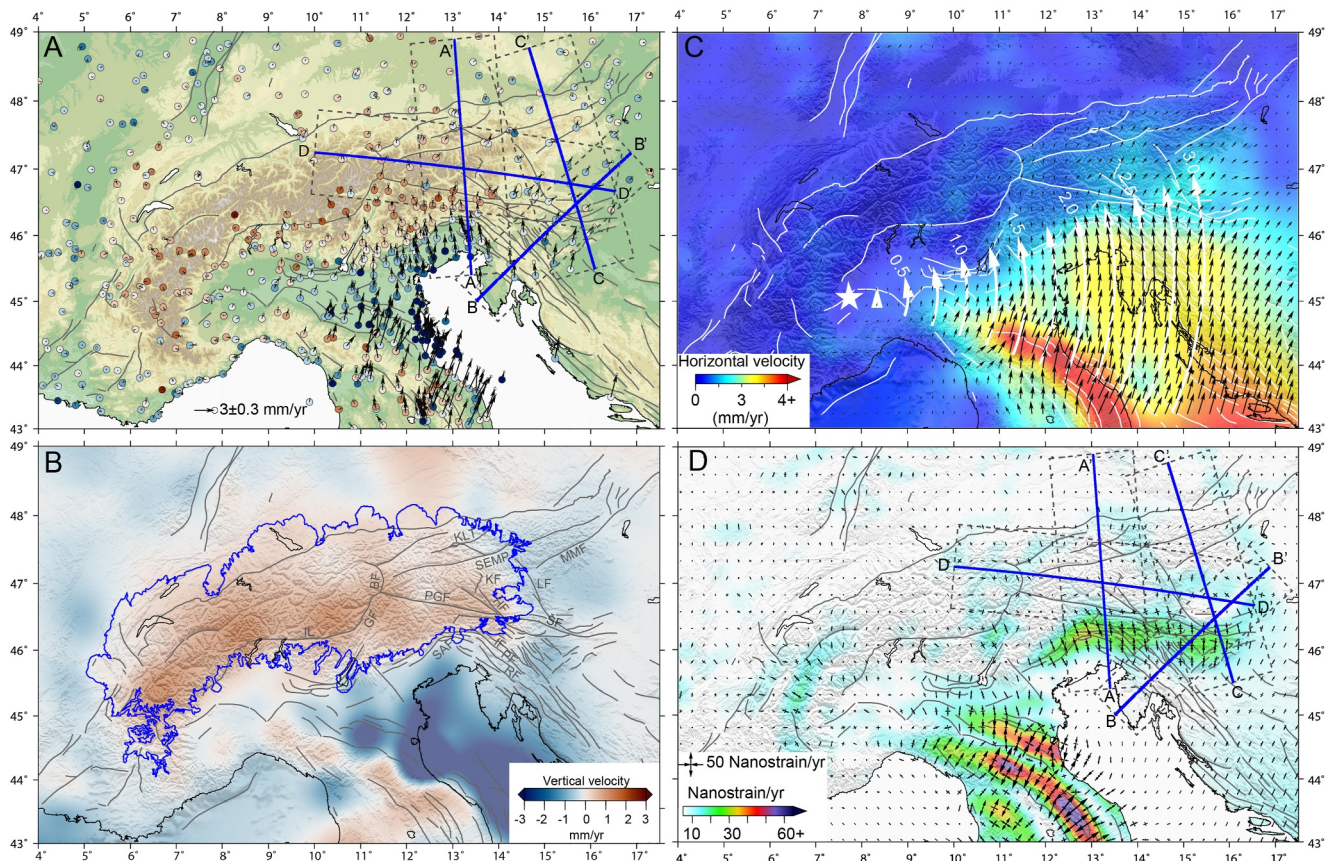
In this section we discuss the available data on the recent deformation of the crust in the eastern part of the Alps, sorted by methods, going from short to long observation timescales (Figure 2). A georeferenced poster map with most of the data discussed here is provided in Grützner et al. (2026).

#### 3.1. Geodetic Data

Since the 1990s, space-based geodesy has significantly advanced the understanding of the European Alps' kinematics. The first Global Navigation Satellite System (GNSS) observations constrained horizontal motions of tectonic units like the Dolomite Indenter (e.g., Battaglia et al., 2004; Calais et al., 2002; Nocquet & Calais, 2003) and the Eastern Alps' eastward extrusion (Caporali et al., 2013; Grenerczy et al., 2000; Reiter et al., 2005). Denser, continuous GNSS networks across specific fault zones in the early 2000s helped determine geodetic fault slip rates, which are key input for estimating the strain energy stored in seismogenic faults (e.g., D'Agostino et al., 2005). Decade-long time-series and advanced analyses revealed significant uplift in the Western Alps (e.g., Nocquet et al., 2016; Pintori et al., 2022; Serpelloni et al., 2013; Walpersdorf et al., 2015) due to glacial rebound, slab/mantle dynamics, and isostatic adjustment to erosion (e.g., Champagnac et al., 2007, 2009; Chéry et al., 2016; Mey et al., 2016; Norton & Hampel, 2010; Sternai et al., 2019).

Today's GNSS time-series provide crustal motion rates showing subtle horizontal and vertical deformation in the Swiss Alpine foreland and Jura Mountains (e.g., Houlié et al., 2018), the Rhine Graben and the South German Molasse Basin (e.g., Pintori et al., 2022; Serpelloni et al., 2022) with sub-millimeter precision. The geodetic rates record vertical and horizontal motion of first-order tectonic units (Figure 1a). Leveling measurements that have been collected for up to 100 years provide relative precisions comparable to GNSS (see Fuhrmann et al., 2013, for the Upper Rhine Graben, Rižnar et al., 2005; Anderlini et al., 2020, for the eastern Southern Alps, or Jouanne et al., 1995, for the Western Alps). The European Ground Motion Service (EGMS, 2025) regularly publishes radar interferometric (InSAR) surface motion maps based on the last 4 years of data collection (Crosetto et al., 2020, 2021). These maps reliably identify local instabilities and are most sensitive to deformation in the E-W and vertical directions. Individually processed InSAR rate maps, usually tied to the regional GNSS velocity field, document vertical motion, for example, in the Western Alps (Mathey et al., 2022) or in the Po Plain and the Southern Alps (Areggi et al., 2023).

The most striking feature of today's vertical GNSS velocity field (Figure 5a; Serpelloni et al., 2022) is the belt of uplift running along the Alpine chain that spatially correlates with topography (Pintori et al., 2022) and the Last Glacial Maximum ice extent (Figure 5b). Maximum uplift rates of 2.0–2.5 mm/yr are concentrated in the Western and Central Alps; lower rates of ~1 mm/yr characterize the region extending from the Eastern Alps to the southern Western Alps. Sternai et al. (2019) highlight the complexity in understanding the mechanisms underlying Alpine uplift. While some models suggest the orogenic root is in isostatic equilibrium (Burov et al., 1999), gravimetric data suggest that the crustal root in the Central-Eastern Alps lacks the buoyancy required to support current uplift (Steinhauser, 1991). Consequently, observed denudation rates (Brocard et al., 2003; Hinderer et al., 2010; Wittmann et al., 2007) would cause less uplift than measured by GNSS (Champagnac et al., 2009). Thus, the uplift likely results from a combination of slab processes, isostatic response to denudation/erosion (Kuhlemann et al., 2002), glacial rebound from deglaciation (Chéry et al., 2016; Mey et al., 2016; Norton & Hampel, 2010), and active thrusting (Anderlini et al., 2020), of which deglaciation and slab/mantle processes possibly dominate (Sternai et al., 2019). In the Eastern Alps, Sternai et al. (2019) suggest that isostatic adjustments from deglaciation and erosion could account for most of the observed uplift. This implies that horizontal shortening and crustal thickening might play a lesser role here. A recent modeling study by Linsalata et al. (2026), however, suggests that today's influence of glacial isostatic adjustment on horizontal deformation is marginal. Conversely, in the Central and Western Alps, surface processes likely explain about half of the uplift, indicating that mantle-related processes, such as slab detachment or asthenospheric upwelling, may also be significant contributors (Sternai et al., 2019).



**Figure 5.** (a) Horizontal (black arrows, Eurasian-fixed reference frame) and vertical (colored circles) GNSS velocities from Serpelloni et al. (2022). Blue lines and dashed boxes mark profiles and their swath widths shown in Figure 6; (b) Continuous vertical velocity field, where the blue line delineates the Last Glacial Maximum ice extent in the Alps (Ehlers et al., 2011); (c) Continuous horizontal velocity field, with colors indicating magnitude and black arrows representing gridded velocity vectors. The Adria-Eurasia rotation pole from Serpelloni et al. (2016) is marked by the white star, with white arrows illustrating the Adria-Eurasia small circles (equal velocity lines) and white numbers denoting velocities in mm/yr; (d) Strain rate map with colors showing scalar values (see Serpelloni et al., 2022) and black arrows indicating the principal axes of maximum compression/extension. In all four panels, topography and faults are as in Figure 1a.

Maximum northward motion of  $\sim 2.5$  mm/yr is measured south of the foothills of the eastern Southalpine Front into Slovenia (Figure 5c). This advance rapidly decays across the front, leading to horizontal strain rates of up to 35 nstrain/yr, with NNW-SSE oriented principal axes as also evidenced by large historical earthquakes (Figure 5d). At second order, 10–25 nstrain/yr are measured along an arcuate extensional belt in the Western Alps accompanied by maximum uplift. The main driver for horizontal tectonic deformation in the Alps are undoubtedly the dynamics of the Adriatic plate, a promontory of the African continent, confined by the Apennines in the west, the Dinarides in the east, and the Southern Alps in the north. Early GNSS works from Calais et al. (2002), Nocquet and Calais (2003), and Serpelloni et al. (2005) showed that—with respect to Eurasia—the Adriatic plate rotates counterclockwise around a pole located in the western Po Plain (illustrated by small circle trajectories in Figure 5c) and is thrust underneath the Southern Alps. This confirmed Anderson and Jackson's (1987) analysis of earthquake fault plane solutions. However, different Euler pole solutions exist, depending on the data used (Battaglia et al., 2004; D'Agostino et al., 2008; Nocquet & Calais, 2003; Serpelloni et al., 2005, 2016). The actual kinematics of Adria have been further refined by splitting up the microplate in a northwestern Adriatic and a southeastern Apulian unit, connected with a hinge at the eastern Adriatic coast between Split and Dubrovnik (e.g., D'Agostino et al., 2008; Mastrolembo et al., 2014; Métois et al., 2015).

To better understand the seismic potential of the eastern Southalpine Front and surrounding faults, several analytical models constrain kinematic parameters such as fault geometry, fault slip rate, and the degree of coupling (e.g., Anderlini et al., 2020; Barba et al., 2013; Cheloni et al., 2014; Serpelloni et al., 2016). The models usually assume a simplified thrust geometry with a northward dip between  $10^\circ$  and  $50^\circ$  constrained by



instrumental earthquakes and structural information (e.g., European Database of Seismogenic Faults EDSF13 and European Fault Source Model EFSM20: Basili et al., 2013, 2022; DISS Working Group, 2025). These models have shown that the Southalpine Front accommodates most of the deformation and accumulates a seismic moment of  $1.3 \pm 0.4 \times 10^{17}$  Nm/yr, equal to a M7.5 earthquake, if rupturing every 1000 years (Cheloni et al., 2014). Serpelloni et al. (2016) generated an elastic block model for the whole Eastern Alps including several intra-orogenic faults to also account for eastward motion toward the Pannonian Basin and suggested  $1.2\text{--}1.5 \pm 0.1$  mm/yr of dip-slip and less than 1 mm/yr of shear along the Southalpine Front. Another 1.4 mm/yr of shear is accommodated by the Fella-Sava Fault, while the PGF only plays a minor role. Anderlini et al. (2020) confirm that, with  $\sim 2.5$  mm/yr, the Montello and Bassano-Valdobbiadene Thrusts (see locations in Figure 1) take up most of the NS-shortening along the Southalpine Front. Farther east, the Friuli segment (where the 1976,  $M_W$  6.5 Friuli earthquake occurred) is thought to accommodate 2.1 mm/yr of slip (D'Agostino et al., 2005). Bechtold et al. (2009) performed a 3D-crustal reconstruction to compare GNSS velocities with structural data to better understand the interaction of the Southalpine Front and the (sub-parallel) strike-slip faults farther east in the Dinarides. We discuss individual geodesy-derived fault slip rates in detail in Section 4.

The Western Alps are less affected by the Adria rotation due to their proximity to the rotation pole (Figure 5c). The observed  $\sim 10\text{--}20$  nstrain/yr caused by NW-SE-extension and up to  $\sim 2$  mm/yr of uplift (Figures 5b and 5d; e.g., Nocquet et al., 2016; Serpelloni et al., 2016; Walpersdorf et al., 2015) are confirmed by InSAR (Matthey et al., 2020), seismotectonic data (Kastrup et al., 2004), and fault-slip analyses (Bertrand & Sue, 2017; Champagnac et al., 2003, 2004). The deformation signals likely result from deep-seated buoyancy forces (e.g., Nocquet et al., 2016; Walpersdorf et al., 2015). If glacial isostatic adjustment is accounted for, the rock-uplift rates exceed erosion rates (Nocquet et al., 2016).

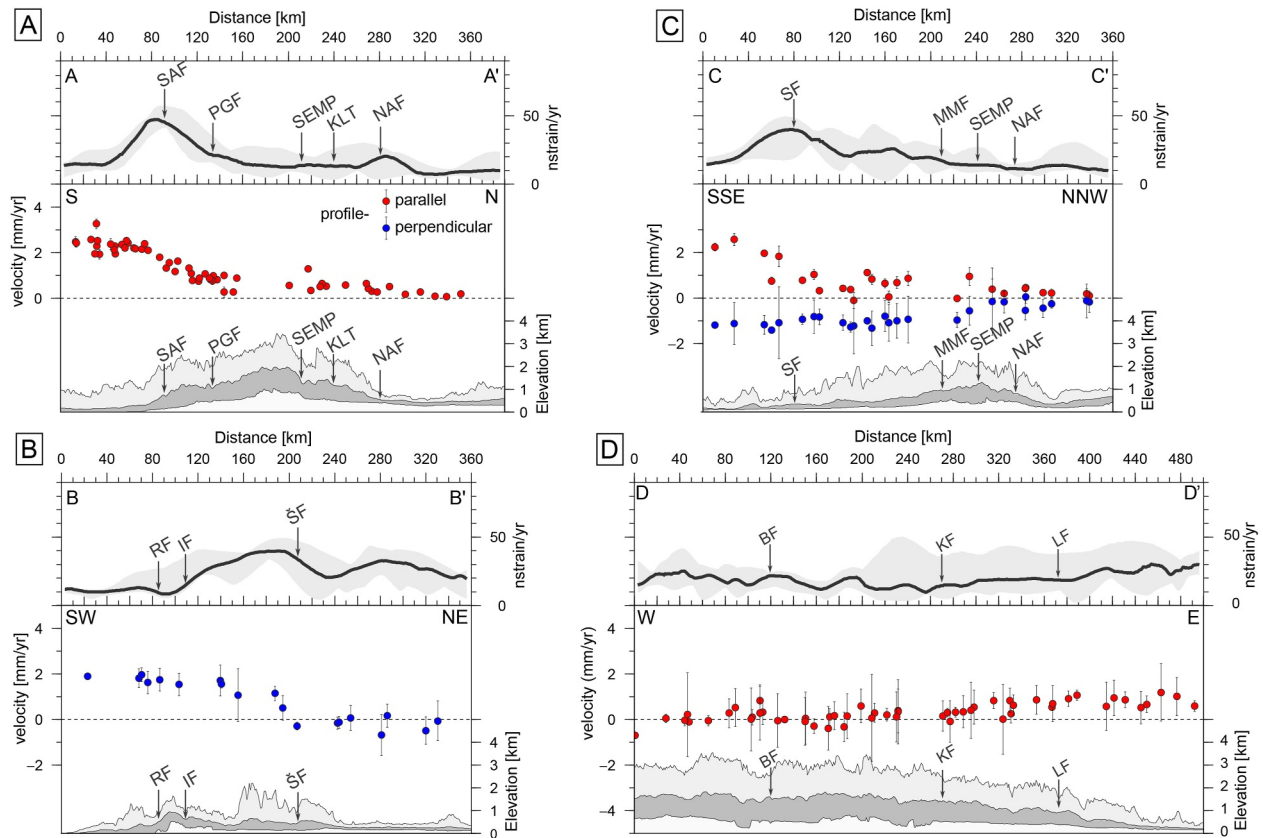
In the northern and western Pannonian Basin, which appear coupled with Eurasia, the Dinarides accommodate the majority of the Adria-Europe collision (Grenerczy et al., 2005). While some studies suggest a high degree of aseismic strain distribution in the thin, high-heat-flow lithosphere of the Pannonian Basin (Bus et al., 2009), others point to significant seismic slip deficits along major structures like the Mur-Mürz and Vienna Basin faults (Hinsch & Decker, 2003, 2010). This suggests that while strain is distributed, these faults may be seismically coupled and capable of generating larger events than those recorded in historical catalogs. Vrabec et al. (2006) filled the gap of geodetic observations on the Istria Peninsula and showed that motion of the peninsula can also be described with Adriatic microplate rotation (to the first order).

Adria's northward movement relative to stable Eurasia decreases from approximately 2.5 mm/yr to 1 mm/yr over a distance of  $\sim 80$  km (between 40 and 120 km along profile A-A', Figure 6a), primarily across the Southern Alpine Front, offering the highest strain-rate values of the Alps (Figures 5d and 6a). Across the Southalpine Front and the PGF, most of the N-advance of the crust diminishes, leading to minimal intra-orogen deformation. However, a residual N-S shortening of about 0.8 mm/yr is accommodated along the northern Alpine thrust front, creating a smaller zone of increased strain (Figure 6a). This geodetically observed shortening is consistent with geological evidence of Quaternary activity along the northern front, as first characterized by the offset of Quaternary terraces (Van Husen, 1971, 1975). More recent studies in the Eastern Alps further support this distributed deformation, suggesting that the northern fringe of the orogen remains tectonically active (Levi et al., 2021).

North of the PGF, GNSS rates indicate  $\sim 1$  mm/yr eastward deflection (Figure 5b), suggesting either lateral locking on the PGF, or lateral extrusion away from the Central Alps' topographic high (e.g., Métois et al., 2015; Ratschbacher et al., 1991a). Reiter et al. (2005) report minor ongoing E-W extension on the Brenner normal fault (BF) and related motion on the Inntal system, on which Serpelloni et al. (2022) is somewhat inconclusive (Figure 6d). A steady increase of the eastward velocity (1 mm/yr) from the northern Central to the Eastern Alps, specifically east of  $13^\circ\text{E}$  (at approximately km 280 in Figure 6d) is evident.

The relatively high compressional strain rates at the Southalpine Front continue to the east, in Slovenia, along an E-W oriented belt of  $20\text{--}30$  nstrain/yr (Figure 5d). Approximately 1.8 mm/yr of shortening is primarily observed across the Sava Folds, and roughly 1 mm/yr of left-lateral movement along the Mur-Mürz and the SEMP Fault (Figure 6c). Between the Dinaric Idrija and Šoštanj strike-slip faults that fork toward SE from the Alpine compressional belt, about 2 mm/yr of right-lateral shear is distributed in a broad region (Figure 6b).

With regard to the two overarching questions formulated in the introduction, the review of geodetic data implies little internal deformation of the Alps. Orogen-wide uplift—mostly driven by post-glacial rebound—slightly



**Figure 6.** Profile-parallel (red) and -normal (blue) velocities of Serpelloni et al. (2022) along  $\pm 70$  km wide cross sections (a–d) outlined in Figure 5a. GNSS velocity components are marked by circles and  $1\sigma$ -uncertainty bars. The top panel of each subfigure displays the median (in black), minimum and maximum (in gray) scalar strain-rates, the bottom panel minimum, median, and maximum elevation in white, dark gray, and light gray. Fault abbreviations as in Figure 5a.

