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Structural inheritances, fault segmentation and seismogenic potential at the front of the eastern Southern Alps (central Carnic Prealps, NE Italy)

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ABSTRACT

New geological and morphotectonic surface data coupled with the revision of the ENI-Exploration & Production seismic lines, made it possible to review the tectonic structure of the Pliocene-Quaternary front of the eastern Southern Alps in the area between the Cellina River and the Tagliamento River (central Carnic Prealps, NE Italy). The eastern Southern Alps are a SE-verging fold and thrust belt in activity from the middle Miocene to the Present. The presence of Paleogene structural inheritances influenced the current structural arrangement of the thrust-belt and the potential seismogenesis, supporting segmentation of the Neoalpine external front. In particular, the presence of the NW-SE trending Mt.Ciaurlec – Palmanova – Pozzuolo structural high, inherited from the W-ward propagation of the External Dinarides during Paleogene, generated lateral lithological facies change and influenced not only the undulation between the Neogene-Quaternary Maniago-Meduno and Toppo-Forgaria Thrusts, but also the segmentation of the outermost portion of the Neoalpine external front consisting into two segments with different geometric and structural characteristics: 1) the ENE-WSW striking Arba-Sequals segment that runs buried under the upper Pleistocene sequences of the piedmont Friuli plain; 2) the W-E Ragogna segment that shows widespread evidence of surface deformation of the Last Glacial Maximum (LGM) alluvial plain. In particular, the long-lasting activity of the Ragogna segment is testified by the late Miocene-Middle Pleistocene angular unconformities, forced drainage anomalies and tilted and uplifted Quaternary palaeosurfaces. A discussion on the seismogenic potential of the investigated structures is proposed.

1. Introduction

Structural inheritance is a critical component of the geological evolution of continental lithosphere: within orogenic belts it has been recognized that important lateral changes in tectonic structures coincide with changes in stratigraphic style. Just like pre-existing fault structures developed during continental rifting may be preferentially reactivated during following contractional tectonics and vice-versa (Butler, 1989; Doglioni, 1992b; Butler et al., 2006), similarly, pre-existing fault structures developed during a compressive tectonic phase may be reactivated during subsequent contractional tectonics characterized by a differently oriented sigma1. Therefore, knowledge of structural inheritance is fundamental to understanding how deformation localizes in the continental lithosphere. Moreover, accretionary wedges, especially during their late collisional stages, consist of numerous reverse faults, mainly with a low-angle setting and a common or opposite vergence. The crustal volumes affected by such contractional features are characterized by overstepping and/or overlapping structures, curved geometries, and complex kinematic patterns. Segment boundaries generally correspond to structural discontinuities such as relay zones and large step-overs, pronounced bends, or branch faults, large cross-faults, and changes in rheology, also linked to inherited lateral discontinuities both structural and stratigraphical. As usual, the along-strike end of a frontal ramp is usually connected across strike to another frontal ramp by a lateral connector (transverse fault, lateral ramp or displacement-transfer zone) that transfers displacement across strike (Schwartz and Sibson, 1989).

Arc-shaped geometries of different sizes and curvatures developed also in the external front of the eastern Southern Alps (ESA), generating a complex system of minor-order structures with different dimensions

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and seismogenic potential. Although several detailed seismotectonic investigations have been carried out (e.g. Benedetti et al., 2000; Galadini et al., 2005; Burrato et al., 2008; Moulin et al., 2014; Poli and Zanferrari, 2018; Viscolani et al., 2020; Poli et al., 2021a; Patricelli et al., 2022; Picotti et al., 2022; Diercks et al., 2023), segment boundaries within major seismogenic sources, and especially their possible impact in terms of partial reactivations of the whole structure and maximum credible magnitude that could be released, has been not sufficiently treated.

Cenozoic-to-recent time interval of the ESA evolution recorded a complex geological history, characterized by episodes of tectonic inversion with reactivation and/or modification of pre-existing structures (e.g. Doglioni, 1992a, 1992b; Castellarin et al., 1992; Zanferrari et al., 2013): stratigraphic and/or structural inherited discontinuities often generated segmentation of the frontal structures (Galadini et al., 2005).

In this paper we describe the relationship among inherited structures, segmentation and seismogenesis of a set of active faults affecting the external front of the ESA in the Carnic Prealps (Fig. 1). In particular, joining new geological and morphotectonic evidence with the structural characteristics at depth (mainly obtained by means of interpretation of a regular grid of industrial seismic lines gently supplied by ENI-E&P), we focused on the influence of the Paleogene inherited WNW-ESE striking, W-verging Dinaric external thrust front on the propagation of the outermost portion of the Pliocene-Quaternary thrust-front.

In this context we revised the geometric, kinematic, dynamic and chronological parameters of the Arba-Ragogna thrust system *Auct.* (Galadini et al., 2005; Burrato et al., 2008; Zanferrari et al., 2008a; Poli et al., 2009) and divided it into two different segments namely Arba-Sequals and Ragogna respectively (AS and RA in Fig. 1).

Moreover on the basis of Wells and Coppersmith (1994) empirical relationships, we recalculated the maximum seismogenic potential of the study structures and compared it with the maximum potential volume of the area according to Petricca et al. (2019, 2022).

2. Regional tectonic framework and seismotectonics

The investigated area belongs to the external front of the eastern Southern Alps in Friuli and it is located at the border between the Carnic Prealps and the adjoining piedmont Friuli plain (Fig. 1). The Southern

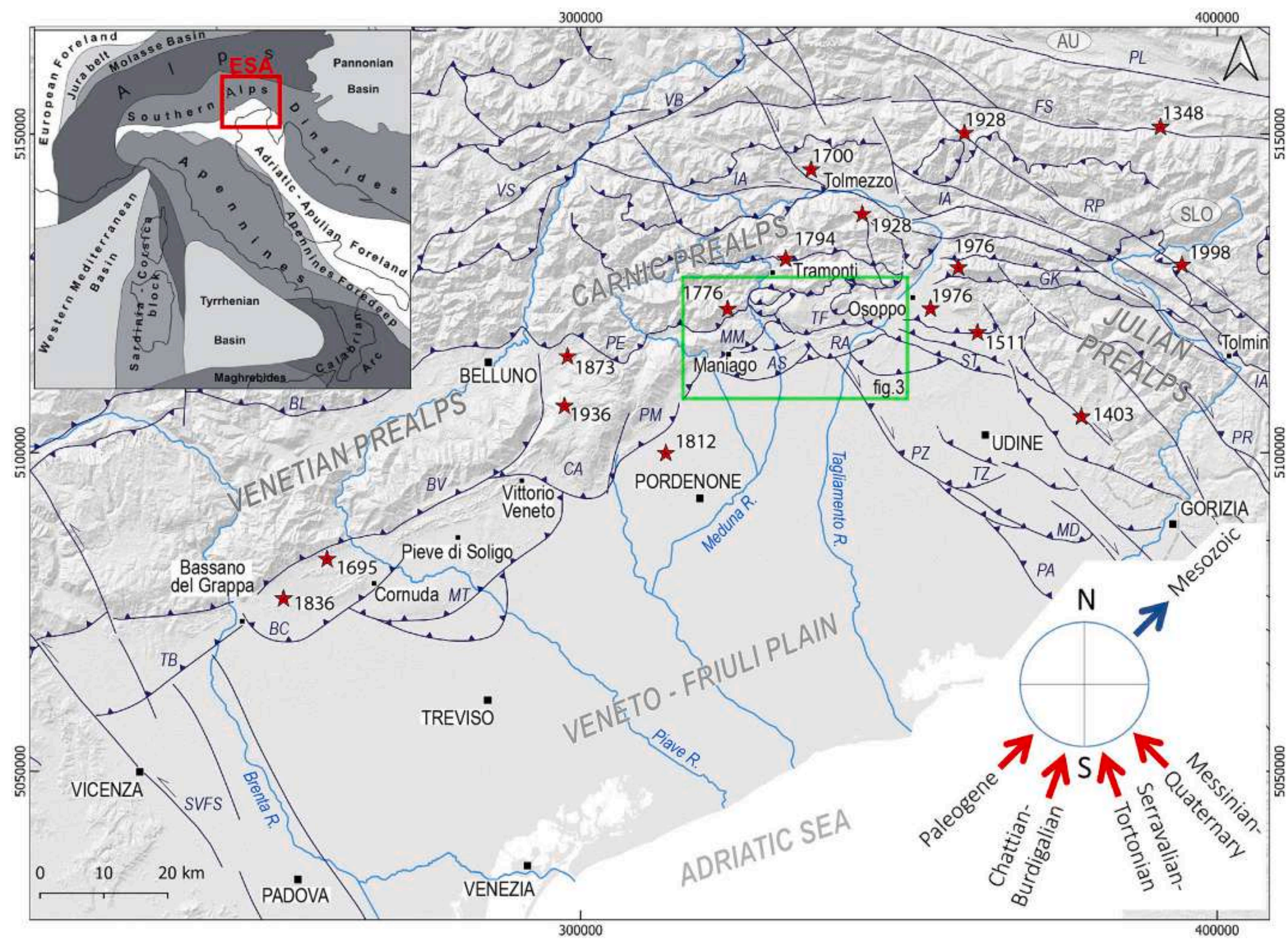

Fig. 1. Structural sketch map of the eastern Southern Alps in NE-Italy and W-Slovenia (modified from Zanferrari et al., 2013). Red stars: historical and instrumental seismicity (Mw > 5.5, according Rovida et al., 2022). Green rectangle: the study area of Fig. 2. Legend: AS: Arba-Sequals Thrust; RA: Ragogna Th.; BC: Bassano-Cornuda Th.; BL: Belluno Th.; BV: Bassano–Valdobbiadene Th.; CA: Cansiglio Th.; FS: Fella–Sava Fault; GK: Gemona–Kobarid Th.; IA: Idrija–Ampezzo Fault; MD: Medea Th.; MM: Meduno Maniago Th.; MT: Montello Th.; PA: Palmanova Th.; PE: Periadriatic Th.; PL: Periadriatic Lineament; PM: Polcenigo-Montereale Th.; PR: Predjama Fault; PZ: Pozzuolo Th.; RP: Ravne–Paularo Fault; RS: Raša Fault; ST: Susans-Tricesimo Th.; SVFS: Schio-Vicenza Fault System; TB: Thiene-Bassano Th.; TF: Toppo-Forgaria Th.; TZ: Terenzano Th.; VS-VB: Valsugana-Val Bordaglia Fault System. On the bottom right the sigma1 orientation of the main tectonic phases which affected NE-Italy, modified after Castellarin et al. (2006). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Alps develop along the northern margin of Adria microplate and represent the S-verging, back-fold and thrust belt of the Alpine chain (e.g. Schmid et al., 2004 and refs. therein), from which they are separated by the Periadriatic Lineament. At present, across NE Italy, GPS studies estimate N—S shortening rates in the order of 2–3 mm/yr (Devoti et al., 2011; Serpelloni et al., 2016, Areggi et al., 2023).

After a long history of rifting and subsidence during the Mesozoic time, eastern Southern Alps experienced compressive tectonics and were affected by two main tectono-sedimentary phases during Cenozoic time span: the Late Cretaceous-middle Eocene (Dinaric) event and the middle Miocene-Quaternary (Neoalpine) event (e.g. Doglioni and Bosellini, 1987; Doglioni, 1990; Doglioni, 1992a; Castellarin and Cantelli, 2000; Castellarin et al., 2006).

In this context, Late Cretaceous-middle Eocene western propagation of the External Dinaric Chain in NE Italy caused the progressive drowning of the Cretaceous Friuli Carbonate Platform, the stack of a few thousand meters of turbidites in the foredeep basins (Tunis and Venturini, 1992) and a considerable crustal shortening (Doglioni and Bosellini, 1987; Zanferrari et al., 2013).