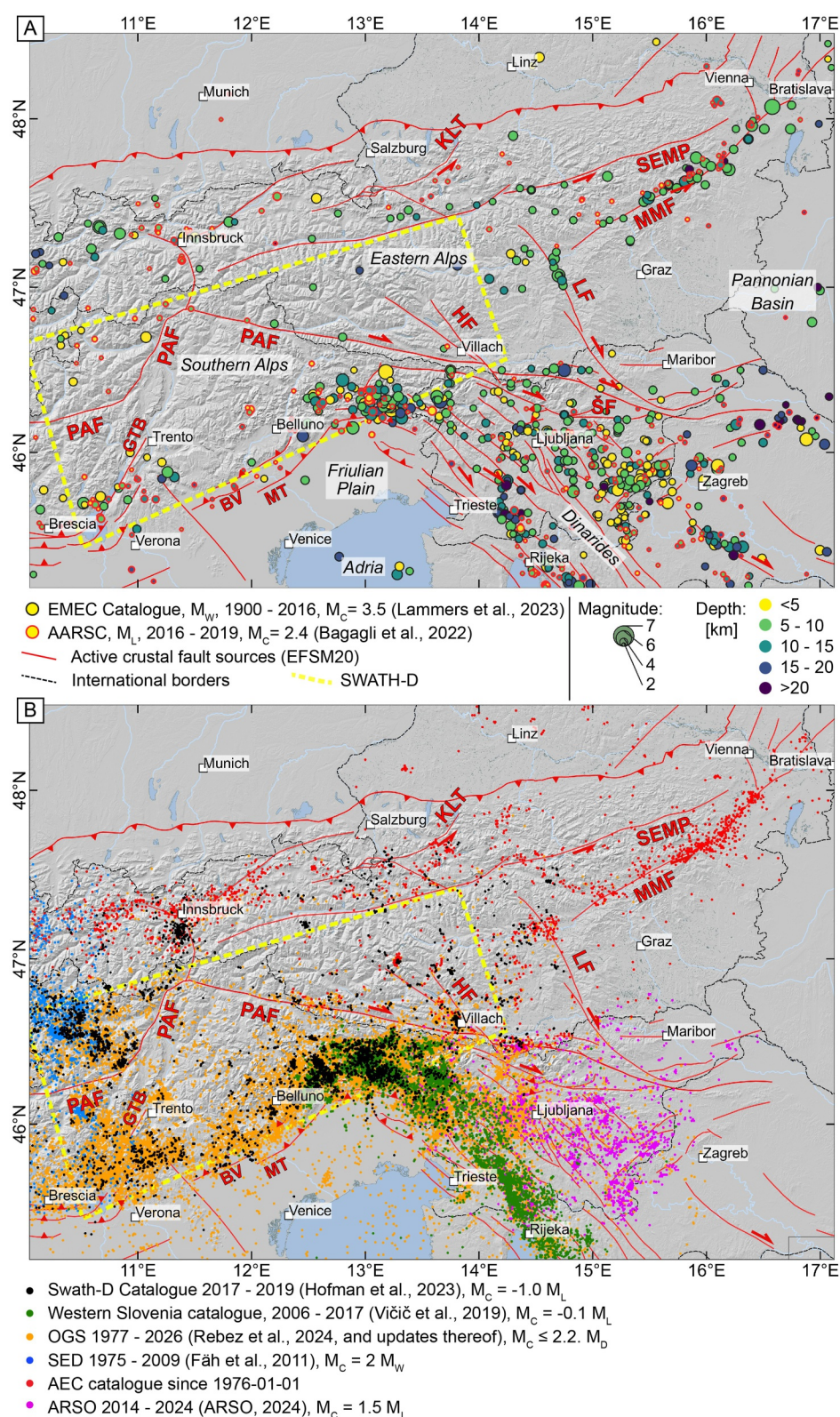
dominates over N–S shortening accommodated along the southern and—to a lesser order—northern margin of the Alps, and eastward escape between the PGF and the NAF. The comparably low horizontal rates suggest a rather mature orogen instead of a re-organization of convergence and orogenesis (Question I). The present-day deformation pattern largely reflects that of the Neogene to Recent evolution of the Alps discussed in Section 2, but at a much slower pace (Question II).

### 3.2. Recorded Seismicity

#### 3.2.1. Spatial Pattern of Seismicity

The present-day seismic activity in the SE Alps is routinely monitored by the national institutes in the region, namely the Swiss Seismological Service (SED), GeoSphere Austria, the Slovenian Environment Agency (ARSO), the National Institute of Oceanography and Applied Geophysics (OGS; Italy), and the National Institute of Geophysics and Volcanology (INGV; Italy). Further, regional to global earthquake catalogs provide insights in the area's seismicity and rupture mechanisms, that is, EM-RCMT (European-Mediterranean Regional Centroid-Moment Tensors; Pondrelli, 2002; Pondrelli et al., 2002), GEOFON (Quinteros et al., 2021), and GCMT (Global Centroid Moment Tensor Project; Dziewoński et al., 1981; Ekström et al., 2012). The bulletins of the different agencies are rather heterogeneous with respect to their time spans, magnitudes of completeness ( $M_C$ ), and the methods applied for earthquake detection, location, and focal mechanisms/moment tensors. Within the framework of the AlpArray project, homogeneous high-quality seismicity catalogs were derived for the first time for the full Alpine area (Bagagli et al., 2022; time range 2015–2019) as well as for the more densely monitored Southern and Eastern Alps (Hofman et al., 2023, 2017–2019). Vičič et al. (2019) published a catalog of relocated earthquakes for western Slovenia for the time span 2006–2017. In Figure 7a, we show a combination of two regional catalogs covering the entire instrumental period and the whole study area. The EMEC—The European-





**Figure 7.** Instrumental seismicity in the Eastern and Southern Alps. See legend for temporal coverage and magnitudes of completeness,  $M_C$ . Faults and topography data as in Figure 1b. (a) Instrumental seismicity from two regional catalogs covering the entire study area, color coded by depth. Symbol size is proportional to magnitude. (b) Instrumental seismicity from different local catalogs. Note the heterogeneous temporal coverage and varying  $M_C$ .



Mediterranean Earthquake Catalog (Lammers et al., 2023) is based on the SHEEC catalog (Grünthal & Wahlström, 2012) but extended beyond 2006. It has a magnitude of completeness of 3.5 and we plotted it for the years 1900–2016. For the years 2016–2019 we plotted the Alp Array Research Seismicity Catalog (AARSC) by Bagagli et al. (2022) with a  $M_C$  of 2.4.

In Figure 7b we compile different regional catalogs with varying temporal and spatial coverage. While the more homogeneous catalog in Figure 7a reflects the long-term distribution of seismicity, the collection of various catalogs in Figure 7b serves as an overview of available seismicity catalogs including smaller events as a reference for localized studies. The OGS catalog covers NE Italy and adjacent regions since 1977 with a temporarily variable  $M_C$  of no more than 2.2 (Rebez et al., 2024; Sandron et al., 2023). Switzerland is in the focus of the SED catalog with  $M_C = 2$  (Fäh et al., 2011). Here we show only those seismic events younger than 1975 that are listed as earthquakes and whose source is SED. For Slovenia, the ARSO bulletins contain events with  $M_C = 1.5 M_I$  for the years 2014–2024 (ARSO, 2024) covering the entire country, and Vičič et al. (2019) published relocated events from 2006 to 2017 for western Slovenia with  $M_C = -0.1$ . The SWATH-D experiment resulted in a local catalog with a  $M_C$  of  $-1.0$  (Hofman et al., 2023). The Austrian Earthquake Catalog (AEC, 2026) catalog includes all recorded earthquakes since the year 1000 and with  $M_L 2.0$ . While the determination of epicenters relied on macroseismic data for most of the 20th century, the instrumental location procedure reached an accuracy of  $\pm 5$  km after the 1976 Friaul Earthquake due to an increase in seismic stations. A magnitude of completeness cannot be easily determined for this catalog because of the long time-coverage and the variation of data quality. For the purpose of informing about instrumental seismicity, we plot all earthquakes in the catalog from 1976-01-01 to 2026-03-11 (Figure 7).

The seismic activity across the Alps recorded in long-term ( $\sim 50$  years) catalogs from local/regional observatories as well as short-term (few years) high-quality catalogs (Bagagli et al., 2022; Hofman et al., 2023) can be described as low to moderate compared to other plate convergence/subduction zones. Larger, damaging earthquakes occur only every tens to hundreds of years and are limited to a few regions (Figure 7). Our study area includes both seismically highly active areas and areas that experience almost no earthquakes in close vicinity. Seismic activity is mostly occurring in the uppermost 20 km of the crust (e.g., Petersen et al., 2021; Vičič et al., 2019; Figure 7a).

The highest seismic activity occurs on thrust fronts in the eastern Southern Alps (e.g., Hofman et al., 2023; Petersen et al., 2021; Pondrelli et al., 2006) and is driven by the convergence of Adria and Europe (e.g., Moulin et al., 2016; Petersen et al., 2021; Poli & Zanferrari, 2018). The 1976 Friuli  $M_W$  6.4 earthquake, the most recent large event in the area, was one of the most damaging earthquakes ever recorded there (e.g., Pondrelli et al., 2001; Poli & Zanferrari, 2018; see also Figure 8).

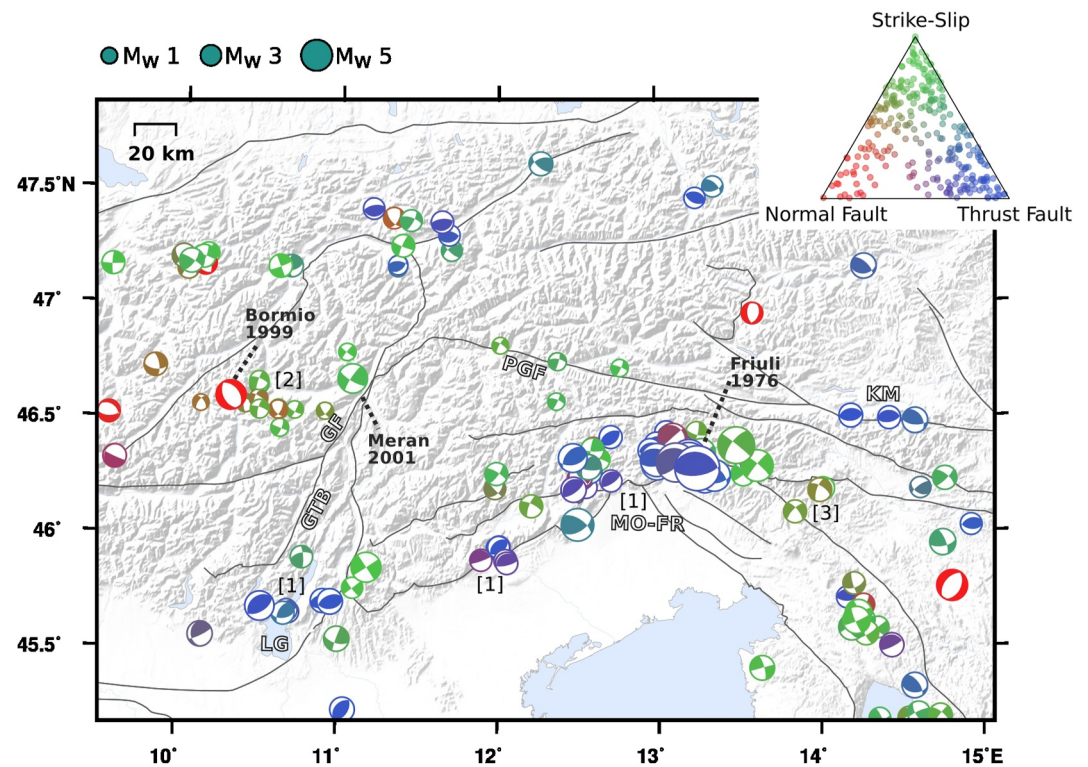
Besides the main thrust structures of the southern Alpine margin, seismicity is significant west of the Giudicarie Fault and south of Innsbruck, in between the 1999  $M_W$  4.9 Bormio earthquake and 2001  $M_W$  4.8 Meran earthquake (Italy) epicenters (Braunmiller et al., 2002; Caporali et al., 2005; see Figure 8). In the southeast of our focus area, at the junction of the Alps and the Dinarides, seismicity remains high on right-lateral, NW-SE oriented strike-slip faults along the Dinarides/Adriatic coast (Figure 8).

In contrast to these higher-activity regions, seismicity north of the Fella-Sava Fault and the Pustertal-Gailtal segment of the PAF is particularly low (Figure 7a). An exception is spatially and temporally clustered activity at the MMF in the Vienna basin at the NE Alpine foreland (Papí-Isaba et al., 2025). Hausmann et al. (2025) report some microseismicity along the Mölltal- and Hochstuhl faults.

In two recent efforts, extensive databases of moment tensor and focal mechanism solutions (Saraò et al., 2021; Sukan et al., 2024) and homogeneous, recomputed moment magnitude data sets (Tarchini et al., 2025) were derived for earthquakes in northern Italy. These efforts will provide critical improvement for seismic hazard assessment and risk mitigation in this seismically active region.

### 3.2.2. Rupture Mechanisms of Earthquakes From Moment Tensor Solutions

Rupture mechanisms of earthquakes in the focus area of this study can be divided in three groups, [1] the southern margin of the Alps, [2] the area west of the Giudicarie Fault, and [3] the transition to the Dinarides in northern Slovenia (see corresponding labels in Figure 8). In Figure 8 we provide an overview of compiled, high-quality moment tensor solutions (MTs).



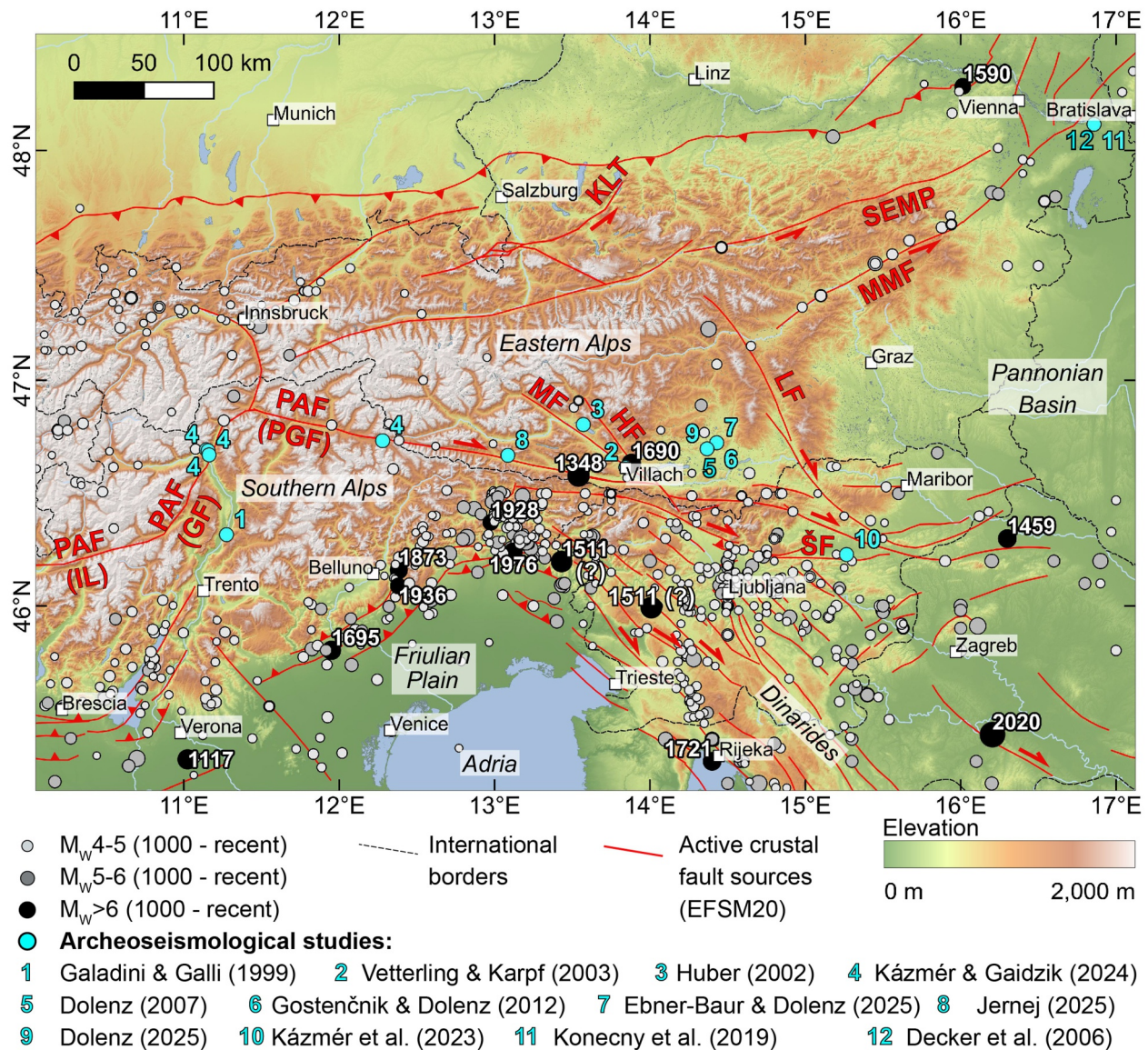
**Figure 8.** Moment tensor solutions of earthquakes between 1976 and 2024 (combined from Saraò et al., 2021; Sugan et al., 2024; Petersen et al., 2021, 2025; INGV, GCMT). Colors refer to the mechanism types as shown in the triangle mechanism plot (inset) with end members pure strike-slip (green), pure thrust faulting (blue), and pure normal faulting (red). Numbers [1–3] indicate three domains discussed in the text: [1] the southern margin of the Alps experiencing dominant thrust faulting, [2] the region west of the Giudicarie Fault (GF), experiencing strike-slip and normal faulting, and [3] the transition zone between the south-eastern Alps and the northern Dinarides, experiencing strike-slip motion. PGF, Pustertal-Gailtal Fault segment of the Periadriatic Fault; GTB, Giudicarie Thrust Belt.

At the southern margin of the Alps [1], the thrust mechanism of the 1976  $M_w$  6.4 Friuli earthquake illustrates the stress field dominated by the N-S to NW-SE directed convergence of the Adriatic and European plates (Figures 5a and 5b; e.g., Petersen et al., 2021; Pondrelli et al., 2006). Accordingly, this mechanism type with E-W to ESE-WNW striking nodal planes is the dominant mechanism type of larger events in the Friuli area and also in the vicinity of Lake Garda. Additionally, strike-slip earthquakes with similarly oriented P-axes ( $\sigma_1$ ) point at changes of the regional stress field resulting in similar magnitudes of horizontal and vertical stresses (Petersen et al., 2021).

Within the seismically active area west of the Giudicarie Fault [2], strike-slip and (oblique) normal faulting mechanisms constitute the dominant faulting style (Petersen et al., 2025; Reiter et al., 2018; Saraò et al., 2021). The 1999  $M_w$  4.9 Bormio normal faulting and the 2001  $M_w$  4.8 Meran strike-slip earthquakes are the most prominent examples of the faulting style in this area (Figure 8; Braunmiller et al., 2002; Caporali et al., 2005). The approximate NNW-SSE orientation of P-axes in this area is in agreement with the regional stress field related to the plate convergence, while the ENE-WSW oriented, horizontal T-axes ( $\sigma_3$ ) of the strike-slip  $M < 3$  earthquakes and the occurrence of extensional normal faulting on NW-SE oriented fault planes indicate large secondary effects on the local stress field (Petersen et al., 2025). In a recent study based on the Swath-D network, precise relocations and MT solutions of  $M_w$  1–3 earthquakes enabled the characterization of multiple short microseismic fault segments, which are oriented in N-S to NW-SE direction and show strike-slip and oblique normal motion (Petersen et al., 2025).

In the transition region between the Alps and the Dinarides [3], focal mechanisms reflect the switch from N-S convergence at the northern boundary of the Adriatic microplate to a transform motion, in which the northern





**Figure 9.** Historical and instrumental seismicity  $M_w > 4$  in the Eastern and Southern Alps and archeoseismological evidence. Historical and instrumental seismicity (circles) with  $M_w > 4$  from the SHEEC database (1000–1899; Stucchi et al., 2013) and the CPTI15 catalog v4 (since 1900; Rovida et al., 2020, 2022). The 1511 epicenter in Slovenia is plotted twice (with question marks) due to an ongoing debate on the location of this event. The location of the 2020  $M_w$  6.4 Petrinja Earthquake is from Herak and Herak (2023). For archeoseismological evidence for the 1348 earthquake, especially in the Po Plain, we refer to Forlin (2023) for further reading. Faults and topography as in Figure 1b.

Adriatic moves northward relative to the continental blocks of the Balkans to the east (Figure 5b). This motion results in right-lateral strike-slip earthquakes on NW-SE striking faults (see also GNSS profile in Figure 6b). The 2020  $M_w$  6.4 Petrinja earthquake in Croatia is a prominent example of the strong seismic activity that can occur on faults parallel to the Dinarides with a right-lateral strike-slip mechanism (Figure 9; Baize et al., 2022; Herak & Herak, 2023). NW-SE striking faults in western Slovenia actually displace the Southalpine thrusts and are seismically active, as evidenced by focal mechanisms of the 1998  $M_w$  5.6 and 2004  $M_w$  5.2 earthquakes in Krn Mountains that occurred on the Ravne Fault (Gosar et al., 2019a, 2019b; Kastelic et al., 2008). Poli and Renner (2004), however, also report a few normal faulting events in western Slovenia with NNW strikes.

A small number of low magnitude strike-slip earthquakes occurred along the Pustertal-Gailtal segment of the PAF in the past years with mechanisms which are in agreement with the right-lateral motion of the fault (Figure 8). Low-magnitude events with a thrust mechanism on E-W striking structures are documented for the segment of the



PAF that cuts through the Karawanke Mountains approx. 100 km to the east, possibly reflecting the minor amount of northward motion still being accommodated here.

In addition to the MTs shown in Figure 8, first-motion focal mechanisms have been reported dispersed in many publications and bulletins for smaller sub-areas with variable information on quality and methodology. For the south-eastern part, Saraò et al. (2021) and Sukan et al. (2024) compiled hundreds of focal mechanisms, often multiple ones for the same events with significant variation in the obtained mechanisms (Saraò et al., 2021). For the north-western part of the study region, we additionally refer the reader to the study by Reiter et al. (2018), focusing on the deformation in front of the Dolomite Indenter. Their first-motion mechanisms and stress field inversions agree well with the shown moment tensors but additionally describe normal faulting at the Brenner detachment, which we cannot see from the MTs.

In summary, instrumental seismicity shows that the Southalpine Front is the most active structure of the Alps. Minor activity is seen along a few large fault systems that accommodated Neogene eastward escape of crustal material like the MMF, and locally in a few areas west of the Tauern Window and the Giudicarie Fault. With regard to our overarching Question I, this implies rather a mature orogen with low internal activity in general. Regarding Question II, instrumental seismicity concentrates along structures active since pre-Quaternary times (see Section 2) and, therefore, mimics the long-term evolution of the Alps. The same holds true for the earthquake mechanisms discussed in this section.

### 3.3. Pre-Instrumental Seismicity

#### 3.3.1. Historical Seismicity

Historical earthquake data for the Alpine region go back 1000 years (Albini et al., 2013; Stucchi et al., 2013), but some Central Europe catalogs cover also the first millennium common era (CE; e.g., Gießberger, 1922; Sieberg, 1940). Nasir et al. (2013, 2023) point out that the Austrian earthquake catalog is incomplete when it comes to historical events, and that even for intensity VIII-IX it is only complete for the last four centuries. In addition, differences in terms of completeness exist.

For the eastern part of the Alps, we consult two historical earthquake catalogs (Figures 1 and 9). The SHEEC database covers the time period 1000–1899 for entire Europe (Stucchi et al., 2013; Figure 9). The Parametric Catalog of Italian Earthquakes CPTI15 v4.0 covers the years 1000–2020 for Italy and adjacent areas (Rovida et al., 2020, 2022; Figure 9). Macroseismic data, that is, shaking intensities are also included in the SHEEC catalog and are available for Italy via the Italian Macroseismic Database DBMI15 v4.0 (Locati et al., 2022). Both the SHEEC and CPTI15 catalogs provide moment magnitudes and epicentral locations. For some earthquakes, the catalogs slightly differ in assigned magnitudes and epicentral locations. For example, the epicenter of the destructive 1348 Villach Earthquake (sometimes also referred to as Friuli Earthquake) is allocated to the Periadriatic Fault in the SHEEC catalog, but to the Fella Sava Fault in the CPTI15 data. The 1928 Tolmezzo Earthquake has a magnitude  $M_W < 6$  in the SHEEC database, but a magnitude of  $M_W 6$  in the CPTI15 data set. In the following, we briefly list a few of the most significant events within the study area.

On 4 May, 1201, an earthquake damaged several castles in Austria. Previously thought to have occurred in Styria, detailed analyses of the historical sources place the damaged buildings in Carinthia, southern Austria (Hammerl, 2005; Hammerl & Lenhardt, 1997). This led to the earthquake being referred to as the Katschberg Earthquake. However, the scarcity and ambiguity of the sources do not allow precisely determining the location and epicentral intensity of the event, let alone the magnitude and depth. For this reason, the location is not included in the Austrian earthquake catalog, and we cannot plot it in Figure 9.

The earthquake of 25 January 1348 is one of the strongest to have hit the Alpine region in historical times. It caused widespread destruction in what is now Carinthia, northeastern Italy, and western Slovenia as evidenced by historical sources (Caracciolo et al., 2021; Hammerl, 1992) and archeological sites (Forlin, 2023). A geological heritage of the earthquake is the massive rockslide at the Dobratsch Mountain, still very much visible near Arnoldstein, 15 km west of Villach (Figure 9). Early studies have placed the epicenter of the event close to Villach and the PAF, but the macroseismic intensities rather point to a source farther south, perhaps on the Fella-Sava Fault (Caracciolo et al., 2021) or even farther south in Friuli (Hammerl, 1992, 1994). Thus, it remains unclear if this earthquake occurred in the interior of the Alps or on their border. The magnitude of this earthquake was probably well above  $M_W 6.5$  or even around  $M_W 7$  (see the review in Caracciolo et al., 2021).

On 25 March 1511, an earthquake caused widespread destruction in western Slovenia and northeastern Italy (e.g., Boschi et al., 1995; Camassi et al., 2011). This event is often also called the Idrija Earthquake, because the earthquake affected the mercury mines in the town of Idrija (the southern label “1511” in Figure 9), or Friuli Earthquake in reference to the destruction that occurred there. The magnitude of the earthquake was probably between  $M_W$  6.5–7.0. Contemporary accounts on surface ruptures do not exist. Modeling of the macroseismic intensities showed that the damage pattern would fit a 50 km-long rupture of the Idrija Fault (Fitzko et al., 2005), and paleoseismological evidence by Bavec et al. (2013) supports this view. However, other studies have not confirmed this (Grützner et al., 2021) or report the 1511 rupture from a fault in NE Italy (Falcucci et al., 2018; also see next section).

On 15 September 1590, a damaging earthquake occurred close to the Northalpine Front, causing damage to churches, monasteries, and other buildings in Vienna. Gutdeutsch et al. (1987) estimated a magnitude of  $M$  6.0–6.3. In a later study, Hammerl and Lenhardt (2013) moved the proposed epicenter by a few kilometers and estimated a lower magnitude of around  $M$  5.75. In the SHEEC catalog, the estimated magnitude is still listed as  $>6$ .

The 4 December 1690 Earthquake with an estimated magnitude of  $M_W$  6.2 caused significant damage and casualties in the Villach area at the western boundary of the Klagenfurt Basin (AEC, 2026; Eisinger & Gutdeutsch, 1994; Rovida et al., 2020, 2022). This is the northernmost earthquake larger than  $M_W$  6 in the eastern part of the Alps, perhaps except the 1201 Katschberg Earthquake, and its seismic source is yet unknown.

The 1695 Asolano Earthquake had a magnitude of  $M_W$  6.4 and likely occurred on the Bassano-Valdobbiadene Thrust (Camassi et al., 2024), although earlier studies assumed it ruptured the Montello Thrust. No surface rupture seems to have been associated with this event, but it caused widespread destruction (Boschi et al., 1995; Guidoboni et al., 2019).

Ljubljana was hit by several damaging earthquakes in historical times (Cecić, 1998; Stucchi et al., 2013). The largest and most damaging event occurred on 14 April 1895 with an estimated magnitude of  $M_W$  6. The causative fault is unclear (Pettenati et al., 2024; Tiberi et al., 2018), and no surface rupture was reported.

The 27 March 1928 (Tolmezzo) earthquake had an estimated magnitude of  $M_S$  5.8 to  $M_W$  6.0 (Poli et al., 2008; Saraò et al., 2021; Sukan et al., 2024) and was probably a strike-slip event (Poli et al., 2000, 2008) without surface rupture.

A report from the 1936 (Belluno) earthquake mentions ruptures that occurred several hours before the event and then moved during the earthquake (Andreotti, 1937). Thus, it is not clear if this phenomenon is related to proper primary ruptures. Sirovich and Pettenati (2004) used macroseismic effects to constrain the earthquake as a  $M_W$  6.3 thrust event on a NW-striking fault.

A larger number of additional historical events with magnitudes between 4 and 6, and thus, potentially damaging, are reported in the historical catalogs (Figure 9). The vast majority of historical earthquakes exceeding magnitude  $M_W$  4 occurred on the Southalpine and Dinaric Fronts. A few strong events may have occurred in the interior of the Alps, such as in 1201, 1348, and 1690. Additional clusters of higher-than-average historical seismicity are located northwest of Verona and in the Ljubljana Basin.

To conclude, historical data on large earthquakes is sparse and allows only very limited insights into the localization of deformation within the Alps. Older events that happened more than 300 years ago come with much higher uncertainties than more recent ones. No large earthquake during the last 1000 years has clearly ruptured the surface, perhaps with the exception of the 1511 and 1936 events. Historical seismicity, therefore, is in line with the observations from recent, instrumental seismicity (Figures 7 and 8) and geodesy (Figure 5), showing that the majority of the seismic moment release concentrates on the active fold-and-thrust belt at the southern margin of the Alps (Serpelloni et al., 2016). This favors the interpretation of a mature orogen instead of a re-organization of deformation (overarching Question I) and a rather continuous deformation pattern over time (Question II).

### 3.3.2. Archaeoseismology

Archeoseismological research has the potential to extend a region's earthquake catalog. Such studies aim at identifying earthquake-related damage or repair structures in archeological sites, and much care is needed to clearly distinguish coseismic effects from other causes of damage (e.g., Caputo & Helly, 2008; Karcz &



Kafri, 1978; Sintubin, 2011; Stiros, 1996). In the eastern part of the Alps, only very few archeoseismological studies have been conducted so far.

Faulted Roman strata were identified by Galadini and Galli (1999) at the archeological site of Eгна in the Adige Valley and the event was dated to the 3rd century CE (marked with #1 in Figure 9). Several sites along the PAF and in its vicinity show archeoseismological damage (Kázmér & Gaidzik, 2024). Evidence for the 1201 earthquake was discovered in Villach (Vetterling & Karpf, 2003; #2 in Figure 9), in Millstatt (Austria) near the Mölltal Fault (Huber, 2002; #3 in Figure 9), in San Candido/Innichen (Italy; damage pre-1284; Kázmér & Gaidzik, 2024; #4 in Figure 9), and probably in Tirol village near Merano (Italy; Kázmér & Gaidzik, 2024; #4 in Figure 9). Another locally damaging earthquake might have hit the same region in the first half of the 13th century, based on observed building damage in Tirol castle and Merano (Italy; Kázmér & Gaidzik, 2024; #4 in Figure 9). Close to Klagenfurt (Austria), an early Roman city sited on top of the Magdalensberg hill has been intensely damaged by an earthquake in the first half of the 1st century CE (e.g., Dolenz, 2007; Gostenčnik & Dolenz, 2012; Ebner-Baur & Dolenz, 2025; #5, #6, #7 in Figure 9). At the Gurina site, 100 km farther west, a Roman settlement probably recorded the same event (Jernej, 2025; #8), thus pointing to either a rather large earthquake or two local ones in close succession. After the Roman city was relocated from the Magdalensberg to the nearby Zollfeld and after it became the regional capital *Claudium Virunum*, it suffered damage in the 2nd and 3rd centuries CE, also interpreted as earthquake-related (Dolenz, 2025; #9). At the Roman city *Celeia* (today's Celje in northern Slovenia), Kázmér et al. (2023) investigated a deformed Roman road and interpreted a damaging earthquake for the time between 200 and 350 CE (#10 in Figure 9, also see Kazmer & Gaidzik, 2025). Much farther to the east, the Roman city of *Carnuntum* between Vienna and Bratislava has recorded damage related to an earthquake in the 4th century CE (Decker et al., 2006; Konecny et al., 2019; #11 #12 in Figure 9). Archeoseismological observations also helped mapping the distribution of building damage caused by the 1348 Earthquake in the Friulian Plain and in the Southern Alps, see Forlin (2023) and references therein.

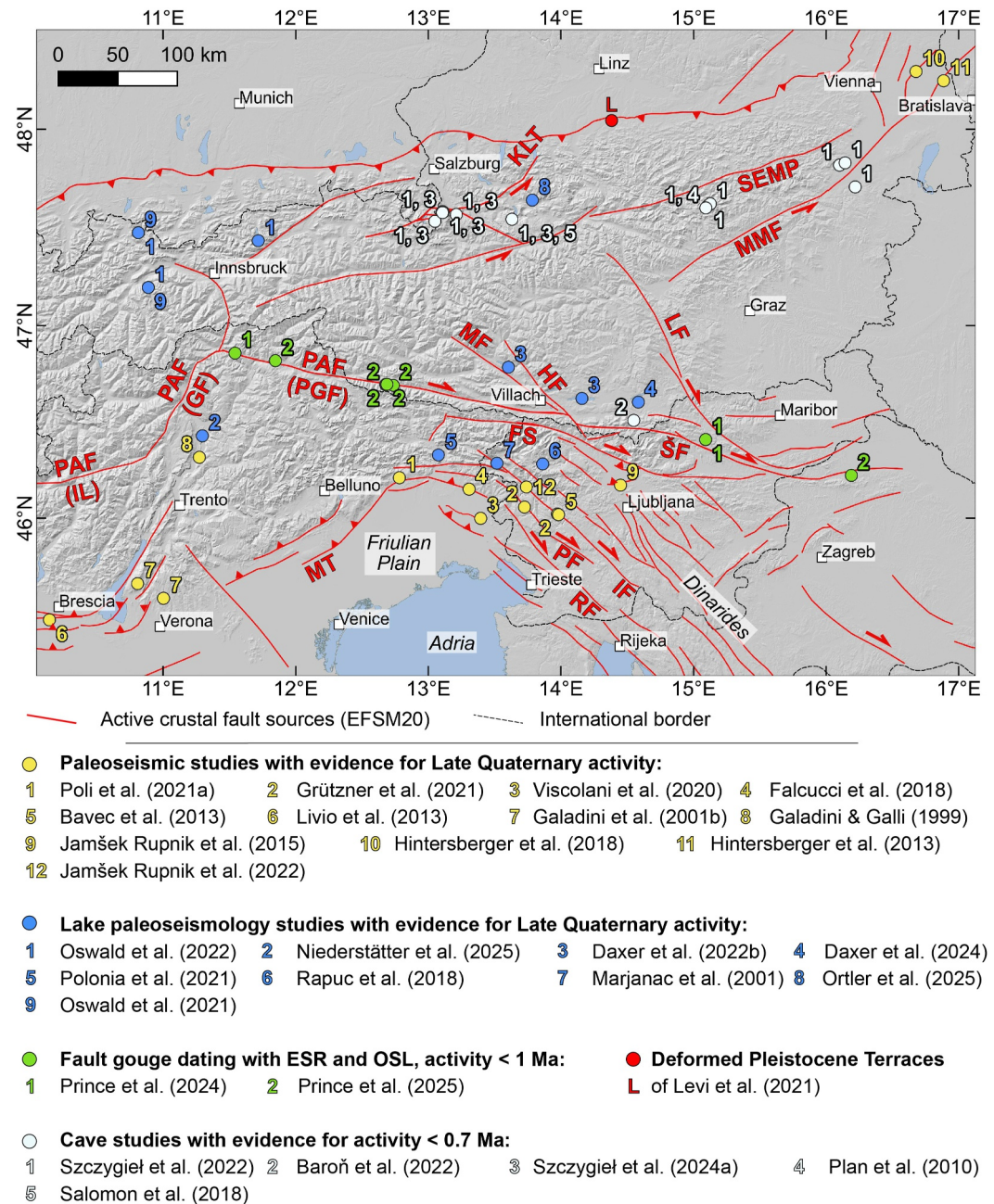
In summary, large seismic events cluster along the southern front of the orogen. Occasionally, they occur in the interior of the Alps (Figure 9), such as in the 1st century CE (near Klagenfurt), in the 3rd century CE at Eгна, in 1348, and in 1690. Strong events are also observed along the MMF. No large earthquake during the last 1000 years has clearly ruptured the surface, perhaps with the exception of the 1511 and 1936 events. Historical seismicity, therefore, is in line with the observations from recent, instrumental seismicity (Figures 7 and 8) and geodesy (Figure 5), showing that the majority of the seismic moment release concentrates on the active fold-and-thrust belt at the southern margin of the Alps (Serpelloni et al., 2016). Regarding our overarching Question I, this pattern implies orogenic maturity instead of a re-organization of mountain building. The pattern is to the first order consistent with the Neogene to recent kinematics of faults in the Alps (Question II).

### 3.3.3. On-Fault Paleoseismology

In paleoseismology, on-fault earthquake data are collected by excavating faults and dating tectonically deformed sediments. However, most of the active faults at the Southalpine Front are blind (e.g., Benedetti et al., 2000; Burrato et al., 2008; Livio et al., 2014) and single faults tend to have low slip-rates and long recurrence intervals for large earthquakes. Thus, non-tectonic processes often outpace tectonic deformation, obliterate the geomorphologic signal, destroy the geological record of large seismic events, or cause non-tectonic overprint (e.g., Jamšek Rupnik et al., 2022). Galadini et al. (2001a) discuss in detail the problems that paleoseismological research faces in the interior of the Alps.

Most paleoseismological studies and similar approaches in the Alps started in the late 1990s and early 2000s (Hürtgen et al., 2020) with studies on the western part of the orogeny. Later on, efforts concentrated on the Southern Alps, Slovenia, and the Vienna Basin (Figure 10). In the following we briefly summarize on-fault paleoseismic studies in the eastern part of the Alps.