In the present structural framework, the NW-SE trending inherited external Dinaric front is referable in the Friuli Plain to the Palmanova-Pozzuolo Thrust-system (PA-PZ) (Placer et al., 2010) (Fig. 2). Particularly, the activity of the Palmanova-Pozzuolo frontal ramp caused the displacement of about 1500 m of the carbonate platform and the development of a NW-SE trending structural high, bordered by two turbiditic basinal domains towards the NE and SW, respectively (Cati et al., 1987; Venturini, 1987; Merlini et al., 2002; Nicolich et al., 2004; Zanferrari et al., 2008a and Zanferrari et al., 2008b; Poli and Zanferrari, 2018; Patricelli and Poli, 2020; Poli et al., 2021b and unpublished ENI industrial seismic lines). At the top of the carbonate anticlinal ramp a reduced thickness of hemipelagic turbidites is present. The north-westernmost portion of the inherited Dinaric external front is represented by the Monte Ciaurlec Thrust, which has been embedded within the Southalpine Chain and presently outcrops in the Meduna valley causing a duplication of the carbonate platform units (Zanferrari et al., 2008a; Ponton, 2010; Poli et al., 2021a).

During the latest Oligocene-early Miocene, the Veneto-Friuli area was part of a distal foreland, with a peripheral bulge initially located across the nowadays shore. The topographic load driven by the far Alpine uplift caused a very weak crustal flexure (about 1° according to Fantoni et al., 2002). The foreland basin slowly spread towards SSW, so that the terrigenous carbonate platforms of the “Cavanella Group” reached the nowadays shoreline only during the Burdigalian. In the Friuli area the Aquitanian-Langhian succession is 600–700 m thick, making part of the piedmont hills (Stefani, 1984; Zanferrari et al., 2008a; Zanferrari et al., 2008b).

Starting from middle Miocene, the ESA were involved into the Neoalpine tectonic event, in which two compressional phases can be

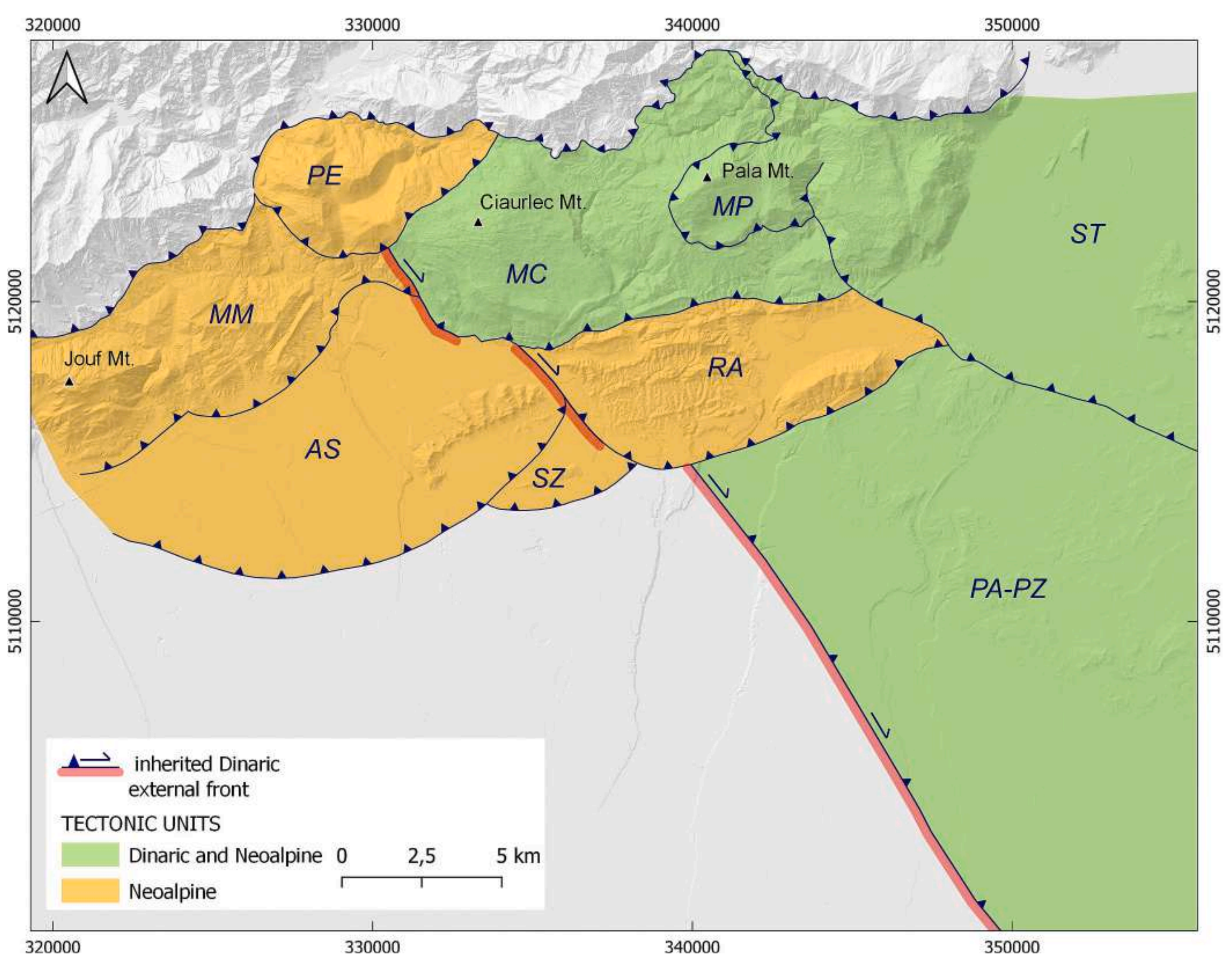

Fig. 2. – Tectonic units of the study area. Acronyms: AS: Arba-Sequals; MC: Monte Ciaurlec; MM: Maniago-Meduno; MP: Monte Pala; PA-PZ: Palmanova-Pozzuolo; PE: Periadriatic; RA: Ragogna; ST: Susans-Tricesimo; SZ: San Zenone.

recognized: the Serravalian-Tortonian (σ1: about NNW-SSE) and the Messinian-Pliocene (σ1 about NW-SE) respectively (Castellarin et al., 1992; Castellarin and Cantelli, 2000; Fantoni et al., 2002).

The Serravallian-early Messinian time span constitutes the tectonically most active period in the eastern Southern Alps history (Castellarin et al., 1992). Rapid exhumation of hinterland units, estimated at around 4 km started at about 11 Ma according to thermal modelling of apatite fission track data (Heberer et al., 2017; Monegato et al., 2010b) and had a strong impact on the Venetian Foreland Basin in terms of both flexural subsidence and clastic input (Fantoni et al., 2002; Mancin et al., 2009). In particular, provenance data on clastic units prove that the main source change triggered by the tectonics along the Valsugana thrust system occurred since the late Tortonian (Zattin et al., 2003; Monegato et al., 2010b).

Flexural subsidence is clearly recorded by the wedge geometry of the Serravallian-Messinian clastic wedge, which passes from >3000 m thick in the sections exposed in the Venetian foothills (Massari et al., 1986) to about 1500 m in the Venetian plain, progressively decreasing to zero in the present day offshore area.

Foredeep deposition stopped in the latest Messinian time (Toscani et al., 2016; Mancin et al., 2009).

The progressive migration towards the NE of the Messinian-Pleistocene NW-SE striking Apennines frontal thrust belt (e.g. Caputo et al., 2010), caused a marked flexuration towards the SW of the Venetian and Friulian foreland (Mancin et al., 2009).

During the late Messinian, subaerial erosion affected the Venetian-Friulian basin due to the sea-level drop during the Mediterranean salinity crisis (Manzi et al., 2005), generating incised valleys not exceeding 300 m in depth (Mancin et al., 2009; Toscani et al., 2016). The following marine ingression (Ghielmi et al., 2010) did not reach the NE-Friuli plain where continental conditions persisted (Toscani et al., 2016), but affected the Messinian paleovalleys up to the present prealpine border. In the Messinian Tagliamento paleovalley near Osoppo, a marine Gilbert-type delta of Late Zanclean age (Osoppo conglomerate) prograded on Zanclean brackish deposits (Monegato, 2006; Monegato and Vezzoli, 2011). Pliocene marine deposits crop out locally along the Veneto prealpine area: Cornuda (Venzo, 1977), Vittorio Veneto (Cousin, 1981); Bassano del Grappa (Favero and Grandesso, 1982) and Pieve di Soligo (Viaggi and Venturini, 1996).

The Neoalpine tectonic event superimposed on the inherited Dinaric structural framework causing the displacement and local reactivation of the pre-existing Dinaric structures (Zanferrari et al., 2013). In this context, the Palmanova-Pozzuolo external front was reactivated during Neogene with a transpressive kinematics causing the persistence of the structural high condition, and the deposition of reduced thicknesses of Cavanella Group and upper Molasse units. Moreover, in response to the about NNW-SSE oriented sigma1, new WSW-ENE reverse splays developed from PA-PZ, like the Terenzano (TZ) and Medea (MD) Thrusts (Fig. 1), characterized by a purely dip-slip kinematics (Venturini, 1987; Poli, 1996; Patricelli and Poli, 2020). A similar evolution affected also the Mt. Ciaurlec inherited structure, whose embedding in the ESA development caused its SW-ward shift with respect to the Palmanova-Pozzuolo front (Fig. 2) (Zanferrari et al., 2008b).

As documented by geological data (Caputo et al., 2010; Monegato, 2006), Pliocene-Quaternary evolution of ESA is marked by the activation and by the southward propagation of the outermost thin-skinned thrust-system that involves both the prealpine area and the adjoining piedmont plain between Veneto and Friuli (Castellarin and Cantelli, 2000; Galadini et al., 2005): a middle to strong seismic activity is documented starting from historical time in Veneto and Friuli prealpine area causing widespread damage and human losses (Rovida et al., 2022; Guidoboni et al., 2019), (Fig. 1). At present the external Southalpine front is arranged in a set of arcuate WSW-ENE to WNW-ESE trending thrust-segments (Galadini et al., 2005), whose terminations are located where the faults are crossed by a transverse structure (e.g. a transfer fault) or where deformation decreases for the presence of another thrust segment with an *en-echelon* relationship (e.g. de Polo et al., 1991; Mirzaei et al., 1999) (Fig. 1). Despite the rather high seismicity level and the well-defined tectonic regime of this region, the identification of individual seismogenic sources and their association to specific historical earthquakes is not always clear because of the structural configuration of the thrust belt, the geometry of the active faults (often low to middle-angle blind thrusts) and the low rates of displacement.

3. Stratigraphy

The pre-Pliocene stratigraphic succession cropping out in the study region ranges from Upper Triassic to upper Miocene (Fig. 3 and Fig. S1 of the Supplementary Material). From both a stratigraphic and rheological point of view, we can identify four main complexes.

a) The Upper Triassic Complex (UTC): it is characterized by a thickness of the order of 1000–1500 m and includes the Dolomia Principale (Upper Carnian-Norian) and the Dachstein Limestone (Rhaetian). This complex largely outcrops at the hangingwall of the Periadriatic Thrust (PE in Fig. 3); at the base of UTC, the evaporitic Travenanzes Fm. locally outcrops (Carnian unconformity).

b) The Lower Jurassic – Upper Cretaceous Carbonate complex (JCCC): it includes stratigraphic successions of two distinct paleogeographical domains. The Soverzene Fm., Vajont Limestone and Fonzaso Fm. lie on top of the Calcari Grigi Fm. north of the Periadriatic Thrust and represent the lower portion of the Mesozoic Carnian-Slovenian basinal succession (Hettangian – Kimmeridgian *p.p.*). Differently, the Lower Jurassic-Upper Cretaceous Friuli Carbonate Shelf (Hettangian-earliest Maastrichtian) is made of a thick limestones succession, about 2500 m thick (Calcari Grigi Fm., Cellina Limestone, Ellipsactinie Limestone and Monte Cavallo Limestone).

c) A 700 m thick, hemipelagic - turbiditic succession (Scaglia Rossa Friulana and Clauzetto Flysch, Selandian-Ypresian in age) (FLY) unconformably covering the Cretaceous carbonates.

d) The mostly terrigenous Miocene sediments, divided into three sedimentary sequences: i) the Aquitanian to Langhian shallow-water mixed carbonate-terrigenous platform of Cavanella Group about 600 m thick (CAV), which overlays unconformably the Ypresian units; ii) an about 500 m thick coarsening and thickening upward succession of Serravallian – Tortonian age marls (Serravallian Tarzo Marl) and lithic arenites (Vittorio Veneto Sandstone) (AT) and iii) the up to 1500 m thick upper Tortonian – lower Messinian conglomerates and arenites (Montello Conglomerate) (MON).

The Pliocene-Quaternary continental succession is mostly composed of sediments resulting from the coalescence of alluvial fans of the piedmont plain. The present-day Tagliamento River flows inside a 60 m deep incision, which was carved during the end of the Late Pleistocene at the withdrawal of the glaciers (Monegato et al., 2007; Fontana et al., 2014); this trenching also caused the incision of the tributary streams including Cosa, Valeriano and Gerchia creeks. Similar trenches, 30 m deep, characterise the apex of the Cellina and Meduna alluvial fan (Avigliano et al., 2002).

The more complete section is outcropping along the Tagliamento River (Paiero and Monegato, 2003; Zanferrari et al., 2008a; Monegato et al., 2010a; Monegato et al., 2023), while other significant sections can be detected along the Valeriano Creek (Monegato et al., 2010a) and the Meduna and Cellina incisions (Zanferrari et al., 2008a; Monegato and Poli, 2015).

The San Pietro di Ragogna conglomerate (Fig. 4a), ascribed to the Gelasian (Martinetto et al., 2012), is the lowermost unit and unconformably overlays the lower Messinian member of the Montello Conglomerate at the foothill of the Ragogna Hill (for location see Fig. 3). The Quaternary sedimentary succession laying on the San Pietro di Ragogna conglomerate (Fig. 4a and b) is made of a stack of sandy gravel and glacial diamicton related to the Tagliamento end-moraine system, its outwash plain and the Arzino alluvial fan (Paiero and Monegato, 2003; Zanferrari et al., 2008a; Fontana et al., 2019). The last

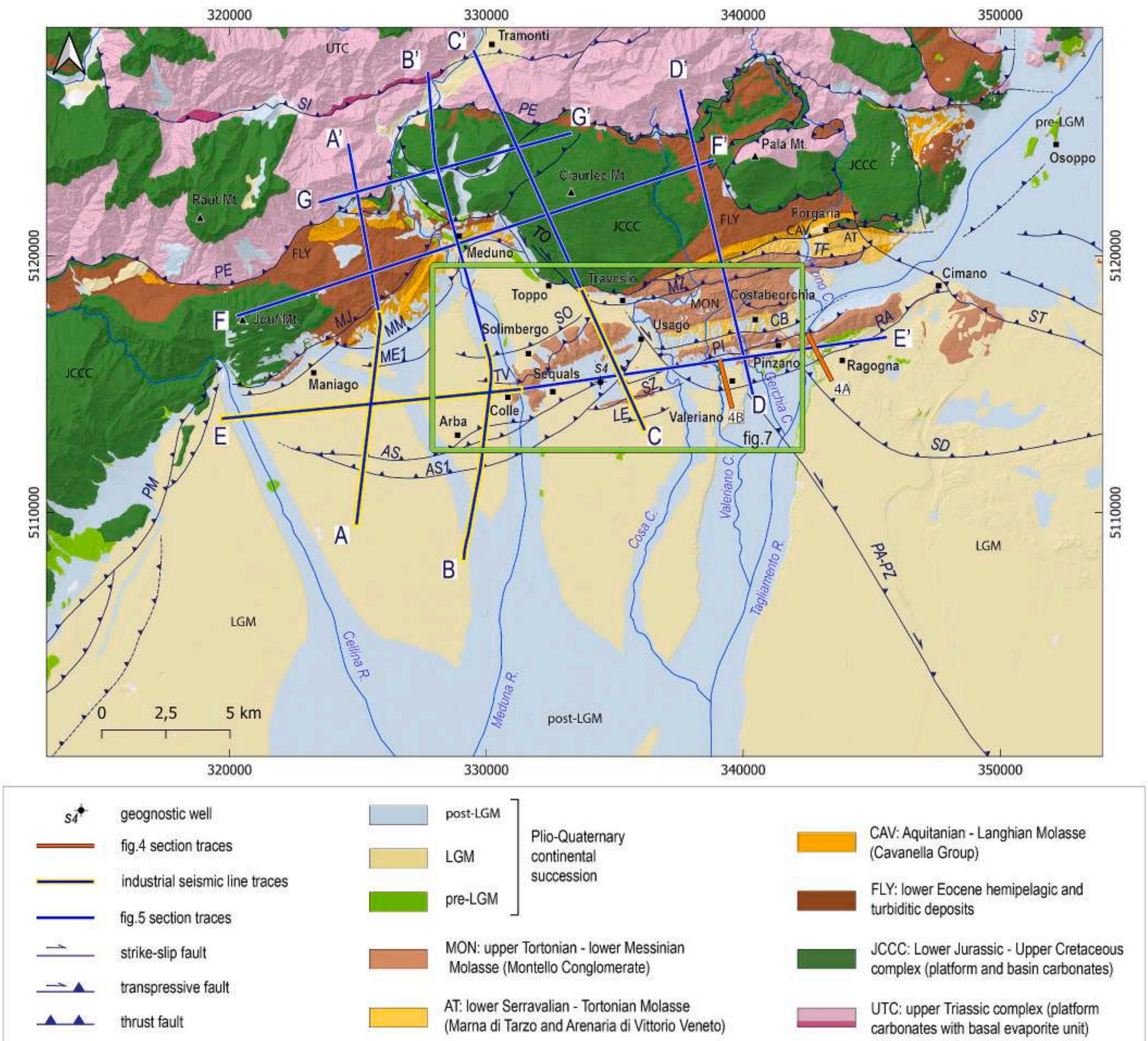

Fig. 3. – Geological sketch map of the Carnic Prealps between Cellina and Tagliamento Rivers (modified from Carulli et al., 2000; Carulli, 2006; Zanferrari et al., 2008a; Zanferrari et al., 2013; Monegato and Poli, 2015 and Poli et al., 2015). Shaded relief from DTM supplied by Friuli Venezia Giulia Region (grid: 5 m). Legend: AS and AS1: Arba–Sequals Thrust system; CB: Costabeorchia Th.; LE: Lestans Th.; MM: Maniago-Meduno Th.; ME1: Meduno 1 external splay of Meduno Th; MJ: Mt. Jouf Th.; MZ: Manazzons Th.; PA-PZ: Palmanova-Pozzuolo Th.; PE: Periadriatic Th.; PI: Pinzano Th.; PM: Polcenigo – Montereale Th.; RA-Ragogna Th.; SD. San Daniele Th.; SI: Silisia Th.; SO: Solimbergo Th; ST: Susans-Tricesimo th.; SZ: San ZenoneTh.; TF: Toppo-Forgaria Th.; TO: Toppo Tear Fault; TV: Travesio Th. Green rectangle is the area of Fig. 7. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

aggradation phase is related to the Tagliamento glacier outwash deposition during the Last Glacial Maximum in the Alps (LGM, Ivy-Ochs et al., 2022). Deposits linked to the LGM end moraine system are dated at 29 to 22 ka cal BP and characterise the topmost part of the succession (Monegato et al., 2007). The pre-LGM unit of the Arzino (8 in Fig. 4) was dated at 40.6–36.3 ka cal BP (recalibrated after Monegato et al., 2010a). The older alluvial and fluvioglacial units (3 in Fig. 4) lay below a thick paleosoil and are ascribed to the Lower-Middle Pleistocene (Fontana et al., 2019).

To the west, the succession variations along the foothills depend on the merging of Cellina, Meduna and Arzino alluvial fans during their Quaternary evolution (Avigliano et al., 2002; Paiero and Monegato, 2003; Monegato et al., 2010a; Monegato and Poli, 2015; Fontana et al., 2019). The deposits cropping out along the Valeriano Creek (Fig. 4b) were dated using radiocarbon and Optic Stimulated Luminescence (OSL) methods (Monegato et al., 2010a); they recorded aggradation and sedimentation phases from the Middle to the Late Pleistocene in the area of interposition between the Meduna and Arzino alluvial fans. In detail the lacustrine succession (unit 4 in Fig. 4b) contains horizons with soft-sediment deformations dated at 243 ± 23 ka BP. The Meduna alluvial fan is made by two LGM lobes whose radiocarbon age of the surface are about 18.5 ka cal BP and 11.2 ka cal BP (Avigliano et al., 2002; Zanferrari et al., 2008a; Monegato and Poli, 2015); these fans have been deeply trenched by Meduna and Cosa streams during the Holocene. The older units crop out discontinuously at the bottom of the slopes and are not younger than the Middle Pleistocene (Monegato et al., 2010a; Monegato and Poli, 2015). The Cellina alluvial fan ended its aggradation at about 14 ka cal BP (Avigliano et al., 2002), older deposits crops out as

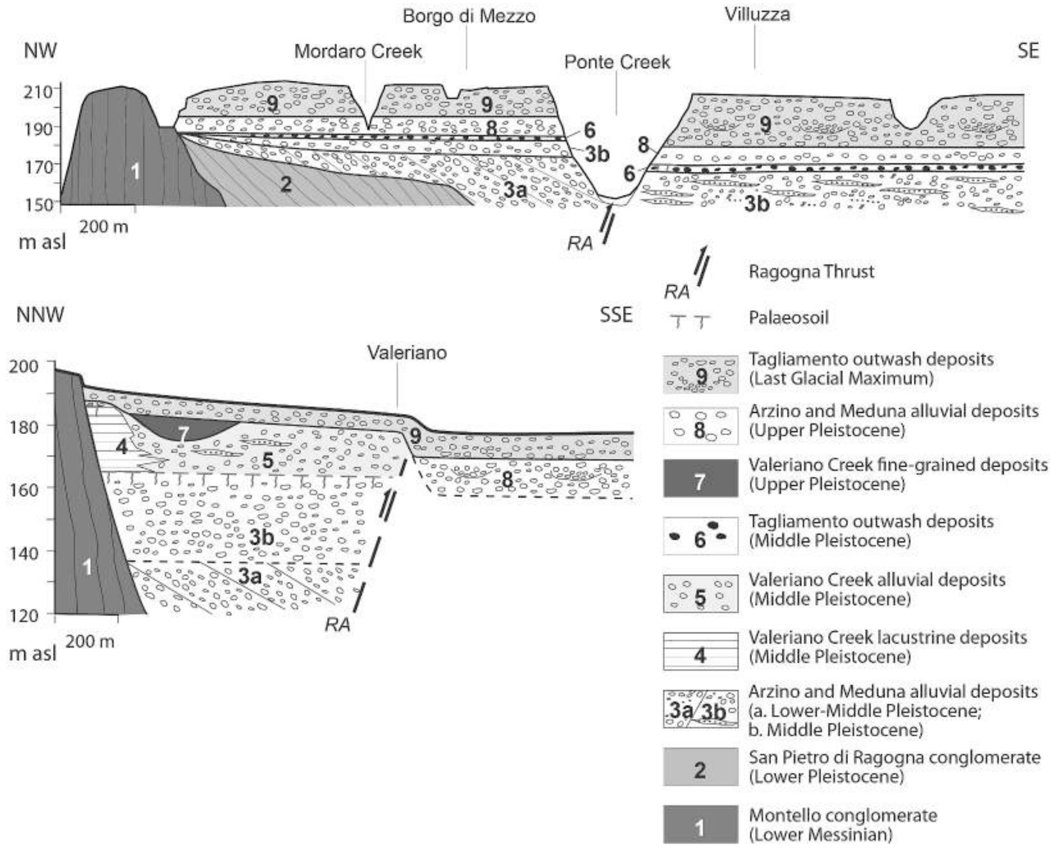

Fig. 4. –a) Stratigraphic and structural sections of Ponte Creek (vertical exaggeration: 5×) and b) Valeriano (vertical exaggeration: 10×). Location in Fig. 3).

conglomerate limbs and terrace in the final reach of the valley (Zanferrari et al., 2008a).