At Lake Achensee (Tyrol, Eastern Alps; blue label #1 in Figure 10), both on-fault and off-fault evidence was found for three paleoseismic events since deglaciation of the basin (Oswald et al., 2021). The latest event occurred at c. 8.3 ka before present (BP) with an estimated  $M_w$  of 6.0–6.3 (Oswald et al., 2022), inducing surface rupture at the lake bottom with vertical offsets of 1–3 m and triggering basin-wide subaquatic landsliding. The surface rupture corresponds to the Pertisau Fault, a short, transpressive, dextral strike-slip fault that connects the main fault traces of the Sulzgraben-Eben Thrust, which delimits major thrust sheets in the Northern Calcareous Alps.



**Figure 10.** The geological record of active faulting in the Eastern and Southern Alps. Paleoseismological studies (yellow) are compiled from the database of Hürtgen et al. (2020, 2021) and own updates. See the text for details on the cave studies. Faults and topography as in Figure 1b, except the Udine-Buttrio Thrust (fault with paleoseismic study #3) from Galadini et al. (2005).

In the Po Plain south of Brescia, Livio et al. (2009, 2013; yellow label #6 in Figure 10) used seismic data, tectonic geomorphology, and paleoseismic trenching to identify strong earthquakes on the Capriano del Colle Fault System. Although being a blind thrust forming an anticline, surface faulting was identified in a quarry on top of the fold and dated to three events between 45 and 5 ka BP. The environmental effects of these events also include liquefaction and are similar to those described in historical accounts of the 1222 Brescia Earthquake.

Galadini and Galli (1999) worked at the archeological site of Eгна in the Adige Valley and identified faulted strata of Roman age (yellow label #8 in Figure 10). They date the most recent event to the 3rd century CE and an

older event younger than 4.5 ka BP, probably on a fault belonging to the Giudicarie system. Farther south in the hills north of Verona, Galadini et al. (2001a) excavated the N-S striking Naole normal fault and dated its last activity to 16.4–5.3 ka BP, which, however, is probably related to lateral spreading (or sackungen) due to the growth of the underlying Mt. Baldo anticline (#7 in Figure 10). In the same study, Galadini et al. trenched another N-S normal fault a few kilometers farther east—the Orsara Fault. This structure belongs to a network of <5 km-long normal faults and was last active between 19.8 and 0.7 ka. The displacement here might be related to a yet unknown, larger blind fault in the area.

Paleoseismological trenches were excavated by Poli et al. (2021a) along the Meduno Thrust in the foothills of the eastern Southern Alps. This work was combined with geophysical prospection and geomorphological analyses (#1 in Figure 10). The authors report the most recent surface faulting event to be younger than 0.65 ka BP, deforming alluvium and colluvium. Judging from the available historical catalogs, the nearby 1776 earthquake with an epicentral intensity of MM VIII–IX and a magnitude of  $c. M_W 5.8$  might be the causative event (Rovida et al., 2020, 2022).

Falcucci et al. (2018) opened three trenches at the northeastern boundary of the Friulian Plain in Italy (#4 in Figure 10), where a small fault scarp offsets fluvial and colluvial units. Here, the Colle Villano Thrust forms part of the longer, right-lateral transpressive Borgo Faris-Cividale Fault and delineates the mountain front. Three surface-breaking events date to >6 ka, to 1.6–1.5 ka, and to <0.5 ka BP. Given the historical record of strong earthquakes, Falcucci et al. (2018) argue that the 1511 Earthquake occurred on the Colle Villano Thrust. This is in line with historical reports of building damage in Friuli. However, Bavec et al. (2013) found evidence for a surface rupture on the Idrija Fault in a trench just north of Idrija, which dates to 1–0.35 ka BP (#5 in Figure 10). Based on these results, they interpret the 1511 event to have occurred on the Idrija Fault, which would explain the severe earthquake damage in this mining town in 1511. Less than 1 km north of Bavec et al.'s trench site, Grützner et al. (2021) found the youngest surface rupture on the Idrija Fault to have happened around 2.5 ka BP (#2 in Figure 10). Thus, the paleoseismological evidence for the 1511 Earthquake remains inconclusive. Jamšek Rupnik et al. (2022) reported surface-rupturing earthquakes on the Idrija Fault in Most na Soči during the penultimate glaciation (<165 ka; #12 in Figure 10). The Predjama Fault had its last surface-rupturing earthquake between 13 and 8.4 ka BP, based on a trenching study in Banjšice, Slovenia (Grützner et al., 2021; #2 in Figure 10). The Vodice Fault in Ljubljana Basin has been found to rupture in the last 86 ka, with a possible last rupture around 9 ka BP (Jamšek Rupnik et al., 2015; #9 in Figure 10). Viscolani et al. (2020) used river terraces to infer activity of the Udine-Buttrio Thrust younger than 20 ka BP (#3 in Figure 10). This is in line with the results of many other studies that investigated the traces of active deformation in the Friulian Plain (e.g., Avigliano et al., 2008; Fantoni et al., 2002; Moulin & Benedetti, 2018; Poli et al., 2021b; Zanferrari et al., 2008).

At the eastern end of the Eastern Alps, trenching studies showed that the sinistral Vienna Basin Transfer Fault and its splays with a vertical component of motion are active, offsetting the Pleistocene Gaenserndorf terrace. Weissl et al. (2017) showed that the Aderklaa-Bockfliess and Markgrafneusiedl Fault were active in the Late Pleistocene. Hintersberger et al. (2013, 2018) report five to six surface-rupturing earthquakes on the Markgrafneusiedl Fault during the last 120 ka, the youngest of which as young as 14 ka BP (#10, #11 in Figure 10).

To summarize, most paleoseismological evidence for surface faulting was found at the periphery of the Alpine orogeny. Reasons are the challenges outlined above and those discussed in Galadini et al. (2001a), Jamšek Rupnik et al. (2022), and in Diercks et al. (2023): active tectonics are difficult to study in the Alps because of competing geological and geomorphological processes that shape the landscape at faster rates. The other reason might be that surface rupturing earthquakes in the interior of the Alps simply did not happen after the end of the last glacial maximum, or that they were very rare. On-fault paleoseismology is very limited in its spatial coverage but provides information on long time scales. It implies that the Alps are a rather mature orogen with minor internal deformation in the sense of our Question I. Fault activity seems to continue to the first order on structures already active in pre-Quaternary times (Question II).

### 3.3.4. Off-Fault Paleoseismology

In the Alps, lake sediments have been used since the 1990s as sensitive and continuous records of seismic shaking (Moernaut et al., 2025). Mass-transport deposits and turbidites that originate from the remobilization of lacustrine sedimentary slopes form the main deposits used for lake paleoseismology. A seismic origin is attributed by attesting synchronous deposition in multiple basins and a thorough trigger evaluation based on spatial and

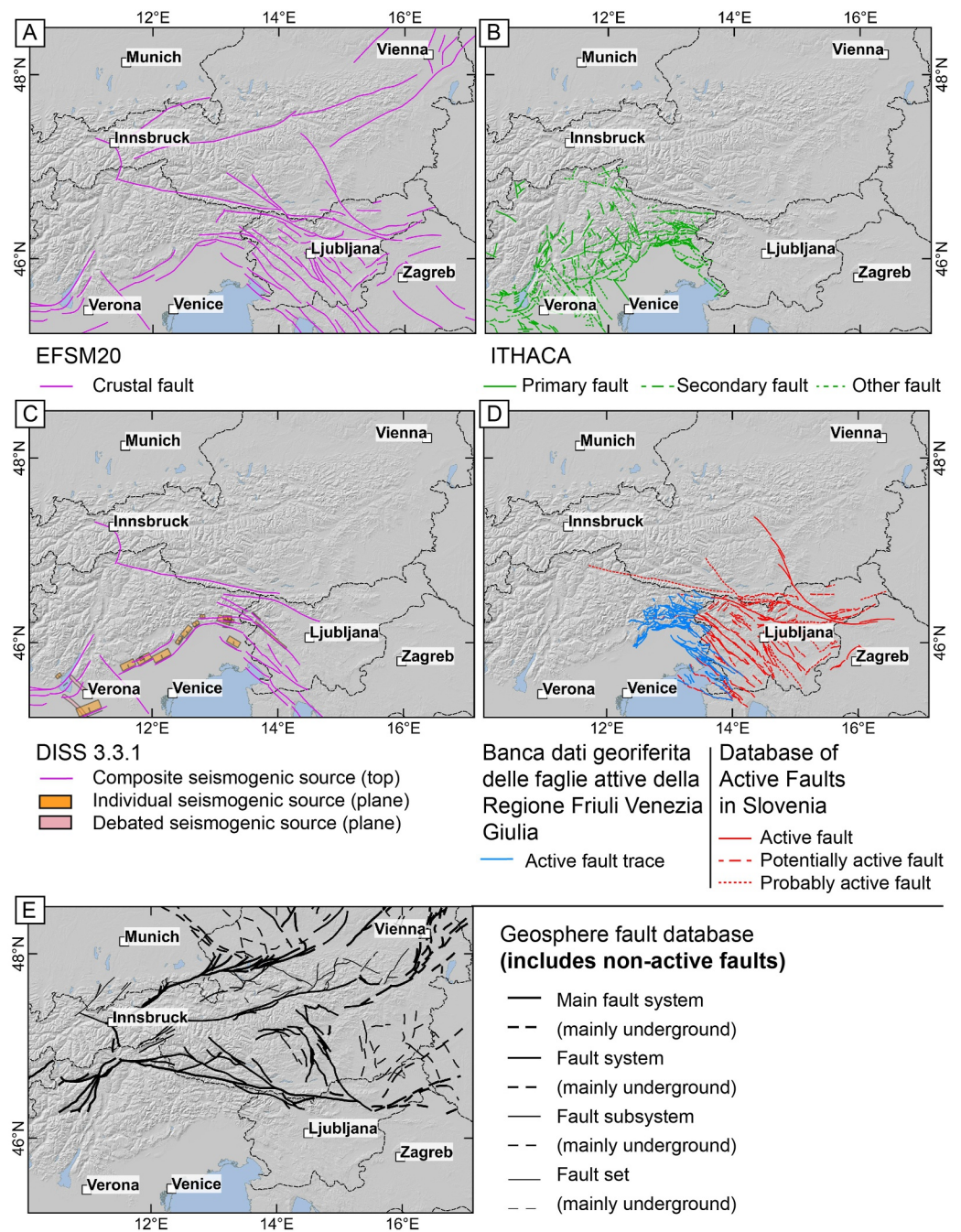


sedimentological criteria (Sabatier et al., 2022). Triggering thresholds for lacustrine paleoseismic evidence are commonly constrained to seismic intensity VI to VII. Unlike many terrestrial paleoseismic archives, the slow and continuous sedimentation process in lakes allows excellent preservation of paleoseismic evidence. Magnitude-epicenter scenarios were developed for paleo-earthquakes in central Switzerland (Kremer et al., 2017) and Tyrol (Oswald et al., 2022; blue label #1 in Figure 10) by comparing seismically-induced sedimentary imprints in multiple lakes in a region (i.e., positive evidence) with the lack of sedimentary evidence during the same period in other lakes (i.e., negative evidence). Whereas many lakes were investigated for paleoseismological purposes in the Western Alps (Wilhelm et al., 2016) and in the central part of the orogen (Kremer et al., 2020), such investigations only started rather recently in the Eastern and Southern Alps.

In Lake Kleiner Montiggler See in the western part of the study area, a seismic seiche deposit was found (Niederstätter et al., 2025, blue label #2 in Figure 10), which temporally coincides with the abovementioned archeoseismological evidence for a surface rupturing earthquake at the nearby Egna site in the 3rd century CE (Galadini & Galli, 1999). This lake study thus forms complementary evidence for a rare M6.5-type earthquake in an overall low-seismicity area within the Dolomites Indenter. In the eastern part of the study area, the high potential for lake paleoseismology was attested by tracing the impact of historical earthquakes in three Carinthian lakes (Millstätter See, Wörthersee, Klopeinersee; Daxer et al., 2022a, 2022b, 2024; #3, #4 in Figure 10), Lago di Cavazzo in Friuli (Polonia et al., 2021; #5 in Figure 10), and lakes Bohinj and Srpénica in Slovenia (Marjanac et al., 2001; Rapuc et al., 2018; #6, #7 in Figure 10). Lago di Cavazzo is close to the epicenters of the 1976–1977 Friuli seismic series and potentially recorded two mainshocks that occurred a few months apart on May 6 and 15 September 1976 (Polonia et al., 2021), indicating the capability of lake sediments to record seismic shaking that occurs in short succession. In Carinthian lakes Millstätter See and Wörthersee, detailed mapping of event deposits induced by historically documented earthquakes (i.e., 1201, 1348, 1511, 1690, 1976) revealed scaling relationships between the “size” of sedimentary imprints and seismic intensity, allowing for semi-quantitative estimations of past shaking intensity (Daxer et al., 2022a). Applying these relations to the 14 ka-long record of Wörthersee highlighted the exceptional impact of the 1348 earthquake in this part of Carinthia: that is, its large-scale lake-wide landsliding outlasts all other events of the past 11 ka (Daxer et al., 2022b). Two events between 11.5 and 14.2 ka BP in the Wörthersee record may have caused similar or even larger shaking intensity. Seismites dated back to 12.8 ka BP were also reported in lake sediments in Srpénica in the Soča Valley in Slovenia (#7; Marjanac et al., 2001). It is important to note the possible influence of changes in sedimentation rate and sediment type on the sensitivity of the lacustrine paleoseismometer. For example, at Lake Bohinj, a change in land-use 3.5–2.0 ka BP significantly increased sedimentation rates and lowered the seismic intensity threshold for the generation of lacustrine earthquake imprints (Rapuc et al., 2018). For the last 2.8 ka in Wörthersee, a sedimentologically stable part of the record, a frequency/intensity relationship was established that is in agreement with the seismic hazard curve that underlies the Austrian seismic hazard map (Daxer et al., 2022b). Recurrence statistics in this period are consistent with a Poissonian (time-independent) earthquake activity. However, both the Wörthersee and Klopeinersee records reveal one (or two) periods of strongly enhanced earthquake activity (“seismic bursts”) around 3.0–3.7 ka BP, including multiple events within a few decades (Daxer et al., 2024). In the more northern Salzkammergut area, Ortler et al. (2025) identified a large mass-wasting event and a combination of soft-sediment deformation with enhanced subaqueous spring activity in Lake Altaussee within the last 2 ka (#7 in Figure 10). Since these two events overlap with the occurrence of two major mass-wasting events in nearby Lake Hallstatt (Lauterbach et al., 2023; Ortler et al., 2024; #8), a seismic trigger seems likely. In Tyrol, Oswald et al. (2021) were able to correlate paleoseismological records from Lake Piburger See and Plansee with independent data on the age of large rockfalls (#9 in Figure 11). They infer that rockfall clusters ~4.1 and ~3.0 ka BP were likely triggered by earthquakes with local magnitudes of  $M_L$  5.5–6.5.

More high-quality paleoseismic archives are needed for establishing regional compilations and constrain the spatio-temporal pattern of such seismic bursts, the occurrence of which may challenge conventional seismic hazard assessments.

Lake sediments provide good temporal resolution for studying Holocene earthquakes, but in mountainous regions like the Alps, challenges arise when attempting to investigate periods predating the last glaciation. In isolated caves, cm-scale deformations can remain preserved for hundreds of thousands of years, with the  $^{230}\text{Th}/\text{U}$  geochronometer enabling precise dating from historical times to 0.5 Ma (Figure 2). The Northern Calcareous Alps (NCA), rich in caves, offer an ideal setting for such research. The NCA are cut by numerous strike-slip fault systems that have previously accommodated the N-S shortening and E-W extension of the orogen. Notably, a



**Figure 11.** Published databases of active/capable faults and seismogenic sources in the study area. (a) EFSM20: European Fault-Source Model 2020 (Basili et al., 2022, 2024); (b) ITHACA: Italy Hazards from Capable faults (ITHACA Working Group, 2019); (c) DISS 3.3.1: Database of Individual Seismogenic Sources (DISS working group, 2025), arrows on planes indicate slip direction; (d) Banca dati georiferita delle faglie attive della Regione Friuli Venezia Giulia (Marchesini et al., 2021; only the active fault traces are plotted here, not the ones that are classified as potentially active) and Database of Active Faults in Slovenia (Atanackov et al., 2021, 2022); (e) Fault database for Austria from GeoSphere Austria (2025). This database does not discriminate between active/inactive faults, but classifies as main fault systems (Großstörungssysteme), fault systems (Störungssysteme), fault subsystems (Teilstörungssysteme), and fault sets (Störungsssets). Topography as in Figure 1b.

significant portion of neotectonic data from the NCA has been derived from cave studies. Karst cave passages that have been offset can act as geomorphic markers as analogs to stream channels on the surface. Passages preferably develop along pre-existing discontinuities in the rock, and if the orientation of these features aligns favorably with

regional stress, their reactivation may result in offsets visible in the cave's morphology. Such deformations were recorded within a fault zone, mimicking master fault kinematics, or farther from the major faults reactivated by the regional stress. As a proof of concept, in central Switzerland, a cave passage offset with damaged speleothems was linked to the 1356 M 6.6 Basel earthquake (Becker et al., 2012).

Paleoseismic studies using secondary evidence have identified the coseismic deformations of the SEMP fault central segment. In the Hochschwab, co-seismic offset was constrained to 118 to 9 ka BP (Plan et al., 2010; white label #4 in Figure 10), while in the Dachstein, soft-sediment deformation of the last glaciation cave sediment was interpreted as co-seismic (Salomon et al., 2018; #5 in Figure 10). A broader analysis by Szczygieł et al. (2022; #1 in Figure 10), based on 172 cave passage offsets from 28 caves between Salzburg and Vienna, revealed a more regional fault behavior (Figure 10). They showed continuous opening of the southern Vienna Basin during the Plio-Pleistocene. However, extensional displacements in the NCA were linked to mass movements rather than gravitational collapse of the orogen. Contrary to earlier suggestions of post-Miocene N-S extension in the NCA (Decker et al., 1993; Peresson & Decker, 1997a), Szczygieł et al. (2022) associated this extensional deformation with Pliocene Molasse Basin inversion at the Alpine front. The NCA underwent successive N-S to NE-SW shortening and E-W stretching, as shown by sinistral cave passage offsets near the SEMP and the MMF. Furthermore, N-S shortening was confirmed north of the Tauern Window, consistent with Alpine indentation. Szczygieł et al. (2024a; #3 in Figure 10) proposed a reactivation mechanism for the Königssee–Lammertal–Traunsee (KLT) fault system, supported by reactivated reverse faults and mode I fractures observed in caves, and indicating a sinistral rejuvenation of KLT. Also, a dextral Lammertal Fault reactivation driven by NNW-compression was recorded in nearby caves. The KLT and Lammertal Faults form a conjugate shear system slightly oblique to the N-S compression, which, together with the presence of evaporites in the fault cores, accommodates shortening more efficiently than the western sector of the SEMP with its orientation perpendicular to the maximum horizontal stress.

$^{230}\text{Th}/\text{U}$  dating of faulted speleothems from NCA caves indicates repeated reactivation of pre-existing structures since the Middle Pleistocene (Plan et al., 2010; Szczygieł et al., 2022, 2024a). The earliest documented reactivation occurred at  $\sim 560$  ( $+100/-60$ ) ka along the KLT. Subsequent slip reactivations, recorded in the Vienna Basin along the SEMP and within the KLT clustered between  $\sim 392$  ( $+18/-16$ ) to  $\sim 287 \pm 6$  ka, with renewed displacements between  $\sim 130$  and 70 ka. The youngest reactivation in caves was documented in the Vienna Basin and postdates  $26 \pm 0.5$  ka (Szczygieł et al., 2022). Here, the fault is moving continuously since about 400 ka as shown by Quaternary growth strata (Decker et al., 2005).