4. Methodology

This study was based on a multidisciplinary approach: in order to investigate ground anomalies possibly linked to the recent activity of the tectonic structures we analysed the detailed 1 m resolution DTM, derived from the LiDAR relief conducted by the Friuli Venezia Giulia Protezione Civile during 2006–2010, with a mean density of four points per square meter and freely available on the Regione Autonoma Friuli Venezia Giulia website (https://irdat.regione.fvg.it/CTRN/ricerca-cartografia/). Then, a detailed geological survey made in selected areas allowed us to validate the morphological observations. Moreover, to reconstruct the structural arrangement at depth we analysed a grid of seismic reflection profiles gently supplied by ENI S.p.A.

The interpretation of ENI industrial seismic lines, including both line drawing and time to depth conversion, was conducted in the MOVE Software (by PetEx Ltd., Edinburgh, version 2022.1). Concerning the adopted velocity model (Table 1), the velocity values of the detected seismostratigraphic units were extracted from the literature (Zanferrari et al., 2008a, b; Toscani et al., 2016; Patricelli and Poli, 2020). Particularly, regarding the middle-late Miocene Molasse, since the marly-arenaceous lower Serravalian-Tortonian Molasse (AT) seismic facies is clearly detectable on seismic lines, two distinct velocity values were used for AT and the overlying dominantly conglomeratic upper Tortonian-lower Messinian Molasse (MON), respectively.

Table 1
Velocity model adopted for the 2D depth seismic lines conversion. Velocity values (p-waves) derived from ENI well-logs and from bibliography.

SEISMOSTRATIGRAPHIC UNITS	VELOCITY P-WAVES [m/s]
Plio-Quaternary Units (HOL, LGM, pre-LGM)	2000
upper Tortonian-lower Messinian Molasse (MON)	3500
lower Serravalian-Tortonian Molasse (AT)	3000
Aquitanian-Langhian Cavanella Group (CAV)	4100
lower Eocene hemipelagic and turbiditic Units (FLY)	3600
Lower Jurassic-Upper Cretaceous Carbonate platform Units (JCCC)	5800

Following the time to depth conversion, deep structural and geological interpretations were joined with the structural and geological field data, partly obtained from the available official maps (Carulli et al., 2000; Zanferrari et al., 2008a; Poli et al., 2015; Monegato and Poli, 2015), partly collected from original field data.

In particular, seven about N-S and about *E*-W striking profiles were constructed across the mountain front (see section traces in Fig. 3), to obtain seriated geological cross-sections (see Chapter 4). The interpolation of the fault lines mapped on each geological cross sections allowed to reconstruct the 3D faults surface model (see Chapter 4) characterizing both the Neogene-Quaternary Toppo-Forgaria and Maniago-Meduno Thrust Systems and the two new segments, i.e. Arba-Sequals and Ragogna. Finally, the additional step dealt with the 3D analysis of the crustal volume comprised between the elaborated fault surfaces, in order to investigate its associated seismogenic potential.

5. Structural setting of the area

The structural evolution of the Carnic Prealpine study area (Fig. 3) is presented below. During Late Cretaceous-middle Eocene, the NW-SE trending Mt. Ciaurlec Thrust (MC in Fig. 2) was part of the W-verging external Dinaric front, superimposing the Friuli Carbonate Platform on the turbiditic and hemipelagic sequences (Clauzetto Flysch and Scaglia Rossa) of its Dinaric foredeep (i.e. the present Maniago-Meduno tectonic unit, MM in Fig. 2 and Fig. 3) (Ponton, 2010; Poli et al., 2021a), and causing the formation of a carbonate structural high which extended SE-ward up to the Friuli Plain (PA-PZ structural unit, Fig. 2).

Later, Dinaric structures were involved in the Neoalpine event characterized by σ1 ranging from NNW-SSE to NW-SE. A set of WSW-ENE striking thrusts, i.e. the Maniago-Meduno Th. (in the western portion) and the Toppo-Forgaria Th. (in the eastern one) developed, giving rise to two S-verging prominent anticlines, the Mt. Jouf (1203 m asl) and Mt. Ciaurlec (1143 m asl) karstic massifs respectively (Fig. 3). The geometry of the Neogene-Quaternary compressive structures was influenced by the Dinaric inheritances because under the Neogene regional compressive stress, the Dinaric structures were partly resumed and folded. In particular, we observed that a) Toppo-Forgaria Thrust re-

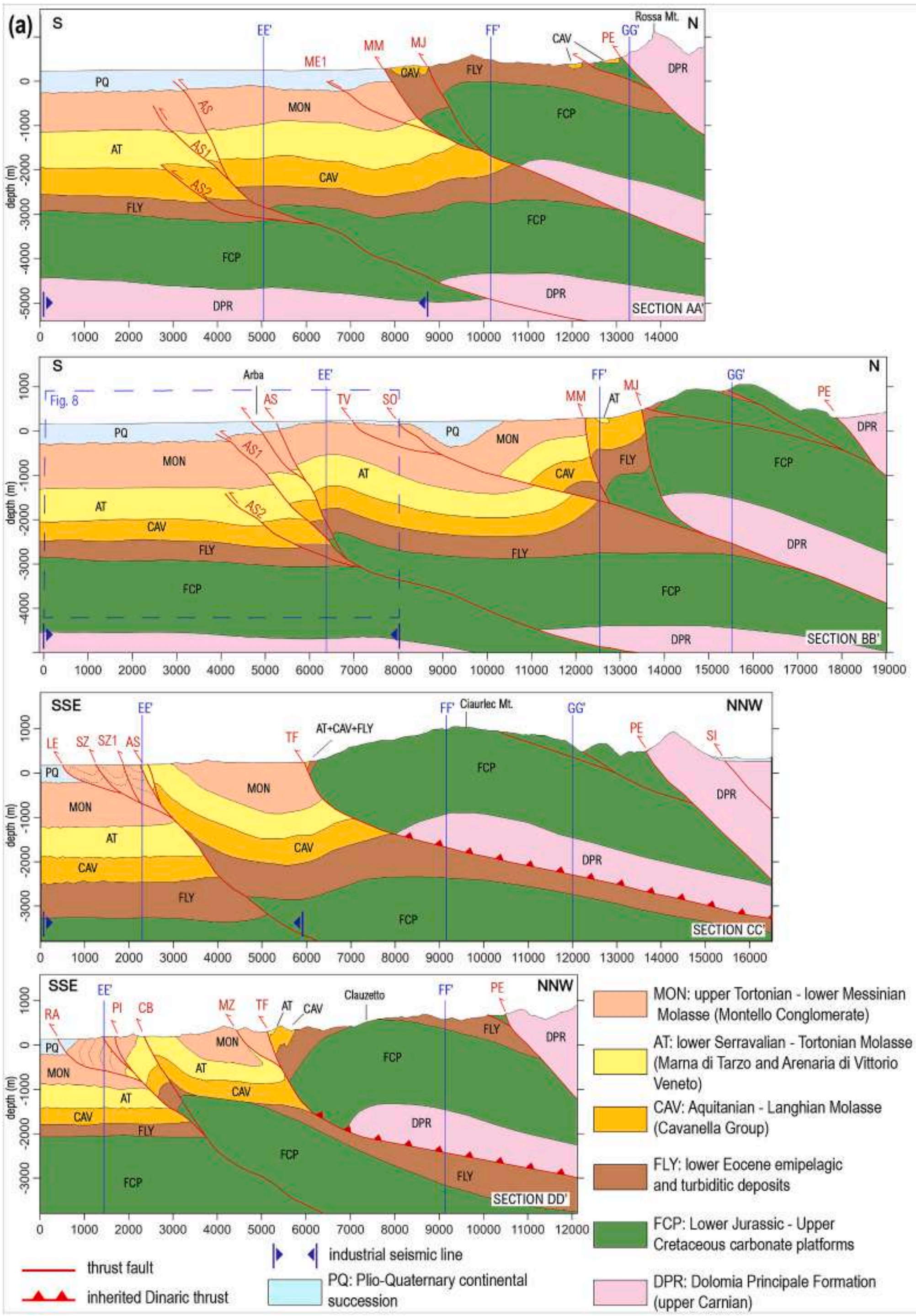

Fig. 5. a – N-S trending geological cross sections AA', BB', CC', and DD'; 5b – about E-W trending geological cross sections EE', FF' and GG'. Location in Fig. 3. Source data: for the piedmont area Zanferrari et al., 2008a and seismic lines gently supplied by ENI, Exploration & Production Division. For the relief: original geological survey by the Authors and Carulli et al. (2000). Legend of tectonic structures: AS, AS1, AS2: Arba–Sequals Thrust-system; CB: Costabeorchia Th.; LE: Lestans Th.; MM: Maniago-Meduno Th.; ME1: Meduno 1 external splay of MM Th; MJ: Mt. Jouf Th.; MZ: Manazzons Th.; PA-PZ: Palmanova-Pozzuolo Th.; PE: Periadriatic Th.; PI: Pinzano Th.; RA: Ragogna Th.; SI: Silisia Th.; SO: Solimbergo Th; SZ, SZ1: San Zenone Thrust-system; TF: Toppo-Forgaria Th.; TO: Toppo transfer Fault; TV: Travesio Th.

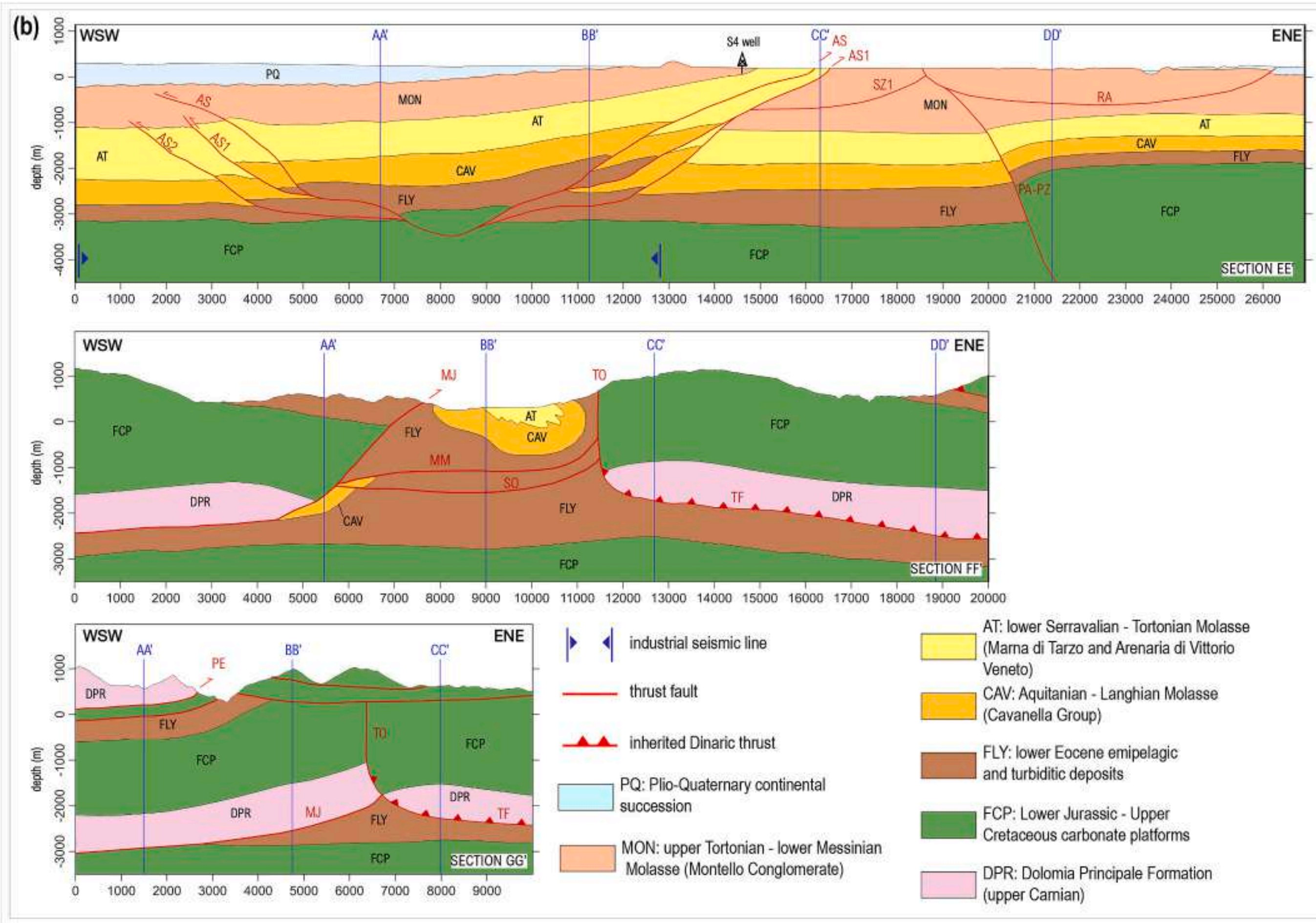

Fig. 5. (*continued*).

activated the low angle W-verging Dinaric ramp as S-verging Neogene detachment (Fig. 5a, Sections CC' and DD') and b) Maniago-Meduno Th. and Toppo-Forgaria Th. join through the Toppo transfer fault (TO in Fig. 3; Fig. 5b, Sections FF' and GG') resuming the NW-SE striking lower Eocene carbonate ramp anticline of the Dinaric Ciaurlec Tectonic Unit; c) the structural high influenced the propagation of the Neoalpine external front. Based on the geological cross sections, arranged in a dense grid (Fig. 3), we reconstructed the 3D surface of the main thrust faults (Fig. 6). Therefore, in the following we describe the spatial and geometric arrangement of the tectonic structures and their

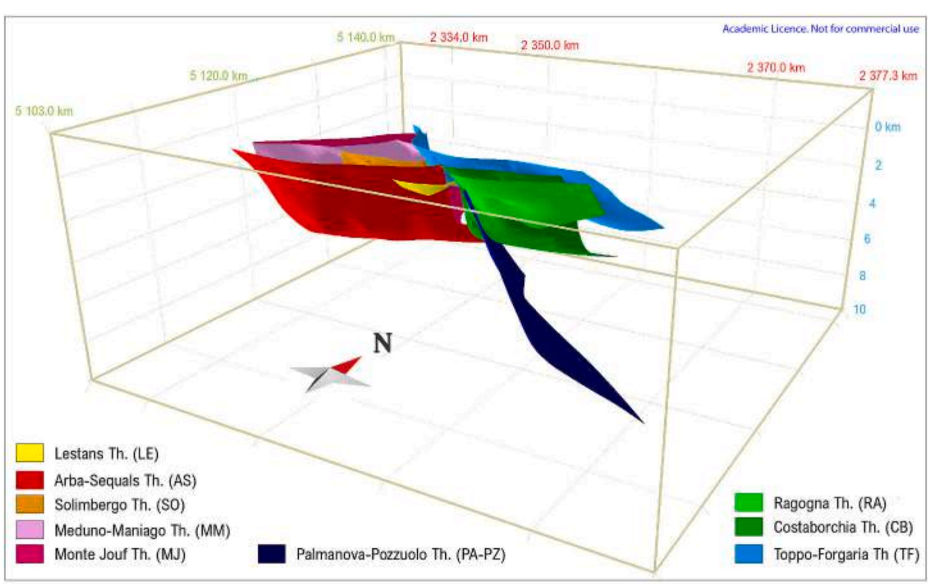

Fig. 6. 3D structural model showing the reconstructed fault surfaces of the study area.

morphotectonic evidence.

5.1. Maniago-Meduno Thrust System

The Maniago-Meduno Thrust System consists of a mostly buried NE-SW trending, SE-verging medium to high angle thrust, extending for about 12 km from Maniago to Meduno (MM in Fig. 3 and in Fig. 5a, Section AA'). At surface it was segmented by Poli et al. (2021a) into two minor splays Maniago and Meduno thrusts that give rise to a series of outcropping NE-SW trending tight folds involving both the lower Eocene hemipelagic and turbiditic deposits and the Miocene terrigenous units (Zanferrari et al., 2008a). At the outlet of the Meduna valley, MM changes in strike giving rise to a NNE-SSW transpressional high-angle lateral ramp (Poli et al., 2021a) (Fig. 5a, Section BB'): here a sedimentary thickness variation of the LGM deposits of about 20 m testifies a vertical throw rate of about 0.6 mm/yr for the last 30 ky (Monegato and

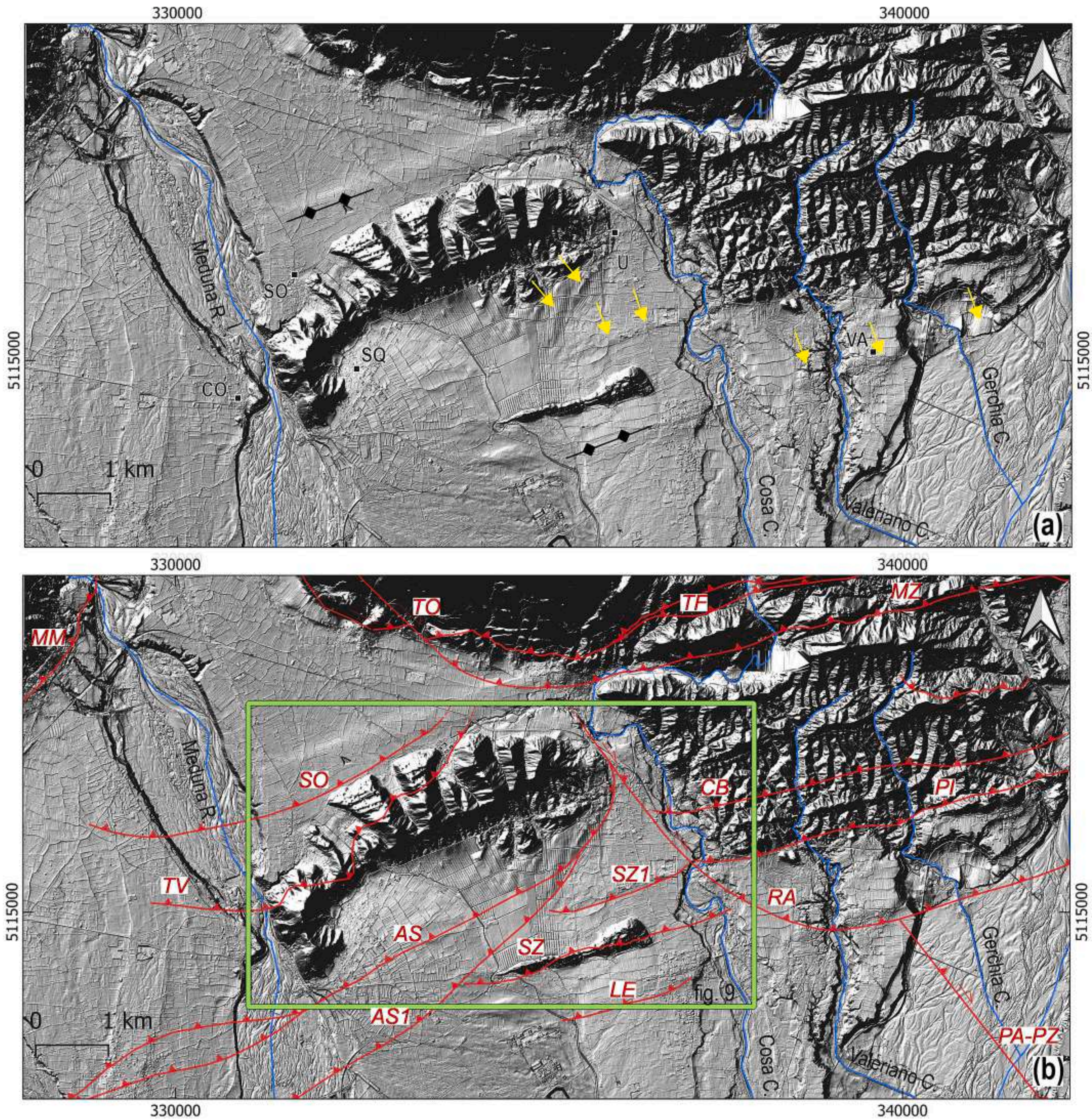

Fig. 7. – a) Topography and morphotectonic anomalies on LGM surface linked to the Holocene tectonic activity. Shaded relief of 1 m DTM with a *Z*-scale factor of 7. Yellow arrows highlight morphological scarps while black lines refers to warped surfaces. b) Interpretation of tectonic structures: AS and AS1: Arba–Sequals Thrust system; CB: Costabeorchia Th.; LE: Lestans Th.; MM: Maniago-Meduno Th.; MZ: Manazzons Th.; PA-PZ: Palmanova-Pozzuolo th. system; PI: Pinzano Th.; RA: Ragogna Th.; SO: Solimbergo Th; SZ and SZ1: San Zenone Thrust system; TF: Toppo-Forgaria Th.; TO: Toppo Ft.; TV: Travesio Th.: Localities: CO: Colle; SQ: Sequals; SO: Solimbergo; U: Usago; VA: Valeriano. Green rectangle: area of Fig. 9. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Poli, 2015). Paleoseismological studies demonstrated that the Meduno Th. involved the Upper Pleistocene-Holocene deposits and proposed that its last seismic event happened in historical times, coinciding with the 1776 earthquake (Poli et al., 2021a). Towards the East, Meduno Th. ends on the Toppo transfer fault (Fig. 3 and section FF' in Fig. 5b).

In the footwall of Maniago-Meduno Th. a set of WSW-ENE striking minor blind reverse structures develop: the Meduno1 Th. in the west (ME1 in Fig. 3) and the Solimbergo Th. in the east (SO in Fig. 3). At depth, seismic lines show that both thrusts displace the bottom of the Plio-Quaternary succession (Sections AA' and BB' in Fig. 5a; Fig. 5 in Poli et al., 2021a). At surface, in the left side of the Meduna River, Quaternary tectonic activity of Solimbergo Thrust is showed by the about 10° towards NNW back-tilting of weakly cemented gravels of the middle Pleistocene (Zanferrari et al., 2008a). Moreover, near Solimbergo, DTM analysis shows that piedmont plain, characterized by the alluvial deposits of the Travesio subsynthem (upper Pleistocene, Zanferrari et al., 2008a), is weakly warped in correspondence of the Solimbergo Th. tip line (Fig. 7 and Figs. S2 and S3 of the Supplementary Material). In the footwall of SO, a minor thin-skinned reverse structure, the WSW-ENE trending Travesio Th. cuts through the upper Tortonian-lower Messinian Montello Conglomerates (Fig. 3 and Fig. 5a, Section BB').