In the Southern Alps, despite being more tectonically active and rich in caves, similar studies remain relatively scarce. In Postojna Cave, located within the damage zone of the NW-SE dextral Predjama Fault, several fallen speleothems were interpreted as potential coseismic damages. These conclusions were drawn by analogy to the damage observed during the 1926 M5.6 earthquake (Šebela, 2008, 2010). However, these deformations have neither been dated nor modeled to estimate their magnitude or source.

Closer to the PAF damage was documented in Obir Cave in the Karawanke Mountains, which is guided by the antithetic sinistral Obir Fault. Here, coseismic deformation was recorded following the 1976  $M_w$  6.4 Friuli Earthquake, which occurred approximately 100 km from the cave. In addition to speleothem damage passage offsets were observed including a maximum sinistral displacement of 40.5 cm (Baroň et al., 2022; #2 in Figure 10). These displaced speleothems enabled the identification of three distinct seismic events. The oldest event, linked to the longest offset, occurred during the Late Pleistocene between  $41.8 \pm 1.3$  and  $18.7 \pm 0.4$  ka. Two subsequent Holocene events caused smaller offsets but remained within a transpressional regime: the first occurred between  $10.73 \pm 0.23$  and  $8.61 \pm 0.15$  ka, while the second took place between  $6.28 \pm 0.24$  and  $5.7 \pm 1.2$  ka (Baroň et al., 2022).

Although most of the active faulting is accommodated at the Southalpine Front and on the strike-slip faults described above, there is also some evidence for Quaternary activity on the northern front of the Eastern Alps. Levi et al. (2021) used borehole stress data, geological data, seismic profiles, and modeling to show that vertical offsets in Pleistocene river terraces were caused by S-dipping thrusts and out-of-sequence thrusting south of Linz after the mid-Pleistocene (label L in Figure 10).

Off-fault paleoseismology studies reveal hints for deformation in the interior of the Alps, spatially somewhat similar to the minor instrumental seismicity observed west of the Tauern Window and the Giudicarie Fault. This



could be interpreted as at least partial re-organization of deformation in terms of our Question I. However, there is a strong spatial bias caused by the availability of suitable archives, and we argue that so far, the data set is too sparse to draw meaningful conclusions from these data alone.

### 3.3.5. Direct Dating of Fault Slip

Direct dating of fault motion on fault gouges relies on frictional heating caused by co-seismic slip that can be detected and dated with trapped charge dating methods such as optically stimulated luminescence (OSL) and electron spin resonance (ESR; e.g., Buhay et al., 1988; Fukuchi, 1992, 1996; Ikeya et al., 1982). In most cases, surface-rupturing earthquakes partially reset the dating systems, resulting in ages older than the actual last co-seismic slip (e.g., Buhay et al., 1988; Fukuchi et al., 1986; Heydari et al., 2024; Tsakalos et al., 2020). In this sense, the ages can be interpreted as maximum ages for surface-rupturing earthquakes along specific segments of the faults.

In the Alps, ESR (Al center in quartz) and OSL (K-feldspar) have been employed to study the Quaternary seismic history of the Pustertal-Gailtal segment of the PAF, the Šoštanj Fault, and the Lavanttal (Labot) Fault (Prince et al., 2024, 2025; green labels in Figure 10). For the PAF, maximum ages of seismic activity given by ESR dating range from around 1,075 to 305 ka, covering the northwestern end of the Pustertal-Gailtal Fault, its center close to the border with Italy, and its far eastern end in Slovenia. Minimum ages given by the signal saturation of OSL range from around 281 to 62 ka and indicate that surface rupturing earthquakes were less likely to occur after this period. At the Šoštanj Fault in Croatia (Figure 10), ESR yielded an age of ~644 ka and OSL yielded ~30 ka, suggesting a younger and more recurrent seismic activity out of the three faults. Prince et al. (2025) also applied ESR to the southern section of the Lavanttal (Labot) Fault, for which they found minimum ages between 2,151 and ~863 ka. This indicates that the fault has not experienced shear heating since then, but as the method relies on the assumption of flash heating due to fault slip, the results do not rule out smaller earthquakes that did not significantly offset the surface or creep. Interestingly, instrumental seismicity on the Lavanttal (Labot) Fault also concentrates on its northern segment while there is almost no seismicity on its southern part (Figure 7).

These studies show that the PAF east of the Giudicarie Fault is characterized by low instrumental seismicity but has had surface-rupturing earthquakes within the last 1 million years. The fault system is oriented almost perpendicular to the present-day maximum horizontal stress (Aiman et al., 2023; Heidbach et al., 2010; Figure 5) which means that it would take a very long time to build up enough stress to be released in a large seismic event. Large historical earthquakes in the vicinity of the PAF are in line with that interpretation. Small earthquakes with a dextral strike-slip focal mechanism on the PAF (see Section 3.2.2) indicate that the fault, even today, mainly acts as a strike-slip structure. Regarding our overarching questions, direct dating indicates that tectonic deformation has become minor in a maturing orogen.

## 4. Active Faults and Slip Rates

Active faults in the Southern and Eastern Alps are typically defined as those that have accommodated deformation during the Quaternary (Atanackov et al., 2021; Galadini et al., 2012). Given that the recurrence intervals of large earthquakes in this region are estimated to span thousands of years (e.g., Grützner et al., 2021; Jamšek Rupnik et al., 2013), both short-term and long-term approaches are needed to assess activity, using the methods discussed in the previous section. Fault geometry is typically inferred from structural-geological maps, complemented by geomorphic and geophysical analyses (Atanackov et al., 2021).

Research on the identification and characterization of active faults in the southeastern Alps has primarily focused on the Southalpine thrusts in Italy (e.g., Benedetti et al., 2000; Falcucci et al., 2018; Galadini et al., 2001b, 2005; Moulin & Benedetti, 2018; Patricelli & Poli, 2020; Patricelli et al., 2022; Poli & Zanferrari, 2018; Poli et al., 2008, 2021a) and the Dinaric and Periadriatic fault systems in Slovenia (Diercks et al., 2023; Jamšek Rupnik et al., 2012, 2022, 2024; Moulin et al., 2014, 2016) as well as the Ljubljana Basin (Jamšek Rupnik, 2013; Jamšek Rupnik et al., 2013). These studies have primarily focused on the most active faults, which exhibit a clear geomorphological expression and allow for the investigation of Quaternary activity.

Faults within Quaternary basins have mostly been targeted due to the feasibility of high-resolution geophysical techniques and paleoseismological methods in such settings. In contrast, identifying active faults in Alpine settings is significantly more challenging. Many faults lack direct evidence of Quaternary activity but could still

be active based on their geometry and regional tectonic context. Since such faults have not yet been systematically investigated, our understanding of active faulting in the region remains incomplete.

#### 4.1. Databases of Active Faults

Systematic mapping of active faults has been conducted in the Slovenian part of the southeastern Alps (Atanackov et al., 2021), while in the Italian sector, efforts have focused on mapping capable faults, that is, faults that have the potential to deform the ground surface (e.g., ITHACA Working Group, 2019; Figure 11). However, seismic source models incorporating simplified faults as composite fault sources have been developed for the entire region (Atanackov et al., 2022; Basili et al., 2008, 2013, 2022, 2024; DISS working group, 2025; Šket Motnikar et al., 2022). For the region of Friuli Venezia Giulia, an active fault database has been published by Marchesini et al. (2021). A fault database for Austria has recently been made publicly available by Geosphere Austria (2025). The European Fault-Source Model 2020 (EFSM20; Basili et al., 2022, 2024) includes Austria, and the Slovenian database includes the PAF and the Lavanttal (Labot) Fault.

All these databases have different levels of geometric and kinematic detail, different input data, and serve different purposes. The EFSM20 (Figure 11a) covers all of Europe and formed the base of the probabilistic European Seismic Hazard Model. Thus, this database includes the largest crustal structures as well as subduction zones and also provides data on seismicity. While seismic source models do not directly correspond to mapped active faults, they include active structures in the form of simplified or composite fault sources and provide regional-scale geometric, kinematic, and activity parameters. In the eastern part of the Alps, it includes the Southalpine thrusts, the Slovenian strike-slip faults with a NW-SE trend, the PAF with the conjugated Hochstuhl and Mölltal faults, the MMF, the SEMP, the Lavanttal (Labot) Fault, and the Brenner (normal) Fault that borders the Tauern Window to the west (Figure 11a).

ITHACA stands for Italy Hazards from CApable faults and is meant to be used in the context of surface faulting hazard (Figure 11b). Therefore, this database contains faults that have “a significant potential for producing displacement at or near the ground surface” (IAEA, 2010). Where available, ITHACA also includes fault slip rates. In our study area, this database is limited to Italy but includes more detailed fault geometries compared to EFSM20 (Figure 11b). It contains more than 2500 line segments of primary, secondary, and other faults, most of which are located along the Southalpine Front and along the PAF.

In contrast to ITHACA, the Database of Individual Seismogenic Sources (DISS) is concerned with faults as sources for ground motion (shaking). It displays both individual seismogenic sources and composite sources (Figure 11c). This encompasses mainly the Southalpine Front and the strike-slip faults in Slovenia, parts of the PAF with the southern Giudicarie Fault, the Fella-Sava Fault, and the Brenner Fault.

The Database of Active Faults in Slovenia is mainly confined to the territory of Slovenia and includes the set of strike-slip faults with a Dinaric trend (NW-SE), called Dinaric Fault System, the Sava and Šoštanj faults as part of the PAF, as well as many other faults outside the Alps (Figure 11d). Large parts of the PAF in Austria and Italy as well as the Hochstuhl Fault are classified as probably active. The Northern Karawanke Thrust is ranked as potentially active and the Lavanttal (Labot) Fault as active.

The regional fault database for the Friuli Venezia Giulia extends beyond the administrative boundaries into Slovenia and provides fault traces in great detail (Figure 11d). It defines a fault as active if there is evidence for motion within the last 40 ka and lists even more segments with potentially active faults that lack clear evidence from this time period (Marchesini et al., 2021). The Geosphere fault database for Austria, containing also fault segments that extend beyond the national border, is based on geological mapping and detailed fault studies (Figure 11e). This database includes faults and fault systems organized hierarchically with different levels of detail and comes with extensive comments and referencing. There is no unified classifier for active faults and slip rates, and the database only contains normal faults and strike-slip faults. Although the Geosphere data set does not distinguish between active and inactive structures, it still represents the most comprehensive fault compilation currently accessible for Austria and thus provides meaningful context regarding the level of existing fault information.

Overall, the database heterogeneity reflects a fragmented state of knowledge across the region. Uneven availability and inconsistent conceptualization of active faults across national data sets constitute a significant

knowledge gap that currently limits the harmonization of fault information and the ability to compare or integrate models across national boundaries.

## 4.2. Fault Slip Rates

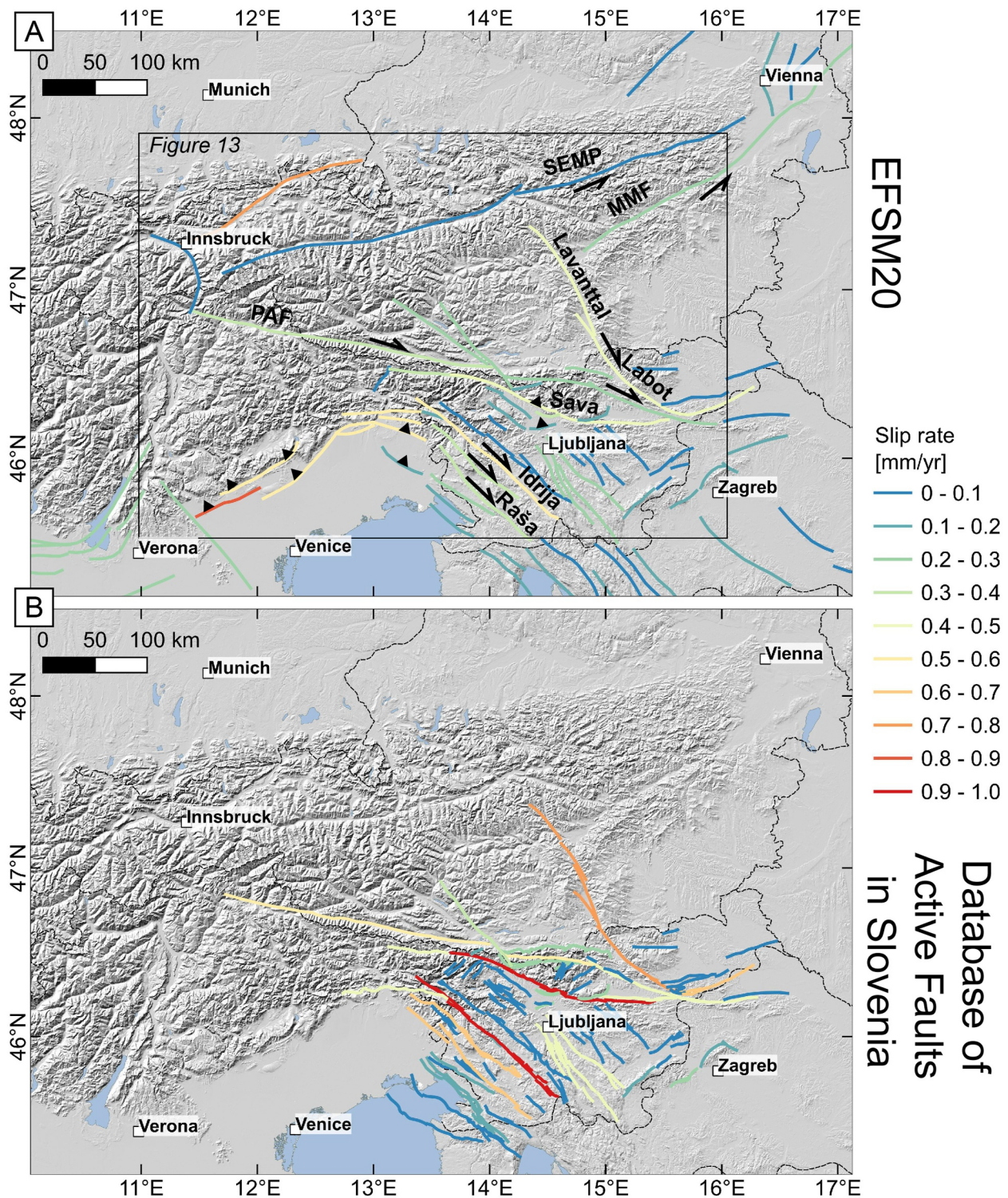
Slip rate estimates are critical parameters for seismic hazard assessment and are included in all seismic source models (Figure 12). They can be derived from short-term geodetic data (e.g., Bechtold et al., 2009; Cheloni et al., 2014; D'Agostino et al., 2005; Serpelloni et al., 2016), from on-fault extensometer measurements (e.g., Gosar, 2020; Gosar et al., 2007), or from long-term geological, geomorphological, and geophysical constraints on cumulative fault offsets. Additionally, slip rates can also be modeled using GNSS velocities combined with assumptions on fault friction, rheological properties, heat flow, and topography (Kastelic & Carafa, 2012; also see Section 3.1). Estimates obtained through different methodologies often show significant variation (e.g., Benedetti et al., 2000; Picotti et al., 2022), which may partly reflect differences in the time windows of observation and modeling assumptions. Since slip rates can vary throughout an earthquake cycle and over a fault's lifespan, short-term and long-term measurements may capture different aspects of fault behavior. Discrepancies in slip rate estimates for individual faults may also be influenced by seismic coupling—the proportion of total slip accommodated seismically versus aseismically. For faults in Slovenia, seismic coupling values have been estimated to range from 0.77 to 0.38 on a scale spanning 0 (freely creeping) to 1 (fully locked) (Zupančič et al., 2024).

Comparisons between geological and geodetic slip rates in western Slovenia indicate general consistency. The N–S components of slip on the largest faults in this region were found to be in the range of 1.79–1.94 mm/yr (Zupančič et al., 2024), aligning with GNSS-derived shortening rates of approximately 1.0–1.5 mm/yr (Serpelloni et al., 2016). This suggests that while different methods capture fault motion over different timescales, they ultimately provide consistent estimates of regional deformation. In the Slovenian database of active faults, only about one third of the faults have observation-based slip-rate estimates, while for the remaining faults slip rates were inferred through comparisons with GNSS data (Atanackov et al., 2021). Due to the heterogeneous nature of the data set, slip-rate estimates vary significantly, necessitating the use of best-estimate values. Based on these, the Sava and Idrija faults emerge as the most active in the region, with slip rates of  $\sim 1$  mm/yr, followed by the Lavanttal (Labot) Fault (0.75 mm/yr) and the Predjama and Raša faults (0.7 mm/yr) (Figures 5b, 12, and 13). When values are adjusted for seismic coupling, Idrija and Sava faults have slip rates comparable to the active thrusts at the Alpine front in Italy (Serpelloni et al., 2016). Exposure dating with cosmogenic nuclides on displaced geomorphological markers was used by Moulin et al. (2016) on the Idrija, Predjama, and Raša faults, yielding a total of  $3.8 \pm 0.6$  mm/yr of right-lateral motion shared by those three faults. These values of more than 1 mm/yr for each individual fault exceed those compiled by Atanackov et al. (2021), especially for the Raša Fault.

Along the Southalpine Front, the protruding Montello Thrust (Figures 12 and 13) seems to be uplifting by 0.5 mm/yr based on geodetic modeling (Barba et al., 2013). This is in agreement with fluvial terrace dating (Benedetti et al., 2000) and Quaternary offsets observed in seismic reflection data (Galadini et al., 2005). Serpelloni et al.'s (2016) elastic block model for the entire Eastern Alps indicates  $1.2\text{--}1.5 \pm 0.1$  mm/yr of dip-slip along the Southalpine Front. Sinistral shear of  $0.6 \pm 0.1$  mm/yr is required in the western segments of the Southalpine Front and  $0.9 \pm 0.1$  mm/yr dextral shear in the eastern segments near the Slovenian border. Also, they find that the Fella-Sava Fault accommodates up to  $1.4 \pm 0.1$  mm/yr of dextral shear, while slip on the Periadriatic Fault is only minor. This is in agreement with a geomorphologically constrained Sava Fault slip rate of 0.5–0.9 mm/yr for the last 2 Ma (Jamšek Rupnik et al., 2012) and probably  $1.8 \pm 0.4$  mm/yr for the last 27 ka (Jamšek Rupnik et al., 2024). Anderlini et al. (2020) refined the kinematic model across the Montello and Bassano-Valdobbiadene thrust fault system (Figure 1) by including vertical InSAR and leveling rates. In agreement with Serpelloni et al. (2016), they found that the Montello Thrust accommodates a fifth of the overall down-dip motion of 2.5 mm/yr, and that this fault is likely shallowly locked (at 5.6 km depth). Ongoing uplift is due to a deeper locking of the Bassano-Valdobbiadene Thrust, resulting in a seismic potential equal to a  $M > 6.5$  earthquake every 1000 years. Farther east, the Friuli segment (where the 1976,  $M_W$  6.5 Friuli earthquake occurred) is thought to accommodate 2.1 mm/yr of interseismic slip during instrumental times (D'Agostino et al., 2005).