5.2. The Toppo-Forgaria Thrust-systems

The WSW-ENE trending, SE-verging Toppo-Forgaria Th. (TF in Fig. 3; Fig. 5a, Sections CC' and DD') widely crops out in the hills between Travesio and Forgaria del Friuli, located at the southern slope of the Mt. Ciaurlec karstic relief. TF Th. is separated by the MM Thrust by means of the Toppo transfer fault (Fig. 3; Fig. 5b, Section FF'). In the Neoalpine stress regime, TF Thrust reutilized the low angle W-verging ramp of the Dinaric Mt. Ciaurlec tectonic unit, giving rise to a widespread S-verging anticline carved in Friuli Carbonate platform, Paleogene Flysch, Cavanella Group and Serravallian-Tortonian Molasse (Fig. 5a, Sections CC' and DD'). At the same time, the NW-SE striking Dinaric Mt. Ciaurlec frontal ramp was re-utilized as lateral ramp controlling the neoalpine SSE-ward thrust propagation (Fig. 5b, Sections FF' and GG'). In the footwall of the Toppo-Forgaria Th. the S-verging Manazzons Th. (MZ in Fig. 3 and Fig. 5a, Section DD') affects the Montello Conglomerate giving rise to displacement of some hundreds of meters.

5.3. Segmentation of the Arba-Ragogna Thrust-system Auct

According to Zanferrari et al., 2008a and Poli et al. (2009), the Arba-Ragogna thrust-system *Auct.* (ARTS) consists of an imbricate fan of NE-SW trending, SE-verging thin-skinned thrusts extending for about 25–30 km in the piedmont plain and involving both the Mesozoic and the Neogene-Quaternary sedimentary sequences. The western termination of the ARTS is located in the Maniago area where deformation decreases because of the presence of another active thrust segment (the Polcenigo-Montereale Thrust-System in Poli et al., 2015), with an *én-echelon* relationship. Towards the east, ARTS is cut by the Susans-Tricesimo Thrust (Poli and Zanferrari, 2018; Patricelli et al., 2022).

On the basis of new morphotectonic and geological surveys, we propose that the Arba Ragogna Th. system *Auct.* is not a unique reverse structure, but it is segmented into two different thrust-systems: the Arba-Sequals (AS) in the West and the Ragogna (RA) in the East, respectively. Notably, the evolution of both structures was strongly driven by the presence of the NW-SE trending deep structural high in the Friulian Carbonatic Platform referable to the inherited Dinaric external front. In particular, moving from the footwall to the hangingwall of the PA-PZ Th. system, the Molasse sequences become thinner (Section EE' in Fig. 5b).

5.3.1. The Arba-Sequals Thrust-system (AS, AS1,AS2)

The Arba–Sequals thrust system runs at the foothill of the Carnic Prealps in the Friuli piedmont plain from Arba to Usago localities (Fig. 3 and Figs. 7, 8, 9). It is composed by three reverse faults: the ENE-WSW striking, S-verging Arba-Sequals blind Thrust (AS), and two splays AS1 and AS2 (Fig. 5a, Sections AA', BB' and CC' and Fig. 8). According to ENI seismic lines interpretation, AS cuts through the Miocene Molasse up to the surface giving rise to the ENE-WSW trending Sequals anticline (Figs. 8 and 9), that plunges 15°-20° towards the SW. Near Colle locality the anticline, here carved in the Montello Conglomerate, shows a periclinal closure. Further West, reflection seismic profiles show that the anticline becomes more and more open, and progressively disappears at depth (Fig. 5a, Sections AA', BB').

The eastern closure of AS near Usago locality is marked by:

1. a well-developed NNE-SSW striking scarp, carved in the Holocene colluvial deposits, highlighting the tectonic effect of the AS at surface (Fig. 7, Fig. 9);
2. the change in strike from N70 to N20 of the boundaries between AT and MON1 and between MON2 and MON3 near Usago (Fig. 9);
3. the superimposition of MON2 unit on the MON3 outcropping in the Cosa Stream, north of Usago (Section HH', Fig. 9b);
4. the South-western plunging of the axis of the Sequals anticline and the outcropping of older terms (AT) towards the East (Fig. 9).

In the footwall of the Arba-Sequals Thrust, two reverse faults develop, the main of which also displaces the base of the Plio-Quaternary sequence but does not reach the surface (AS1 in Fig. 8). The further external thrust (AS2) stops its deformational activity inside the middle Miocene Molasse.

5.3.2. The Ragogna Thrust-system (RA)

The Ragogna Thrust-system develops in the eastern sector of the Carnic prealpine area, from Valeriano to Cimano localities for about 13 km (Fig. 3). It strikes N80° and is cut in its eastern edge by means of the Susans-Tricesimo Th. The Ragogna Unit, developing on top of the inherited Dinaric structural high (Sections. DD' and EE' in Fig. 5a and b), is responsible for the Pliocene-Quaternary polyphase growth of the S-verging Ragogna anticline carved on the Miocene Molasse and Pliocene-Pleistocene continental sequences. The WSW-ENE trending Ragogna tight anticline, whose southern limb is overturned (Zanferrari et al., 2008a; Fig. 5a, sez. DD'), is further affected by a set of S-verging reverse faults: Costabeorchia Th. and Pinzano Th.

Conversely to AS, the Upper Pleistocene-Holocene activity of the RA Th. is testified by scattered morphotectonic evidence. Along the left bank of the Tagliamento River, downstream of the Pinzano gorge, the Pleistocene succession unconformably overlays the lower Messinian conglomerate with vertical attitude (Fig. 4a, see location in Fig. 3). Actually, the whole succession, from the Messinian unit onwards, shows the classic progressive unconformity stack (sensu Anadón et al., 1986). Three angular unconformities are visible along the slope: the first bounds the lower Messinian conglomerate (85° dip towards the SE) with the San Pietro di Ragogna Conglomerate (about 45° dip) of Gelasian-Calabrian age (Martinetto et al., 2012). These units are clearly distinguishable not only for their different inclination but also for their dissimilar petrographic provenance related to the evolution of the Tagliamento drainage basin (Monegato, 2006). The second angular unconformity is located between the San Pietro di Ragogna Conglomerate and the Arzino coarse conglomerates (30° dip towards the SE) of Lower (Calabrian?)-Middle Pleistocene (Fig. 4a). The third unconformity bounds this latter unit with an Arzino conglomerate unit (Fig. 4a and b). These sediments were buried by middle to Upper Pleistocene glacial and fluvioglacial deposits; the outwash sediments of the last glacial advance of the Tagliamento glacier at 21 ka Cal BP crop out at the top of the left bank (Paiero and Monegato, 2003; Fontana et al., 2019).

In addition, along the valley of the Ponte Creek (Fig. 4a), which rests on the tip-line of the Ragogna Thrust, the bounding surfaces are displaced of several meters, with an increase of displacement towards the

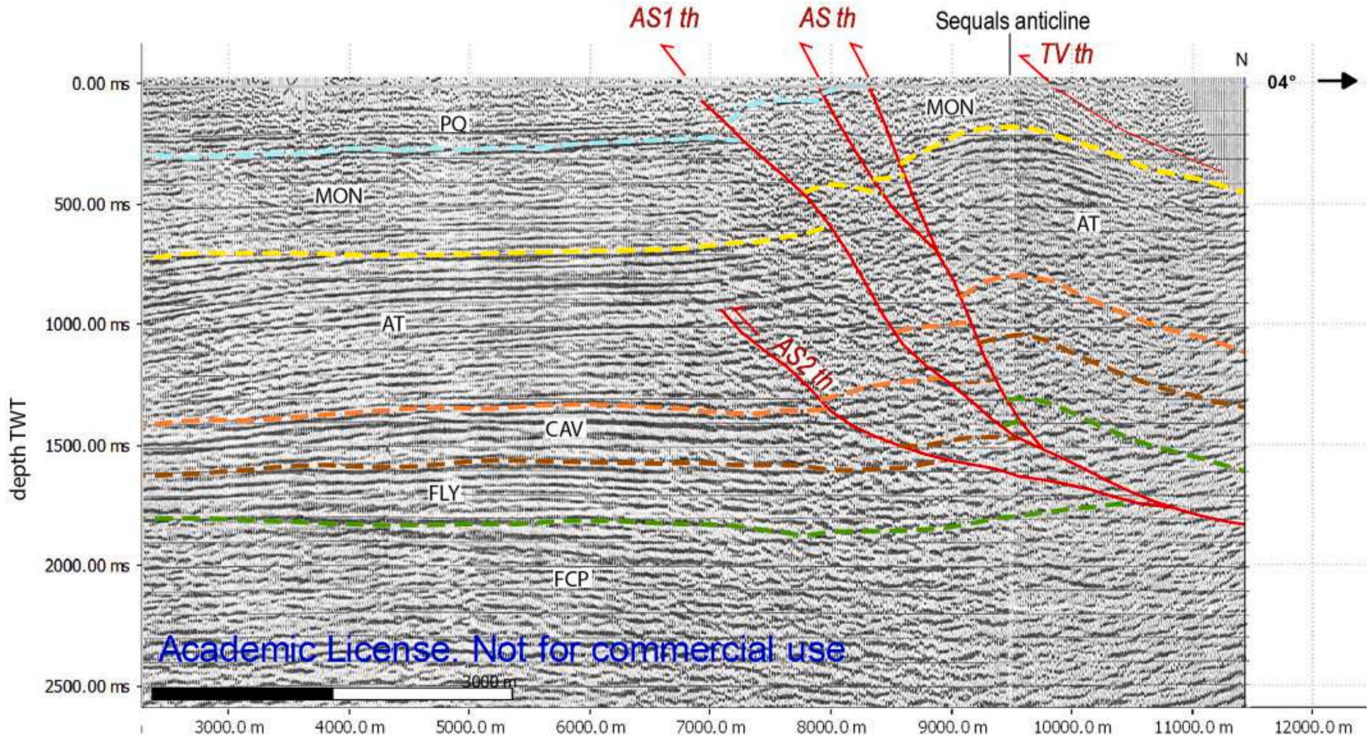

Fig. 8. –Reflection seismic profile and geological interpretation of the foreland verging Arba-Sequals thrust-system (for location see geological cross section BB' in Figs. 3 and 5a). Legend: FCP: undifferentiated Lower Jurassic–Upper Cretaceous carbonate platforms; FLY: Lower Eocene hemipelagic and turbiditic successions (Scaglia Rossa Friulana and Clauzetto Flysch); CAV: Aquitanian–Lower Serravallian Cavanella Group; AT: Lower Serravalian–Tortonian (Marna di Tarzo and Arenaria di Vittorio Veneto Fms.); MON: Upper Tortonian–Lower Messinian Montello Conglomerate; PQ: Pliocene-Quaternary continental succession. AS, AS1, AS2: Arba Sequals Thrust-system; TV: Travesio Th.

oldest. The surface of the left bank, dated at 21 ka Cal BP, shows about 4 m displacement across the valley.

Along the right bank of the Tagliamento River the progressive unconformity stack is lacking of the San Pietro di Ragogna conglomerate, so the lower-Middle Pleistocene unit of the Arzino alluvial fan (30° dip) rests here on the sub-vertical Messinian conglomerate.

Westwards, down to the Valeriano Creek (Fig. 3; Fig. 4b), the stratigraphic succession changes significantly from the portion located on the hanging wall to that in the footwall of the fault. This fact was highlighted by OSL and pollen data of the units located on the hangingwall (Monegato et al., 2010a). Besides, the topmost unit of the succession is related the last glacial advance of the Tagliamento glacier, dated at 21 ka Cal BP (Monegato et al., 2007). The important time gap of >200 ka suggests that the preservation from burial was due to the uplift of the hangingwall. Instead, the presence of a thick Upper Pleistocene succession in the footwall of the Ragogna Thrust (unit 8 in Fig. 4b), lacking in the hangingwall, suggests that during the Late Pleistocene the sedimentation bypassed the most proximal part of piedmont plain.