The Mur-Mürz Fault in Austria and its continuation into the Vienna Basin has been studied with different approaches (Figure 13). Slip rates derived from seismic moment release of the fastest fault segments are in the order of 0.7–1.1 mm/yr (Hinsch & Decker, 2003, 2010). GNSS studies by Grenerczy et al. (2000) and Grenerczy (2002) show about 2 mm/yr; Serpelloni et al. (2022) report c. 1 mm/yr of left-lateral motion. Geological data indicate a

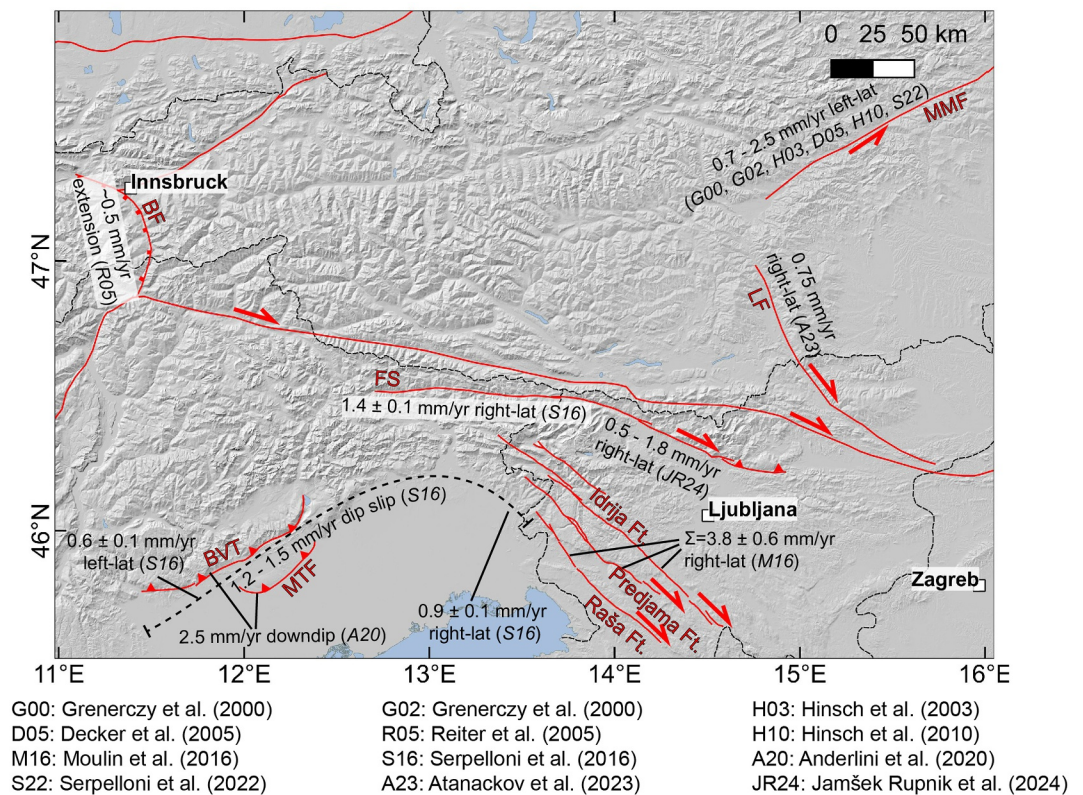




**Figure 12.** Fault slip rate estimates according to (a) European fault source model EFSM20 (Basili et al., 2022, 2024) and (b) the Database of Active Faults of Slovenia (Atanackov et al., 2021). Topography as in Figure 1b.

slip rate of 1.6–2.5 mm/yr (Decker et al., 2005) and Papí-Isaba et al. (2025) describe an increase in seismicity since 2021. In contrast, the EFSM20 database assigns a slip rate of only 0.3–0.4 mm/yr for the MMF and the Vienna Basin. Reiter et al. (2005) reported E-W extension across the Brenner normal fault in the order of





**Figure 13.** Fault slip rates discussed in the text. Topography and fault names as in Figure 1b.

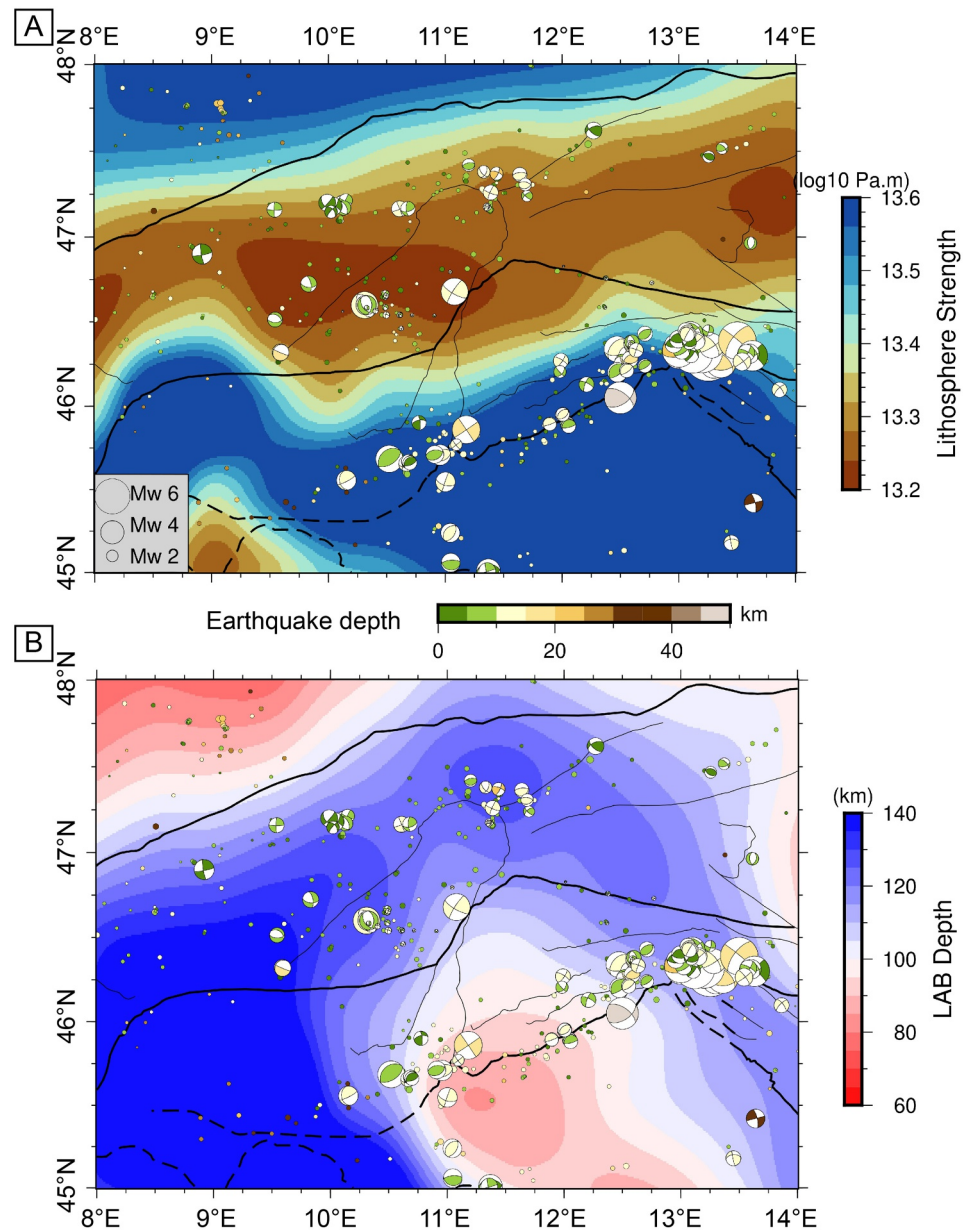
~0.5 mm/yr based on geodetic data, while it is only assumed to have a slip rate of 0–0.1 mm/yr in EFSM20. Argante et al. (2026) argue for a slip rate of  $3.0 \pm 0.7$  mm/yr over the last million years based on 2D thermo-kinematic inverse modeling of ultra-low temperature thermochronology data (cooling ages). Thrusting at the Sub-Tauern ramp is estimated to be about 1 mm/yr based on GNSS data (Reiter et al., 2005, 2018), but this is not considered in EFSM20. Similarly, EFSM20 does not categorize the faults at the Northalpine Front of the Eastern Alps as active, but Levi et al. (2021) proved Quaternary activity from geological archives. The mentioned discrepancies and the fact that EFSM20 shows systematically smaller slip rates than the Slovenian database and the Friuli thrusts require caution when using or interpreting seismic source models.

Overall, slip rate data imply a rather mature, internally slowly deforming orogen (Question I) with deformation concentrated mainly along its boundaries and along large internal structures that have been active since the pre-Quaternary (Question II).

## 5. Discussion

### 5.1. Distribution of Deformation Since c. 1 Ma?

The data presented in the previous sections illustrate the key features of recent deformation in the eastern part of the Alps (also see Grützner et al., 2026). Driven by the northward motion of the Adriatic Plate at a current rate of <3 mm/yr at the longitude of the Friulian Plain, the vast majority of deformation is accommodated at the Southalpine Front as observed by instrumental and historical seismicity. This region hosts today's highest number of earthquakes and most of the historical events larger than  $M_w$  5 (Figures 7 and 9). That is, the majority of the seismic moment is released on north-dipping thrust faults (Figure 8; Serpelloni et al., 2016). GNSS data show here a sharp drop in northward velocities and the highest strain rates in the entire Alpine realm (Figures 5c and 5d). Field investigations on active faults revealed that many of the frontal thrust faults have had surface-rupturing events in the Late Quaternary (Figure 10). Consequently, the entire Southalpine Front is considered active and capable of producing strong earthquakes (Figures 11 and 12; Burrato et al., 2008; Galadini et al., 2005). Slip-rate estimates, however, vary from a few tens of a millimeter of dip-slip per year (Atanackov et al., 2021; Basili

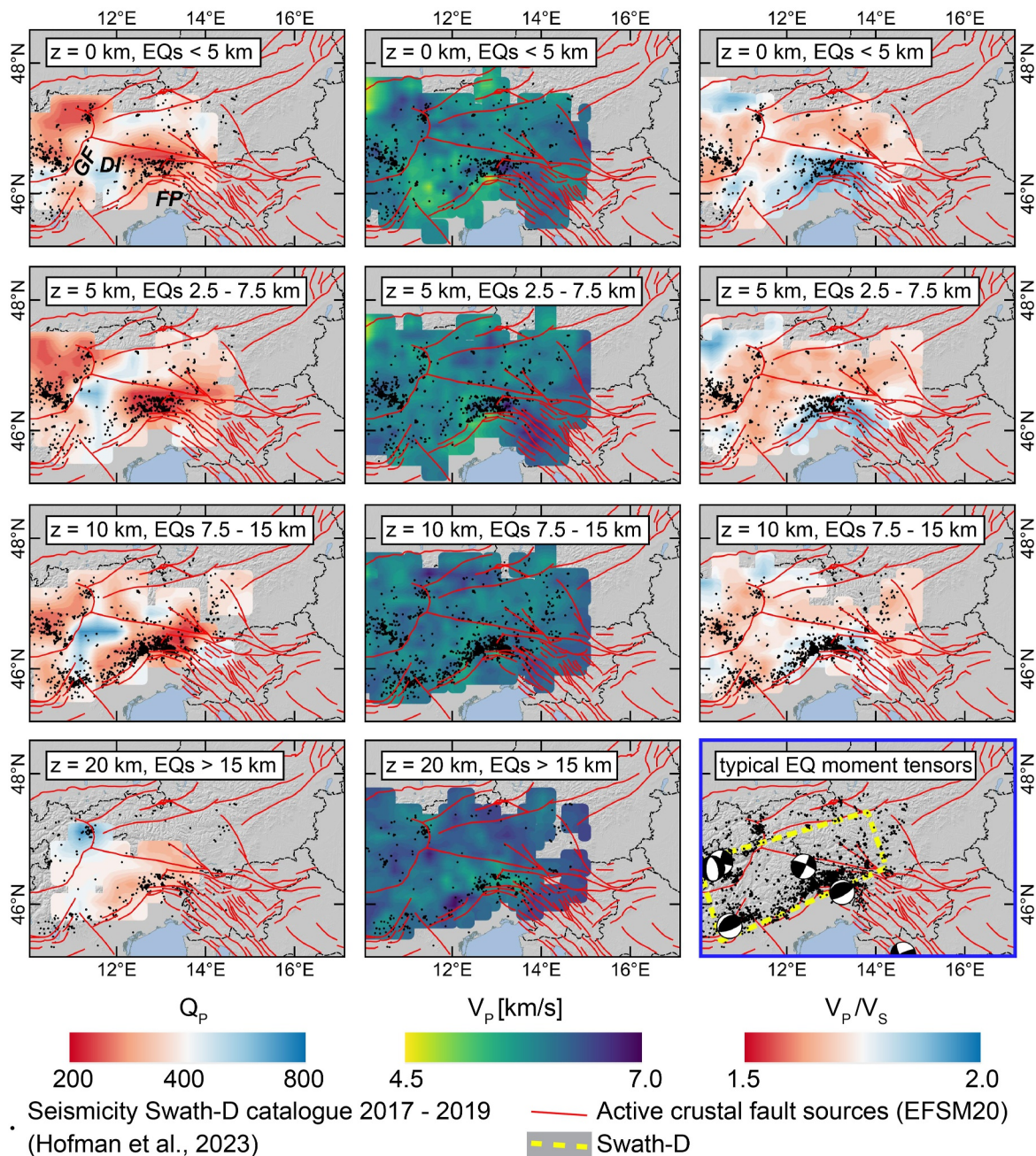


**Figure 14.** (a) Lithospheric strength derived from yield stress calculations (Spooner et al., 2022) and (b) thermal Lithosphere-Asthenosphere Boundary (LAB, depth to the  $\sim 1300^\circ\text{C}$  isotherm) depths derived from the conversion of shear-wave tomography models (Kumar et al., 2022). Seismicity color-coded by depth from the AlpArray seismic catalog (Bagagli et al., 2022), moment tensors as in Figure 8 but scaled by  $M_w$ . Black lines are the faults similar to Figure 3.

et al., 2022, 2024) to up to 2.5 mm/yr of dip-slip plus 0.6–0.9 mm/yr of strike-slip (Benedetti et al., 2000; Burrato et al., 2008; Serpelloni et al., 2016), depending on the observational time window.

Similarly, the Dinaric Fault System in Slovenia, comprising NW-SE striking strike-slip faults, exhibits significant earthquakes and fault slip during instrumental, historical, and geological times (Figures 7–9). Slip rates in the western Dinaric Fault System are as high as 1 mm/yr (Atanackov et al., 2021), although even higher slip rates were estimated from dating offset geological markers (Moulin et al., 2016) on the Idrija, Predjama, and Raša faults (Figures 7, 9, and 12). Geometrical considerations allow not more than 4.7 mm/yr of dextral shear across the western part of the Dinaric Fault System and strike-slip structures farther north/northeast like the Sava Fault and the PAF (Grützner et al., 2021; Serpelloni et al., 2022). Since probably 2.5–3 mm/yr of slip is accommodated by



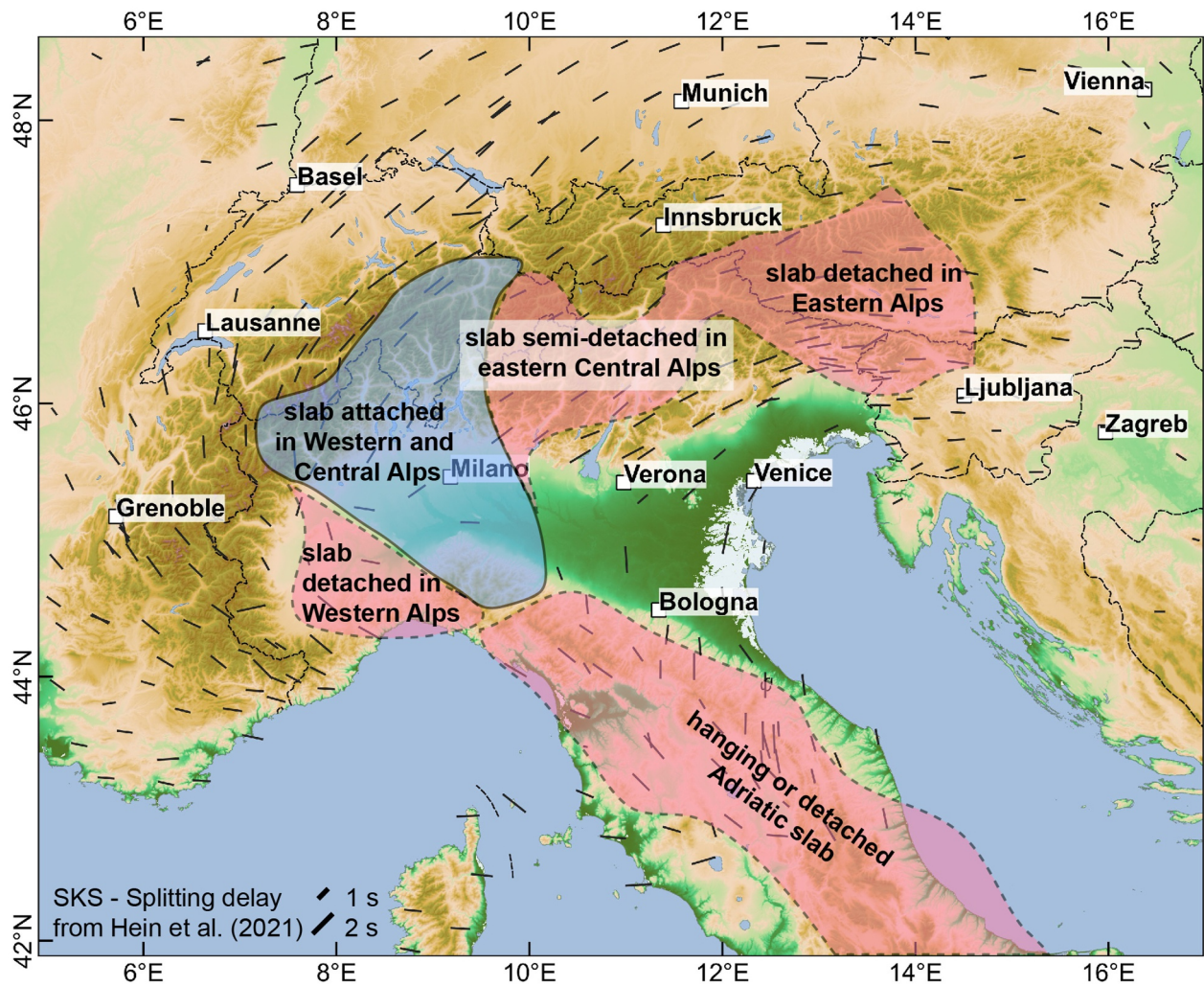


**Figure 15.** Seismicity (Hofman et al., 2023) and seismic parameters probing the crustal structure (Jozi Najafabadi et al., 2022, 2023). 0-, 5-, 10-, and 20-km depth slices of the P-wave quality factor  $Q_p$ , P-wave velocity  $V_p$ , and the ratio of P- and S-wave-velocities  $V_p/V_s$ . The lower right panel shows representative regional earthquake moment tensor solutions from Figure 8. DI, Dolomite Indenter; GF, Giudicarie Fault; FP, Friulian Plain. Faults and topography as in Figure 1b.

faults in Slovenia, linking the Alps to the Dinarides (Atanackov et al., 2021; Moulin et al., 2016), the remainder of the SE-directed dextral shear must be accounted for farther north.

Although instrumental seismicity on the PAF is rather low (Figure 7), a few small earthquakes with moment tensor solutions consistent with dextral strike-slip are documented for the Pustertal-Gailtal segment (Figure 8; Petersen et al., 2025). Farther east along the fault, small seismic events show thrust motion on E-W striking fault planes. In the vicinity of the PAF, strong historical events occurred, especially around Villach and farther east toward the Pannonian Basin (Figure 9). This is supported by archeoseismological observations, speleothems, and lake sediments archiving strong ground motions. On longer time scales, the PAF hosts large, but rare earthquakes





**Figure 16.** Mantle flow directions as suggested by SKS shear wave splitting (black lines, from Hein et al., 2021), overlain by slab geometry underneath Alps (and Apennines) at c. 240 km depth interpreted by Handy et al. (2021).

as implied by fault gouge dating (Prince et al., 2024, 2025). The long recurrence intervals are most likely caused by its unfavorable orientation with respect to the present-day stress field (Aiman et al., 2023) at least in its western Pustertal-Gailtal segment. The same is true for the eastern part of the Fella-Sava Fault parallel to the PAF, which is thought to be the more active structure (e.g., Serpelloni et al., 2016). Geodetic displacement rates show almost negligible strain of  $\sim 10$  nstrain/yr along most of the PAF but reveal higher values of up to 20–30 nstrain/yr in the Sava Folds and the Karawanke Mountains (Figure 5d), where, however, seismicity is rather low. Reiter et al. (2018) report minor right-lateral motion on the PAF at the northern boundary of the Dolomite Indenter to its northward motion relative to stable Europe.

West of the Giudicarie Fault and north of the Insubric Line, a cluster of seismicity shows mainly strike-slip focal mechanisms and normal faulting on  $\sim$ N-S to NW-SE trending planes (Figure 8, see also earthquake relocations outlining fault segments in Petersen et al., 2025). Notable historical events and instrumental earthquakes like the 1999  $M_w$  4.9 Bormio event happened in close vicinity (Figures 7–9), but field studies have not identified Quaternary active faults in the geological record yet (Figure 10), nor is significant geodetic strain ( $<10$  nstrain/yr) observed here (Figure 5). Reiter et al. (2018) derived a transtensional stress regime based on strike-slip and normal faulting focal mechanisms. According to them this *Central Alpine extension domain* is characterized by NE-ward extension at an acute angle to the Dolomite Indenter related to the higher velocity of the indenter east of the Giudicarie Fault (Reiter et al., 2018).

Elevated seismicity, both in the instrumental and historical records, characterizes the ENE-striking, sinistral MMF. Sinistral focal mechanisms are consistent along the MMF (e.g., Brückl et al., 2010; Papí-Isaba et al., 2025). Also, the area near Innsbruck between the western half of the SEMP system and the northern Alpine front has significant instrumental seismicity (Figure 7) as well as few significant historical events (Figure 9). This seismicity is probably related to thrusts rooting in the Sub-Tauern Ramp (Reiter et al., 2018). While successful archeoseismological investigations and paleoseismic studies were only conducted in the Vienna Basin at the far eastern end of the MMF, the lake record and cave research proved Quaternary activity in the area (Figure 10). Offset river terraces along the Northalpine Front also testify to tectonic activity (Levi et al., 2021; Figure 10). Interestingly, geodesy does not see significant strain accumulating here (Figure 5d). Moment tensor solutions from this area are sparse and inconclusive.

Almost no seismicity, neither on instrumental nor historical time scales, is to be found in between the PAF and MMF systems (Figures 7 and 9), and there is no documented geological record of active faulting (Figure 10). Geodesy shows slightly elevated strain accumulation of  $>10$  nstrain/yr in a NNW-SSE trending corridor along the western side of the Lavanttal (Labot) Fault that is also spatially correlated with the switch from slow surface uplift to the west toward slow subsidence toward the east (Figures 5b and 5d). Some instrumental seismicity occurs at the northern half of the Lavanttal (Labot) Fault, but not on its southern portion. This is in line with the lack of shear heating events along this fault during the last  $\sim 1\text{--}2$  Ma (Prince et al., 2025). However, GNSS data suggest recent dextral motion at the Lavanttal (Labot) Fault at  $0.5\text{--}1$  mm/yr (Pavlovčič Prešeren et al., 2005) and the fault is marked as active/capable in two fault databases, respectively (Atanackov et al., 2021; Basili et al., 2024; Figure 11). Popotnig (2009) showed tectonic geomorphology features, distribution of seismicity, and fault plane solutions indicative for active faulting on the southern portion of the fault.

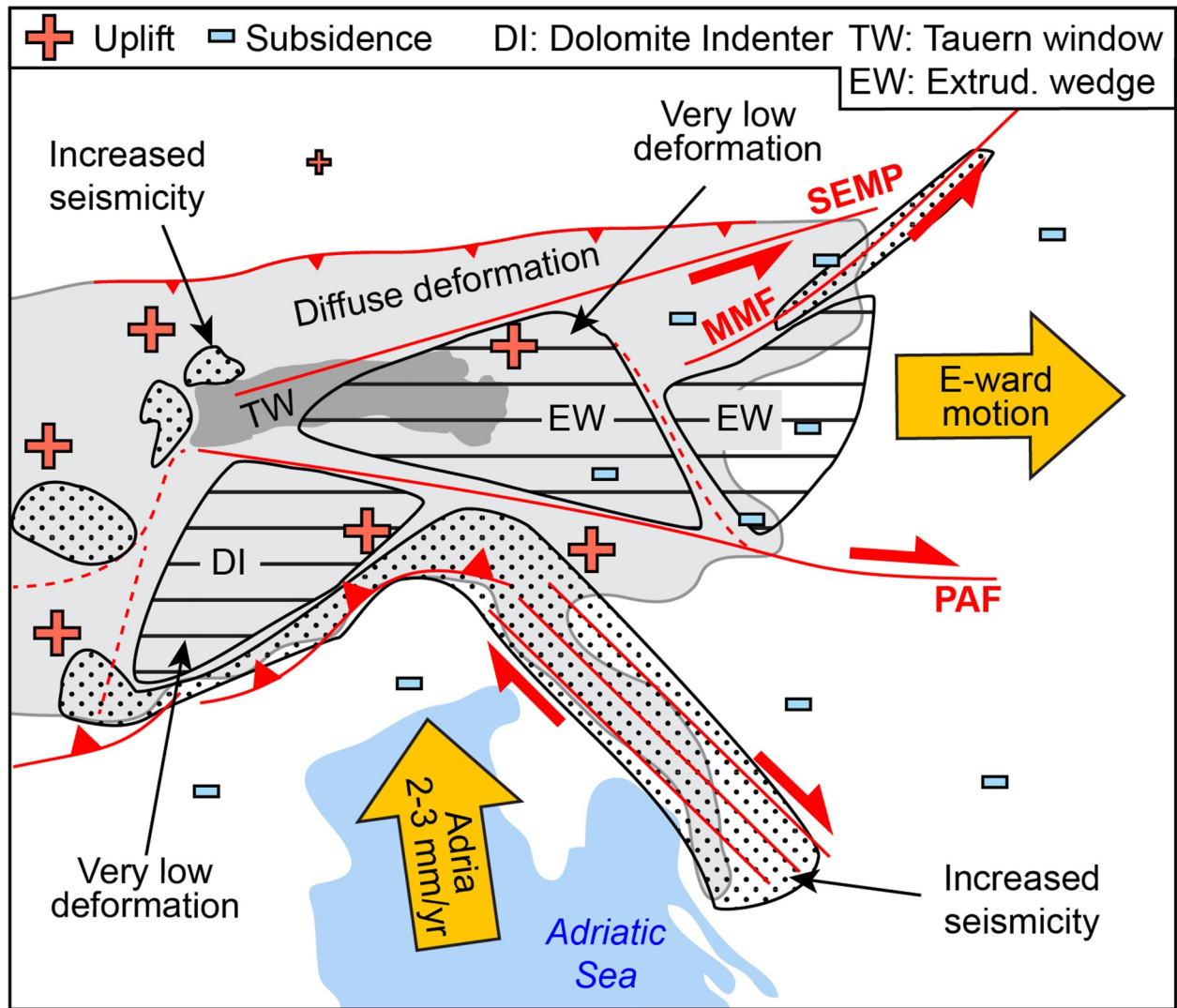
A lack of seismicity on all time scales also characterizes the Dolomite indenter, which acts as a more or less stable block (see next section for a more detailed discussion on the role of crustal strengths on the deformation pattern). However, archaeoseismological evidence for a strong 3rd century CE earthquake at the Egna site implies active tectonics at the western boundary of the Dolomites Indenter, or perhaps at its western boundary in relation with the Giudicarie Fault (also see Reiter et al., 2018).

Recently, Kissling (2024) argued that the GNSS-constrained rotation of Adria might reflect internal surface deformation that is mechanically decoupled from the middle and lower Adriatic crust. However, the consistency of the GNSS velocity data across the entire Alps and its forelands (Figure 5a) is hard to explain with internal deformation only. Highest N-ward velocities are found at the northeastern edge of Adria with amplitudes steadily declining toward the west, and the GNSS vectors change direction across the main fault zones such as the PAF. This indicates that both, the rotation of the Adriatic plate and the internal deformation of the orogen, are indeed captured by geodesy. Anderson and Jackson (1987) showed that rotation of Adria is constrained by seismicity and fault-plane solutions. AdriaArray, a SE-ward continuation of AlpArray along the eastern Adriatic coast down to Albania will hopefully shed more light on this so-far sparsely instrumented region to better understand the structure and kinematics of the Adriatic block (Kolínský & Meier, 2023).

## 5.2. Crustal Control on the Present-Day Deformation Pattern

Spooner et al. (2020) derived the steady-state thermal field of the Alps and validated it with observed sub-surface temperatures. They show that most of the seismicity of the Alps occurs along the  $275^\circ\text{C}$  isotherm, which corresponds to depths of c. 10 km for most of the orogen (also see Figure 7b). Beneath the  $450^\circ\text{C}$  isotherm (c. 20 km depth), seismicity is largely absent, indicating bulk quartz-feldspathic conditions. Only few seismic events in the European forelands occur in the lower crust, where temperatures  $<450^\circ\text{C}$  suggest a less mafic lithology than expected. This is in agreement with a seismically constrained structural and density model by Spooner et al. (2019) showing that seismicity and ongoing crustal deformation concentrates in regions with changes both in crustal thickness and density. Spooner et al. (2022) explored the relationship between long-term lithospheric strength and the distribution of seismicity. While in the northern Alpine foreland seismicity occurs in weak crustal domains, seismicity distribution in the southern Alpine forelands correlates with the integrated lithospheric strength. Earthquakes happen predominantly in areas of relatively weak lithosphere around the Adriatic plate. We observe this along the entire Southalpine Front. Both temperature and composition reflect a weaker orogenic crust in the interior of the Alps compared to the transition to the stronger Adriatic lithosphere in the south (Figure 14a). Hence, the interior and northern front host mostly upper-crust, low-to-moderate seismicity in contrast to the larger





**Figure 17.** Summary of the active crustal deformation in the Eastern Alps and eastern Southern Alps. Light gray shaded area is the simplified 1000 m topographic contour.

earthquakes in the south. Despite the thicker lithosphere (Figure 14b), weakening of the orogenic lithosphere is related to the higher temperature in the thicker orogenic crust (Kumar et al., 2022; Spooner et al., 2020), allowing it to extrude eastwards.

To better understand the relation between crustal properties and ongoing deformation we compare seismic velocity and attenuation models (Jozi Najafabadi et al., 2022, 2023) with earthquake occurrence (Hofman et al., 2023) and kinematics (Petersen et al., 2021, 2025), all recently derived from the temporary Swath-D dense seismic network, and GNSS displacement rates (Serpelloni et al., 2022).

The seismic wave propagation velocities and attenuation properties provide qualitative insights into rheological parameters, for example, density, fluid content, and/or porosity (Figure 15). High seismic P-wave velocities ( $V_p$ ) suggest stronger and more consolidated rocks, for example, magmatic rocks have generally higher  $V_p$ -values than sedimentary basins. High  $V_p/V_s$  ratios indicate the presence of fluids, for example, in intrusions, fluid-filled cracks, or a porous rock with saturated pore space. P-wave attenuation (expressed by the inverse of the seismic quality factor  $Q_p$ ) describes the energy loss of seismic P-waves when passing through a medium due to dissipation as heat or inelastic deformation. For Swath-D, a crustal  $Q_p$  model was derived from attenuation values of local earthquakes. A high quality factor  $Q_p$ , equivalent to a low P-wave attenuation, suggests the absence of

fluids/fractures, while a low QP suggests a strongly pre-fractured rock volume. Seismic parameters suggest that the crust in the eastern Southern Alps can be broadly divided into three zones with different physical characteristics, (1) the Friuli area, (2) the Dolomite Indenter, and (3) the area west of the indenter.

1. The Friuli area (Friulian Plain FP and the mountain front to the north of the plain, Figure 15) in the southeast is deforming due to Adria–Europe convergence. It is marked by folding, faulting, and crustal shortening, a high  $V_p/V_s$  ratio (Jozi Najafabadi et al., 2022), and increased strain along the NNW–SSE direction (Figure 5d). Seismicity is highest here and moment tensor solutions of the largest events confirm thrusting (Figure 8). Elevated  $V_p/V_s$  ratios in this region indicate the presence of dense Mesozoic limestones and dolomitic formations. Additionally, a significant P-wave attenuation anomaly (low QP values; Jozi Najafabadi et al., 2023) has been identified. Given the region's widespread active thrust faulting and high seismicity, it is likely that this region is mechanically weakened and damaged, and that it is characterized by extensive fluid-filled cracks. This explains the low QP and high  $V_p/V_s$ -values and may also indicate zones of intense deformation and active fluid circulation (confirmed by the location of active tectonic structures in the available fault data bases; Figure 12).
2. Conversely, the Dolomite Indenter (DI in the top left panel of Figure 15) appears to act as a mechanically stronger block relative to its surroundings; GNSS velocities report no strain (Figure 5d), seismicity is low, and the QP values are extremely high especially at seismogenic depths of 5–10 km. Faults within the DI are either inactive or accommodating strain through slow, aseismic slip, while deeper faults to the south remain seismically active. High  $V_p$  and low P-wave attenuation are consistent with the presence of dense Permian volcanics (Tadiello & Braitenberg, 2021), which likely extend to the base of the upper crust. The short- and long-term observations at the DI agree with each other and correlate with the extent of the volumetrically abundant Lower Permian plutons (285–274 Ma; Marocchi et al., 2008) intruding the Paleozoic basement, capped by the min. ~2.5 km-thick Athesian Volcanic Complex (e.g., Morelli et al., 2012; Rottura et al., 1998; Visonà et al., 2022). A lack of Alpine metamorphic overprint (Bousquet et al., 2012b) and present-day lower temperatures compared with the northerly and westerly adjacent Austroalpine units (Spooner et al., 2020) suggest that here the crust could behave mechanically more rigid than the Austroalpine units (Spooner et al., 2022). This provides an example of how inherited geological features govern regional shortening geometries, strain partitioning, and seismicity distribution at the Southalpine Front (Sieberer et al., 2023, 2025). It is important to emphasize, however, that the seismic observations do not necessarily represent the tectonic state during the northward indentation of the Adriatic Plate in the late Oligocene to Miocene. At that time, the mechanical properties along the strike of the eastern Southern Alps may have been more homogeneous. The current preservation or recovery of high strength within the DI likely developed over time following the onset of Adria indentation.
3. Farther west of the DI, west of the GF, GNSS strain rates increase again (Figure 5d) and QP values are low but slightly higher than the even lower values in the Friuli area. This region exhibits intermediate values for all compared parameters— $V_p/V_s$  ratios, P-wave velocity, and seismic activity rates—falling between those observed in the other two regions (Friuli and DI). Seismic activity here often manifests in small-magnitude swarms (Figures 7b and 8; Petersen et al., 2025), but single, larger events like the 1999  $M_w$  4.9 Bormio earthquake can occur. Earthquake rupture mechanisms, strike-slip and normal faulting, deviate from the thrust events in Friuli, thus indicating a different stress field. Smaller differential stresses here than in the Friuli area make it more likely to permute principal stress axes  $\sigma_1$ ,  $\sigma_2$ , and  $\sigma_3$ , thus switching between different Andersonian stress regimes.

The influence of crustal strength on seismicity is also seen in the distribution of stress drop. Moratto et al. (2026) analyzed more than 1500 well-recorded earthquakes between 2016 and 2023 in the Southern Alps and found distinct tectonic domains. Picozzi et al. (2026) used small earthquakes between 2016 and 2025 in the same region to map fault segmentation. Similar to Petersen et al. (2025), they find that the spatial patterns of seismicity align with the QP and  $V_p/V_s$  ratios studied by Jozi Najafabadi et al. (2023).

### 5.3. Crustal Deformation - A Response to Slab Tearing, Slab Break-Off, or Subduction Polarity Switch?

Deformation in the Alps is a result of processes both on plate-scale (crustal deformation) and on lithosphere-scale (slab break-off). Thermomechanical modeling indicates that the deceleration of the Alpine slab retreat initiated a rotation of Adria in counterclockwise direction, with a rotation pole located in the Western Alps (Schuler et al., 2025), as also inferred from seismicity (Anderson & Jackson, 1987) and geodesy (e.g., Serpelloni

et al., 2022). This can also be attributed to the fact that the Hellenic slab southeast of Adria and the Calabrian slab southwest of Adria advance toward the southern tip of the Adriatic microplate, thus reducing the influence of the African plate on Adria to the southern tip (Schuler et al., 2025). As a consequence of the transition from coherent northward motion to counterclockwise rotation of Adria, the horizontal velocities of the northern part of Adria decrease (Schuler et al., 2025). This results in the relatively low horizontal velocities observed in the southern Alps today (Figure 5).

Mantle dynamics beneath the Southern Alps are influenced by mantle flow beneath Adria (Figure 16). The advancing Hellenides-Dinarides and Apennines-Calabria subduction zones east and west of Adria, respectively, cause asthenospheric escape both southward and northward from beneath Adria (Király et al., 2018a, 2018b; Schuler et al., 2025). This escape flow, together with the accelerated retreat of the Carpathian subduction, leads to trench-parallel mantle flow beneath the Central and Southern Alps (Schuler et al., 2025), as also suggested by seismic anisotropy (Hein et al., 2021; Kovács et al., 2012; Link & Rumpker, 2023; Figure 16). Mantle flow can strongly influence how and when slab break-off events occur (Király et al., 2021).

On lithospheric scale, vertical uplift rates can be strongly influenced by slab break-off (e.g., in the Alps: Fox et al., 2015, 2016; von Blanckenburg & Davies, 1995; Kuhlemann, 2007; Schlunegger & Castelltort, 2016; in the Dinarides: Balling et al., 2021; Randjelovic et al., 2025). In the Alps, slab break-off is thought to have occurred at around 20 Ma in the Eastern Alps, while in the Western and Central Alps the European slab is probably only partially detached (Handy, 2025; Handy et al., 2021; Kästle et al., 2018; Paffrath et al., 2021; Zhao et al., 2016; see Figure 16). A study using cooling ages and geomorphology in the Western Alps by Gemignani et al. (2025) suggests the break-off to have occurred in the Oligocene instead of the Pliocene as inferred from a Plio-Pleistocene cooling pulse (Champagnac et al., 2007; Fox et al., 2015; Glotzbach et al., 2011).

The topographic imprint caused by a slab break-off event depends on the velocity at which break-off happens. A slow (e.g., ~20 Ma of necking, ~2 Ma of tearing, Piccolo et al., 2026) break-off process propagating with a few centimeters per year is thought to result in very minor surface signals; conversely, a rapid (~10 Ma of necking, ~0.14 Ma of tearing) break-off with horizontal propagation velocities of several centimeters to meters per year would result in a short, but intense topographic response that quickly diminishes (Duretz et al., 2011; Gün et al., 2025; Maiti et al., 2024; Piccolo et al., 2026). Crustal uplift as response to slab break-off might be relatively immediate, but the geological record of increased erosion and sedimentation in the forelands probably comes with a delay of up to 5–8 Ma (Schlunegger & Castelltort, 2016). Thus, a slab break-off at ~20 Ma or earlier will not exert a dominating control over the present-day topography of the eastern part of the Alps as its signal should long have vanished. Thus, the large-scale tectonic picture observed today cannot be controlled by already teared or currently tearing slabs.