In the hangingwall of the Ragogna Th., Valeriano and Gerchia creeks are confined in narrow incisions with noticeable meandering trend (Fig. 7); downstream of the tip-line of the thrust the streams become more straight with braided style.

Near Valeriano locality, the RA thrust gives rise to an about 4 m high morphological scarp (Fig. 7). The westward retreat of the scarp (Fig. S4 of the Supplementary Material) highlights the abrupt change of RA strike, which acquires a subvertical NNW-SSE trending geometry (Figs. 7 and 9), implying an increase of the dextral horizontal component of RA.

5.3.3. *San Zenone (SZ) Th. system*

The San Zenone Th. system (SZ in Fig. 3; Fig. 5a, Section CC' and Figs. S4-S6 of the Supplementary Material) accommodates deformation between Arba-Sequals and Ragogna Ths. It is composed of three S-verging thrust planes: San Zenone 1 (SZ1), San Zenone (SZ) and Lestans (LE) Thrusts. Near San Zenone Hill, the homonymous thrust (SZ) generates a widespread cataclastic zone in the Montello Conglomerate and a S-verging sharp frontal ramp-anticline at the easternmost edge of the Hill (Zanferrari et al., 2008a). The arrangement of San Zenone Thrust System at depth is shown in the clipping of industrial seismic line of Fig. S6 of the Supplementary Material. The recent tectonic activity of San Zenone 1 Th. is testified by the morphological scarp (see yellow arrows in Fig. 7 and Fig. S4 of the Supplementary Material), while Lestans Thrust gives rise to a weak warping of the topographic surface (Fig. 7 and Fig. S4 of the Supplementary Material). Their recent tectonic activity is also supported by the changing drainage pattern of the Cosa creek which varies downstream from meandering to rectilinear (Fig. 7).

6. Discussion

6.1. *Structural inheritances*

The external front of the eastern Southern Alps in Friuli consists of a set of active arcuate fan of SE-verging, SW-NE trending, thin-skinned mostly blind thrusts. The lateral terminations of the thrusts are located where deformation decreases because of the interference with another active thrust segment, often influenced by structural inheritances. The structural model of the Carnic Prealps here reconstructed (Figs. 3 and 5) shows that the external front of eastern Southern Alps is articulated with four SE-verging thrust systems, highlighting their Pleistocene-Holocene tectonic activity: the Maniago-Meduno, the Toppo-Forgaria, the Arba-Sequals and the Ragogna Thrust Systems.

The Maniago-Meduno (MM) and Toppo-Forgaria (TF) Thrust Systems, connected by the NNW-SSE striking Toppo dextral transfer fault, run at the base of the carbonatic anticlines of Jouf Mt. and Ciaurlec Mt. respectively, causing the overthrusting of the lower and middle Molasse on the Montello Conglomerate at the forelimb. At the front of the MM and TF Thrust Systems, two further reverse systems are present: the

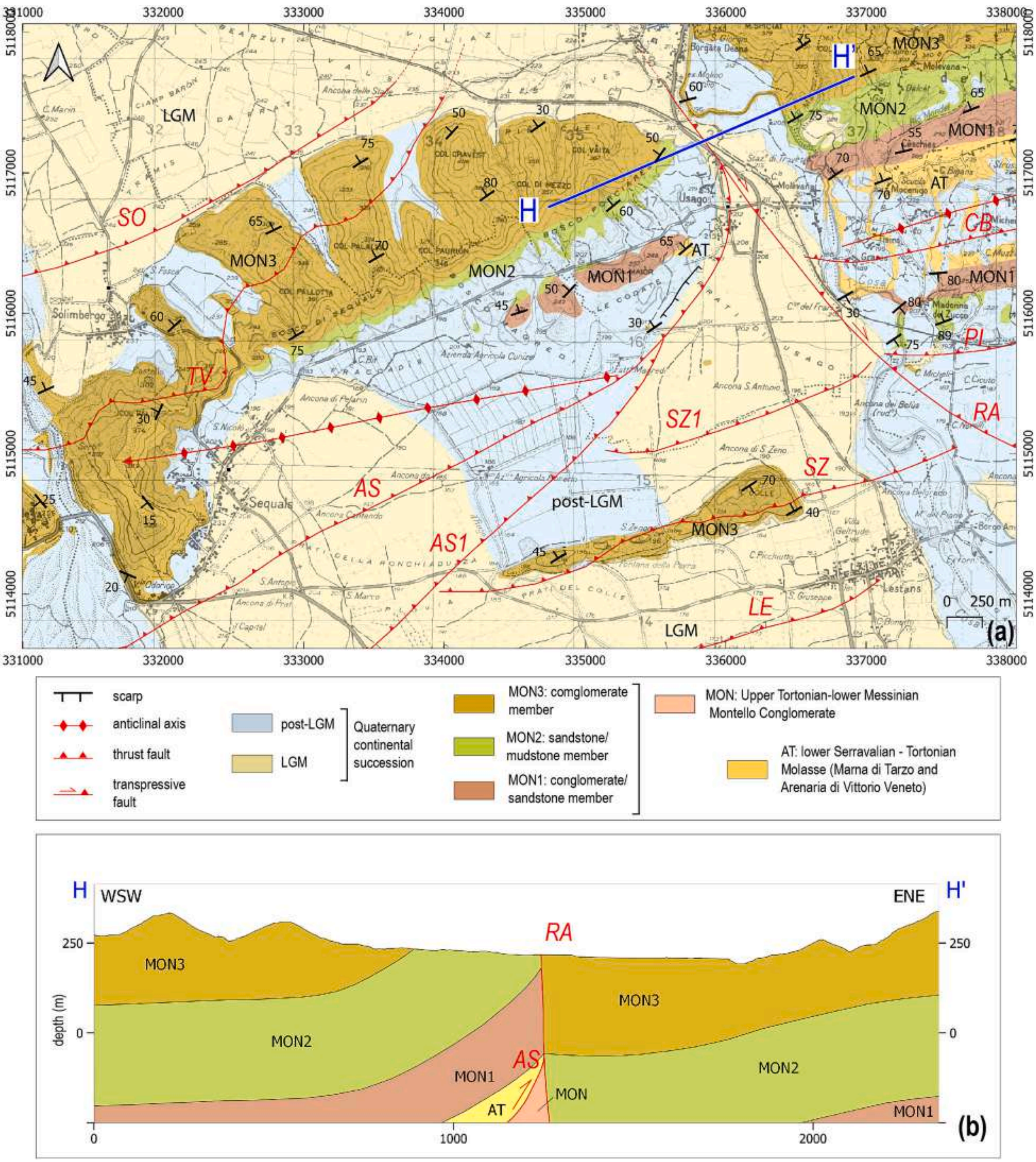

Fig. 9. – (a) Clipping of the geological map of the Usago area (see location in Fig. 7). AS, AS1: Arba-Sequals Thrust-system; CB: Costabeorchia Th.; PI: Pinzano Th; RA: Ragogna Th.; SZ1: San Zenone Th; TV: Travesio Th. (b) the WSW-ENE oriented geological section HH' pinpoints the anomalous lateral contact within the upper Molasse, linked to the mutual lateral closure of AS and RA.

western Arba-Sequals (AS) and the eastern Ragogna (RA) Thrust Systems, which both involve the Molasse succession. However, the eastern sector appears intensely deformed by means of a series of N80° trending tight anticlines and synclines, while the western area is characterized by wider fold. The along strike WSW-ENE oriented EE' profile (Fig. 5b, section trace in Fig. 3) highlights that AS and RA define two distinct thrust systems. Regarding the recent tectonic activity, AS does not show surficial evidence of late Pleistocene-Holocene tectonic activity, except for the morphological scarp near Usago (Figs. 7 and 9). Conversely, RA shows numerous morphotectonic evidence testifying the persisting tectonic activity from almost early Pliocene up to the Present (Figs. 4, 7 and S5 of the Supplementary Material). In this context, the persistent Plio-Quaternary tectonic activity of RA is testified by the unconformity stack between the lower Messinian to the uppermost Pleistocene stratigraphic units laying on the southern limb of the Ragogna ramp anticline, on the left banks of the Tagliamento River (Fig. 4a). The major unconformity (about 45°) is the oldest and encompass part of the Messinian and the Pliocene. The second unconformity (15°) separates the Lower Pleistocene unit from the Lower?-Middle Pleistocene one. The third (about 10°) divides the Lower?-Middle Pleistocene unit from the late Middle Pleistocene ones. The thickening of Upper Pleistocene units across the RA points to the ongoing activity of the fault.

Accordingly, the collected results show that AS and RA have slightly different structural characteristics in terms of geometry and surficial and deep evidence, such as the structural setting of the two anticlines. The Sequals anticline is sharp and plunges towards the West, while the Ragogna one is tight and overturned in the southern limb. Moreover the eastern and the western sectors are characterized by different thickness in the Molasse Units. These aspects suggest that the structural evolution of this sector of the Carnic prealpine front could be strongly controlled by inheritances such as the structural high linked to the Dinaric external front.

In this context, it is important to remark the polyphasic evolution of the investigated area: at the activation of the Neoalpine tectonic phase, the present Carnic prealpine region was already characterized by a Dinaric structural architecture, with a NW-SE elongated structural high represented by the carbonate ramp anticline of the Palmanova-Pozzuolo-Mt.Ciaurlec external Dinaric front, overthrusting the turbiditic succession of the Dinaric foredeep (Fig. 10a) (Ponton, 2010; Poli et al., 2021a). During Miocene, the Neoalpine tectonic event (with sigma1 ranging between NNW-SSE and NW-SE) involved the pre-existing Paleogenic structures and lead to the development of the SE-verging Southalpine fold and thrust belt. In this context, the Maniago-Meduno Th. and the Toppo-Forgaria Th. formed and gave rise to the Mt. Jouf and Mt. Ciaurlec SSE-verging anticlines. On the pre-existing weak zone corresponding to the forelimb of the Dinaric Mt. Ciaurlec anticline, the NW-SE striking Toppo transfer zone also developed. The Toppo transfer zone favored the SE-ward migration of the TF unit with respect to the MM, creating new accommodation space progressively filled by the deposition of lower and middle Molasse during Tortonian (Fig. 10b). The activity of TF and MM persisted also during upper Tortonian-lower Messinian, when the carbonate anticlines (Mt. Jouf and Mt. Ciaurlec) continued to grow acting as a by-pass for the Montello Formation deposition, concentrating downstream at the footwall of TF and MM. Following this stage, the SE-ward propagation of the Southalpine front continued to be affected by Dinaric inheritances also during Miocene and Pliocene. On the SE-ward propagation of the Toppo transfer fault, the deep inherited Dinaric front separates the western Sequals tectonic unit from the eastern Ragogna one (Fig. 10c). Based on these assessments, the comparison between the two sectors highlights that the Ragogna unit developed at the top of the inherited dinaric structural high and was certainly affected also by the forward position of the polyphase Mt.Ciaurlec anticline. Differently, the AS unit developed at the footwall of the Dinaric tectonic unit, where the carbonate platform is located deeper in the subsurface and the outcropping neoalpine *ss.* anticline of Mt. Jouf is located in a backward position. Notably, the mutual lateral closure of AS and RA is located right in correspondence of the deep inherited Dinaric front. Therefore, it seems likely that the Dinaric discontinuity has been reactivated since Miocene, during the Neoalpine event, considering that the lateral ramp of RA is set on the upward continuation of the Dinaric inheritance itself. The persistent upwarping of the structural high also during Neoalpine phase is testified also by the E-W variation of the Molasse units in thickness (Section EE' in Fig. 5b).