Elevated low-relief landscapes in the Eastern Alps and the location of paleophreatic cave levels, both inferred to have formed at former base levels, indicate that in the Pliocene, a long-wavelength uplift affected the Eastern Alps without significant dissection into individual blocks with different uplift histories (Gradwohl et al., 2024a; Robl et al., 2015, 2017). This implies that major tectonic activity (or at least: uplift of fault-bounded blocks) at the main intramontane fault zones had already largely ceased in the Pliocene or late Miocene (Gradwohl et al., 2024a, 2024b). Other, independent lines of evidence support this view. Wagner et al. (2010), looking into cave deposits of the Mur River, found a post-Miocene uplift signal, but lasting longer than what would be expected from crustal response to slab break-off. Cave deposits from between the Periadriatic and Sava faults suggest as much as 900 m of valley incision during the last 2 Ma driven by uplift (Häuselmann et al., 2015), which contrasts with data from the Northern Calcareous Alps (Häuselmann et al., 2020). The present-day vertical velocities are only fractions of a millimeter per year (Figure 5c), implying that the post-Miocene uplift seen in the studies discussed above was indeed pulse-like, and thus, perhaps related to a deep-seated process like slab tear (cf., van Gelder et al., 2020). Other studies on thermochronology, however, indicate that erosion rates did not increase in the Alps at 5 Ma (Fox et al., 2016). Dixon et al. (2016) emphasize the control that previous glaciations exert on Holocene erosion rates, and that the formerly unglaciated parts of the Eastern Alps are characterized by very low erosion rates in general. Miocene and younger basin fills within and around the Eastern Alps show rotations about vertical axes, which implies at least some post-extrusion strike-slip tectonics (Márton et al., 2000), but the sediments exhibit little vertical deformation (e.g., Kováč et al., 2004; Sachsenhofer et al., 2003). Legrain et al. (2015) also document a post-Miocene uplift signal based on erosion rates from the Koralpe, the mountain range west of the Lavanttal (Labot) Fault. Because of the lack of ongoing subsidence in the Molasse basin (Genser et al., 2007) and because of



long-wavelength uplift in the Eastern Alps in general, they conclude that a mantle process might have caused the signal rather than crustal response to ongoing Adria-Europe convergence. However, the relation of the observed uplift to the slabs at depth remains elusive. At least in the eastern Southern Alps, subsidence of the Alpine foreland is in line with elastic deformation due to ongoing shortening (Anderlini et al., 2020). Thermochronology data along the TRANSALP section (running N-S at c. 12°E) indicate that here the pro-wedge of the Alps has switched from north to south of the PAF, perhaps after a slab break-off event in the mid-Miocene (Eizenhöfer et al., 2021). This view fits the localization of active deformation along the southern front of the orogen. The process of subduction reversal in the Eastern Alps could still be ongoing with a slow Adria indentation into the European mantle lithosphere, fitting geomorphological observations (Eizenhöfer et al., 2021) and explaining the diffuse imaging of the subduction polarity in tomographic studies (e.g., Kummerow et al., 2004; Kästle et al., 2020; also see Figure 16). However, others imply a rather rapid Miocene slab break-off (Handy et al., 2015) and most studies now agree that there was no subduction polarity switch at all (Brückl et al., 2010; Handy et al., 2021; Kästle et al., 2018, 2020, 2025; Mitterbauer et al., 2011). If no subduction polarity switch occurred, thermochronological data would imply that mantle and crustal processes are largely decoupled (Eizenhöfer et al., 2023).

#### 5.4. Ongoing E-Ward Extrusion?

Lateral extrusion has significantly shaped today's Eastern Alps. It occurs during continental collision, when crustal blocks are displaced laterally from the collisional site toward its margins (Ratschbacher et al., 1991a, 1991b). The process is driven by tectonic escape, which involves horizontal motion of crustal wedges, and extensional collapse, where thickened and topographically elevated crust becomes gravitationally unstable and flows toward lower elevations. Both processes cause crustal movements perpendicular to the plate convergence direction. Lateral extrusion is facilitated by the presence of weak lateral boundaries, such as subduction retreat or a large hypsometric gradient (Molnar & Tapponnier, 1975; Peresson & Decker, 1997a, 1997b; Ratschbacher et al., 1991a, 1991b; Robl et al., 2008; Sperner et al., 2002).

Ratschbacher et al. (1991a, 1991b) define lateral extrusion in the Eastern Alps as the result of (a) N-S shortening between Adria and Eurasia, (b) resistance from the Bohemian Massif acting as a rigid backstop, (c) a previously thickened and thermally weakened Eastern Alpine crust, and (d) a weak lateral boundary along the Pannonian Basin, further influenced by subduction retreat in the Carpathians. While the fundamental boundary conditions, such as the highly deformed Alpine orogen and the mechanical contrast with the resistant Bohemian Massif, have remained unchanged, the regional stress field and kinematic framework have evolved through time. A key transition occurred with the cessation of Carpathian subduction between c. 9 and 6 Ma, when subduction became jammed by the thick, non-subductable continental crust of the Trans-European Suture Zone (running from the North Sea to the Black Sea) (Peresson & Decker, 1997b). This interruption was accompanied by a substantial stress reorganization, leading to low-strain slip reversal on major fault systems, including the SEMP and the MMF. Consequently, lateral extrusion was interrupted during the Pliocene and re-established with sinistral slip along major fault zones resuming in the Pleistocene as documented for example, in the Vienna Basin (Decker et al., 2005; cf. Grützner et al., 2026).

The dextral PAF and the faults south of it remain active, as shown in Sections 3 and 4. However, the key to diagnosing tectonic extrusion lies in the wedges' motion between the dextral PAF to the south and the sinistral SEMP to the north, as well as between the sinistral MMF and the dextral Lavanttal (Labot) Fault. Thus, confirming sinistral activity along the SEMP, MMF, and possibly the KLT and Inntal faults, as well as dextral motion along the Lavanttal (Labot) Fault is essential to validating the relative eastward motion of the central and eastern wedges (Figure 17). Structural data from secondary faults indicate sinistral reactivations during the Mid- and Late Pleistocene, with the compression axis deviating from N-S north of the Tauern Window to NE-SW toward the Vienna Basin (Decker et al., 2005; Plan et al., 2010; Szczygieł et al., 2022, 2024a). Meanwhile, the Northalpine Front remains in a N-S compressive regime (Levi et al., 2022). GNSS velocities (Figure 6a; Caporali et al., 2013; Grenerczy et al., 2000; Serpelloni et al., 2022) and sparse focal mechanisms confirm this motion pattern, though those data sets cover mostly the northwestern margin of the Eastern Alps (Reiter et al., 2018), the MMF (Bus et al., 2009; Papí-Isaba et al., 2025), and the Vienna Basin (Decker et al., 2005). The deformation rate along the western segments of the SEMP and the Northern Calcareous Alps is below the detection threshold (Figures 5a and 5c), but a few focal mechanisms indicate thrusting north of the Tauern Window (Sugan et al., 2024; also see Figure 8). Even these scattered data points allow for comparisons between Miocene geodynamics and present-day deformation. Reconstructions by McPhee and Handy (2024) using TRANSALP (western Tauern Window) and

EASI (eastern Tauern Window) transects provide averaged N-S shortening rates for 23–14 Ma and 14 Ma to present. Along TRANSALP, shortening was estimated at 72 km (translating into  $\sim 8$  mm/yr) in the older phase, and 66 km (4.71 mm/yr) since 14 Ma. Along the EASI profile, shortening was estimated at 31 km (3.44 mm/yr) in the older phase and 12 km (0.86 mm/yr) since 14 Ma. Shortening was accompanied by E-W extension and eastward displacement at 4–6 mm/yr (Linzer et al., 2002; McPhee & Handy, 2024; Wölfler et al., 2011). Today, northward motion decreases from 2 to 3 mm/yr in the Southern Alps to  $\sim 1.2$  mm/yr at the PAF, decreasing further to  $< 0.5$  mm/yr at the Northalpine Front (Figures 6a and 6c). This translates into an eastward extrusion rate of  $1.4 \pm 0.2$  mm/yr along the MMF (Bus et al., 2009). However, present-day motion is probably accommodated farther west on the northern Lavanttal (Labot) Fault rather than the Katschberg normal fault, which played a crucial role during major extrusion phases (Ratschbacher et al., 1991a, 1991b). Prince et al. (2025), however, argue that the southern half of the Lavanttal (Labot) Fault has probably not hosted surface-rupturing earthquakes in the last  $> 1$  Ma, and it is also characterized by a lack of seismicity (Figures 7 and 9). This might indicate that this fault segment either slips aseismically or in smaller earthquakes, although Popotnig (2009) argues for ongoing activity and increased horizontal strain of 10 nstrain/yr parallels the fault trace to the west (Figure 5d).

The fast axis direction identified by two-layered shear-wave splitting (Link & Rumpker, 2023) potentially hints toward (a) ENE-ward asthenospheric flow, synchronized with the eastward extrusion of the Eastern Alps, and toward (b) shortening across the WSW-striking, deep-rooted faults along the Southalpine Front and the SE-striking faults in Slovenia like the Sava and Idrija faults. A more detailed study using Swath-D data only (Link & Long, 2024) speculates that the asthenospheric flow pattern relates to a suggested slab break-off rather than orogenic escape; further work is needed to clarify this.

When comparing the peak Miocene phase of extrusion with Pleistocene structures and present-day Eastern and Southern Alpine dynamics, the current processes no longer fit *sensu stricto* Ratschbacher et al.'s (1991a, 1991b) definition of tectonic extrusion. At orogenic scale, the necessary topographic gradient for Alpine displacement toward the Pannonian Basin, previously facilitated by Carpathian subduction, is no longer present. However, the key factor appears to be the at least eightfold reduction in the shortening rate and the fact that the vast majority of the remaining N-S convergence is now being taken up at the Southalpine Front. Today's indentation rate of Adria, reaching  $\sim 2.5$  mm/yr in the southern Eastern Alps (Figures 5a and 6a) does not translate into significant N-S shortening north of the PAF, suggesting that most of this motion is accommodated along this line, as previously noted by Brückl et al. (2010). Despite this, the Eastern Alps remain in a persistent state of N-S compression due to the motion of Adria. Once Miocene-type kinematics were re-established in the Pleistocene, these stresses were again preferentially accommodated along strike-slip fault systems, locally resembling Miocene extrusion patterns. This dynamic is also reflected in the Pleistocene and present-day geodynamics of the Carpathians and the Pannonian Basin (Jarosiński, 2005; Szczygiel et al., 2024b, 2026), which partially echo earlier Oligocene–Miocene far-field effects rather than representing their continuous persistence (Peresson & Decker, 1997b; Sperner et al., 2002). While much slower, eastward Alpine extrusion reinitiated in the Pleistocene (Figures 5a and 6c). Given that the mechanisms and rates have changed, yet the movement vectors remain largely the same, the current Eastern Alpine tectonics might be understood as “tectonic extrusion *sensu lato*.”

### 5.5. Building on Limitations: Future Research Directions

While today's Alpine GNSS time-series provide sub-millimeter displacement rates to monitor the large-scale deformation pattern, the stations are spatially too sparse to understand the nature of slip (or creep) on individual faults (e.g., Gratier et al., 2013; Harris, 2017; Mathey et al., 2020; Župančič et al., 2024). If combined with InSAR and using improved InSAR processing strategies, dense cross-fault profiles would have the potential to reveal creeping versus locked faults (e.g., Mathey et al., 2022; Metzger et al., 2021; Rouet-Leduc et al., 2021). While InSAR has been successfully used to detect slope deformation and mass movements in the Alps (e.g., Carlà et al., 2019; Schlögel et al., 2015), active fault mapping studies are rare (Anderlini et al., 2020; Areggi et al., 2023; and in the Western Alps: Mathey et al., 2022) due to high vegetation and the dominant, N-S-directed shortening, to which InSAR is least sensitive.

The AlpArray and Swath-D experiments allowed unprecedented insights into the tectonic activity of the Alps and their lithospheric structure. For the first time, a dense network covered the Alps, also allowing for a homogeneous processing of the full area. However, the temporary deployment of Swath-D introduces sampling bias when it comes to analyzing orogen-wide seismicity patterns. Our approach therefore is to interpret only regional data sets

covering the entire study area (Figure 7a). Additional local catalogs result from variable network geometries, different methods for event detection and location, and have different completeness magnitudes (Figure 7b). Interpreting a compilation of local catalogs would likely allow for additional insights, but requires a careful homogenization procedure, which is beyond what this review can deliver. However, when visually comparing Figures 7a and 7b, we do not expect a significant change to our overall broad spatial and temporal interpretations.

Some clusters of instrumentally observed seismicity do not easily fit into the overall tectonic framework as outlined above (Figures 7 and 8). This concerns, for example, seismicity west and north of the Giudicarie Fault and west of the Lavanttal (Labot) Fault. Studies focused on these regions could shed light on the underlying mechanism and help to disentangle seismicity contributions from still ongoing glacial unload, sediment redistribution, tectonics, or mantle-driven (Sternai et al., 2019).

Spatial bias is also a problem in field studies on active faults and on the geological record of strong ground motions. Cave studies are mainly carried out in limestones, reducing the spatial coverage. In the eastern part of the Alps, crystalline basement and metamorphic units cover wide stretches between the PAF and the SEMP (Schmid et al., 2004), yielding fewer caves. Lake paleoseismology is restricted to suitable archives that are not equally distributed across the orogen. Paleoseismological studies are usually carried out on structures that are already thought to be active. Another problem for paleoseismology is its dependence on suitable young sediment as a deformation marker. This largely precludes the applicability to those parts of the Alps that were glaciated during the LGM (see Figure 5c; Grützner et al., 2026) with few exceptions like Jamšek Rupnik et al. (2022). Not only do glaciations remove or rework the young sedimentary cover, but also reset the landscape record, hindering tectonic geomorphology studies and paleoseismology on faults with very long earthquake recurrence intervals. Similar to lake paleoseismology, archeoseismology needs suitable sites and long records. While theoretically archeoseismology could go back in time as far as human occupation, so far the oldest analyzed records are from Roman times. A challenge to all archeoseismological studies is the unambiguous identification of seismic shaking as the cause of the observed structural damage or its repairs (e.g., Sintubin, 2025), and the precise determination of the causative ground motion. Modeling the building response to earthquakes of different magnitudes and distances from the archeological object is a promising avenue to achieve more quantitative results (e.g., Hinzen et al., 2011, 2016, 2022).

## 6. Conclusions

We draw a general picture of the present-day deformation of the eastern part of the Alps (Figure 17) by combining data from various methods on various spatial and temporal scales (see also detailed compilation in Grützner et al., 2026). Recently published studies on the crustal and mantle architecture and evolution of the Alps, mainly derived from large-scale geophysical experiments in the framework of AlpArray and SPP 4DMB, provide insights into crustal control on the localization of deformation and on the role of mantle processes and geometry in shaping the orogen. The very low tectonic deformation rates in the Alpine region, paired with rapidly occurring, non-tectonic processes complicate the analysis of active tectonics. However, long time-series, dense monitoring networks, and the integration, cross-comparison and evaluation of different approaches, data sets, and competing models using multiple lines of evidence allow drawing a coherent picture.

- The northward movement of Adria with respect to Europe largely controls the horizontal deformation pattern of the eastern part of the Alps.
- Crustal strength controls the localization of seismicity, leading to almost non-deforming and seismically quiet blocks such as the Dolomite Indenter, and to belts of activity surrounding those regions.
- The vast majority of today's horizontal deformation is accommodated as shortening on reverse faults along the Southalpine Front ( $\sim 2$  mm/yr) and as dextral shear on the neighboring strike-slip Dinaric Fault System in western Slovenia ( $\sim 1.5$  mm/yr).
- Minor, but detectable horizontal deformation (escape) is still accommodated on the dextral SEMP/MMF fault systems ( $0.5\text{--}1$  mm/yr), on the PAF that already accommodated the eastward extrusion of crustal material in the Miocene, and across the NAF ( $<0.8$  mm/yr). Thus, the eastward extrusion of crustal material is still ongoing, but under different boundary conditions than in the Miocene, and it is much slower; minor hinterland shortening is also instrumentally detectable.
- Diffuse deformation is detectable north of the SEMP. West of the Giudicarie Fault, diffuse deformation seems to be governed by more regional or local processes.



- Slab break-off does not control the present-day vertical deformation pattern, but mantle flow around the still-attached slabs may facilitate the eastward motion of crustal material. Instead, culminating at 1.5–2 mm/yr along the highest mountain chains, today's uplift rates seem to be primarily controlled by isostasy due to ice melt (unloading) since the Last Glacial Maximum.

The deformation pattern is consistent across our different observational time scales from instrumental to geological data. This lends confidence to the interpretation of slowed-down tectonic deformation within the Alps instead of a re-organization of deformation as a response to mantle processes.

## Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

## Availability Statement

Seismic catalogs and moment tensor bulletins are from the following sources:

- Hofman et al. (2023), Petersen et al. (2021, 2025), Sugan et al. (2024), Saraò et al. (2021).
- INGV (Italy): Scognamiglio et al. (2006), <http://terremoti.ingv.it/en>.
- GCMT (Lamont-Doherty Earth Observatory of Columbia University, USA; <https://www.globalcmt.org/>): Dziewoński et al. (1981), Ekström et al. (2012).
- GEOFON: <https://geofon.gfz-potsdam.de/eqinfo/list.php>.
- SHEEC database: Grünthal et al. (2013), Stucchi et al. (2013).
- EMEC—The European-Mediterranean Earthquake Catalog: Lammers et al. (2023).
- AlpArray Research Seismicity Catalog: Bagagli et al. (2022).
- Catalogo Parametrico dei Terremoti Italiani (CPTI15): Rovida et al. (2020, 2022).
- OGS earthquake catalog for northern Italy: Rebez et al. (2024), Sandron et al. (2023).
- SED catalog for Switzerland: Fäh et al. (2011).
- Austrian Earthquake Catalog: AEC (2026), available on request <https://geosphere.at/en/data/services/earthquake-information>.
- Slovenian Earthquake catalogs: ARSO (2024). [https://potresi.arso.gov.si/doc/dokumenti/porocila\\_in\\_publika\\_cije/](https://potresi.arso.gov.si/doc/dokumenti/porocila_in_publika_cije/).
- European Archive of Historical EArthquake Data (AHEAD): Albini et al. (2013), <https://doi.org/10.6092/ingv.it-ahead>.

Topographic data shown in maps:

- SRTM topography: NASA Shuttle Radar Topography Mission (2013).
- GEBCO bathymetry: GEBCO (2024).

Fault databases:

- European Fault-Source Model EFSM2020: Basili et al. (2022, 2024).
- ITaly HAZards from CAPable faults ITHACA: ITHACA Working Group (2019).
- Database of Individual Seismogenic Sources DISS 3.3.1: DISS working group (2025).
- Banca dati georiferita delle faglie attive della Regione Friuli Venezia Giulia: Marchesini et al. (2021).
- Database of Active Faults in Slovenia: Atanackov et al. (2021, 2022).
- Tektonische Linien und Kraterränder—Austria Fault database: GeoSphere Austria (2025).

GNSS velocity field:

- Serpelloni et al. (2022).

Paleoseismology database:

- The Paleoseismic Database of Germany and Adjacent Regions PalSeisDB v1.0: Hürtgen et al. (2020, 2021).

Plotting software:

- GMT: Wessel et al. (2019).

- matplotlib: Hunter (2007).
- QGIS: QGIS (2025).

An A0-sized map with most of the data discussed here is available at <https://doi.org/10.5281/zenodo.19206213>.

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