Regarding this, numerous studies based both on analogic and numerical modelling (Doglioni, 1992b; Orjuela et al., 2021; Ruh et al., 2013 and references therein) analysed the genesis and the evolution of transfer zones in thrust wedges, investigated their control over thrusts propagation during ongoing shortening and compared the structural-geological evidence developed in the two different sectors from one side to the other of the transfer zone.

In this context, Calassou et al. (1993) concluded that the presence of inherited shear zones represents a predisposing factor for the development of transfer zones, e.g. lateral ramps, tear faults or strike-slip faults. Such structural elements, modelled as horizontal step in the backstop, control the subsequent evolution of the thrust wedge. In detail, the geometry of the propagating thrusts is strongly influenced by the entity of the backstop offset: little horizontal offset of the backstop causes the development of a single continuous frontal thrust system characterized by a slight bend in correspondence of the transfer zone (Ruh et al., 2013). Differently, longer horizontal offset of the backstop lead to the alternate propagation of thrusts from one side to the other of the transfer zone (Calassou et al., 1993; Ruh et al., 2013), with the development of the oblique ramps of the thrusts starting exactly from the horizontal step of the backstop (Fig. 11a). Moreover, the modelled ongoing shortening causes the development of steeper surface slopes and thrust sheets with large faults offsets in the frontal zone pushed by the promontory (Ruh et al., 2013).

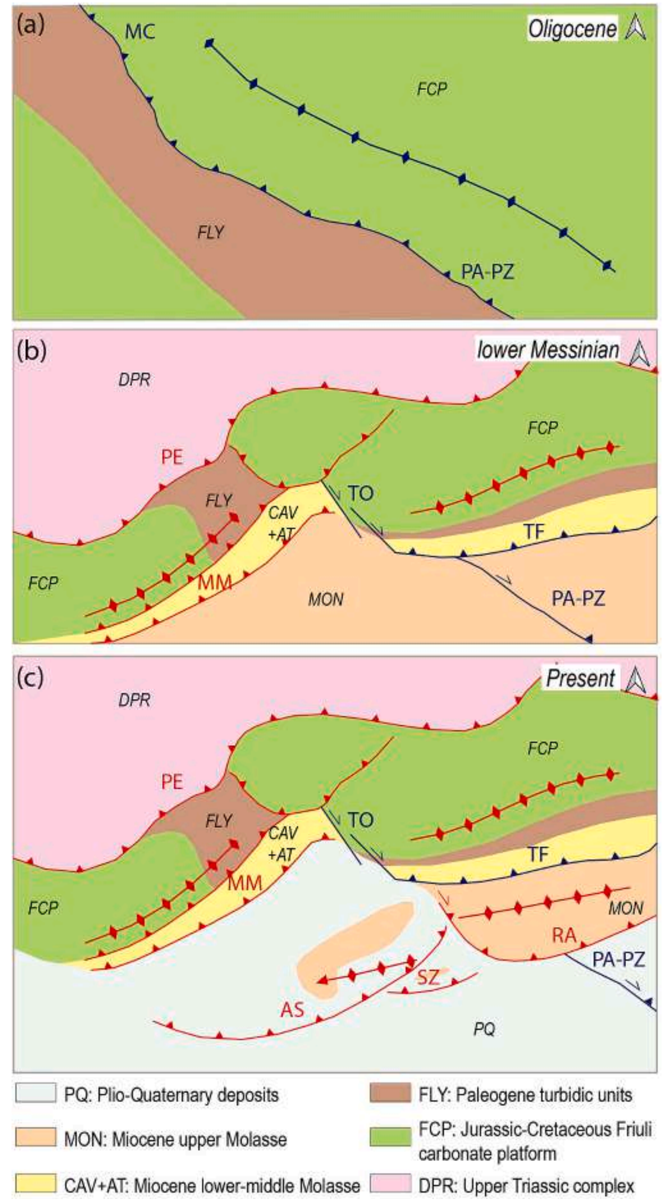

Fig. 10. - Schematic representation of the polyphasic evolution of the investigated area of the carnic prealpine front. Legend: AS: Arba-Sequals Th.; MC: Mt. Ciaurlec Th.; MM: Maniago-Meduno Th.; PA-PZ: Palmanova-Pozzuolo Th. system; PE: Periadriatic Th.; RA: Ragogna Th.; SZ: San Zenone Th.; TF: Toppo-Forgaria Th. Blue faults are reactivated Dinaric inheritances; red faults are Neolpine structures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6.2. *Seismogenic sources and potential maximum magnitude*

At present, the numerous surficial geological and morphotectonic

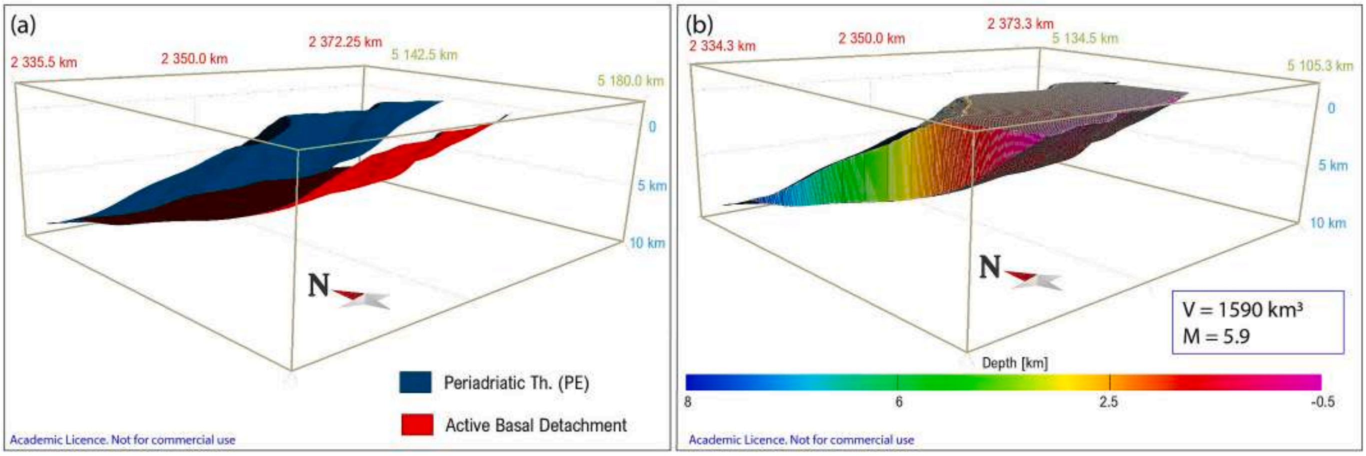

Fig. 11. . 3D tectonic surfaces defining the investigated crustal volume; (b) computed potential volume contained between the Periadriatic Thrust at the back and the Active Basal Detachment at the front.

evidence show that 4 distinct thrust systems accommodate deformation in the investigated area, which potentially represent 4 independent seismogenic segments. Even though the instrumental seismological data reveal a low seismic activity in recent times, two medium earthquakes are reported on the historical catalogue (DBMI, Locati et al., 2022): the 1776 (Mw 5.8, Io 8–9) and the 1794 (Mw 5.96, Io 8–9) (Fig. 1). Based on paleoseismological analysis, Poli et al. (2021a) referred the 1776 earthquake to the historical activation of the Meduno Th. (i.e. the eastern segment of the Maniago-Meduno Thrust-System), while for the 1794 earthquake (located in the upper Tramontina Valley, at the hangingwall of the Periadriatic Thrust) no seismogenic source was still clearly identified. In this regard, the characterization of the seismogenic source represents a key aspect for the seismic hazard assessment of the area, since the source parameters define the estimates of maximum seismogenic potential. Based on the 3D structural model elaborated, the seismogenic source parameters were calculated and, according to the empirical relationships of Wells and Coppersmith (1994), the associated maximum expected magnitude M(RA) and M(RLD) were estimated for all the presented structures. The results, collected in Table 2, show that the considered seismogenic sources are capable to generate 6 to 6.4 Mmax earthquakes.

If compared with the Database of Italian Seismogenic Sources (DISS Working Group, 2021, v. 3.3.0), the estimated magnitude values confirm the seismogenic potential of Maniago-Meduno source, but they actually reduce the seismogenic potential of Sequals source. In this regard, it is worth to remark that the DISS includes a unique frontal seismogenic structure referable to the Arba-Ragogna Thrust System (Burrato et al., 2008; Mw 6.5). Conversely, the proposed model assesses for the presence of two distinct sources in the frontal sector, characterized by smaller extension and thus able to release lower seismogenic potential.

Based on the proposed structural model, the inherited Dinaric front, reactivated during the Neoalpine phase, not only controlled the structural evolution of this sector of Carnic Prealps, but also plays a fundamental role in the seismogenesis of the area. Since it influenced the lateral extension of the seismogenic structures (segmentation), it indirectly affects the seismogenic potential. Regarding this, the role of geometric and structural barriers controlling the seismogenic process has been investigated since long ago, assessing that they can act as stopper of the coseismic rupture propagation but also as initiator of rupture (Aki, 1979; Sibson, 1986; Sibson, 1989). Many examples are documented from around the world (Aki, 1989; Pizzi et al., 2017; Sathiakumar and Barbot, 2021; Madarieta-Txurruka et al., 2022). Accordingly, it can be hypothesised that zones of structural discontinuity (e.g. step-over, bend, structural barriers) could define single crustal volumes, within which one or more seismogenic sources are present.

In the past, Bath and Duda (1964) investigated the correlation between volume and seismogenesis, computing the empirical relationship which relates seismic potential of an earthquake with the crustal volume affected by the aftershock series associated to the main event. More recently, following Bath and Duda (1964), Petricca et al. (2018, 2019, 2022) proposed an innovative approach based on the estimation of the seismogenic potential of an area starting from the volume. Particularly, the Authors define the potential seismic volume as the seismogenic crustal volume comprised between the basal fault plane and its conjugated plane, both for normal (“*graviquake”)*, and compressive (“*elastoquakes*”) earthquakes (Doglioni et al., 2015). In this context, the seismogenic potential is strongly controlled by the seismogenic thickness, while the geometric parameters of the sources are included through the shape ratio C (which indicates the ratio between length of the source and maximum depth of activation). Considering a mean source dip angle of 30°, and varying the shape ratio C within the range of characteristic values for thrust faults in Italy, Petricca et al. (2019) estimated maximum magnitude values comprised between 5.75 (C = 2) and 6.45 (C = 4) for eastern Southern Alps.

Because of the low seismic activity characterizing the Carnic prealpine region, and particularly since no seismic sequences were registered in recent times (ISIDe Working Group, 2007; Locati et al., 2022), we adopted the volumetric approach by computing the potential seismic volume of the area starting from the elaborated 3D structural model (Fig. 11). Particularly, we quantified the crustal volume comprised by the Periadriatic Thrust plane and the Active Basal Detachment sensu Petricca et al. (2019), represented by the Arba-Sequals and Ragogna

Table 2
Geometric parameters of the seismogenic sources and maximum potential magnitude estimates according to Wells and Coppersmith (1994).

SOURCE	Length (km)	Hmax (km)	Dip mean	Width (km)	Rupture Area (RA) (km2)	M (RA)	M (RLD)
Arba-Sequals	13	6.5	25°	15.4	200	6.4	6.1
Ragogna	11	6.5	20°	19	209.5	6.4	6.0
Maniago-Meduno	12	7	30°	14	168	6.3	6.1
Toppo-Forgaria	11	4.2	25°	10	109.3	6.2	6.0

frontal structures. Both surfaces were reconstructed by integrating the interpretation of seismic lines and geological field and bibliographic data (Carulli et al., 2000; Zanferrari et al., 2008a; Poli et al., 2015, 2021a).

Within the regional structural framework, the investigated portion of the Carnic prealpine front is bordered to the West by the step-over zone between Polcenigo-Montereale Thrust-system and Maniago-Meduno Thrust system and to the East by the Susans-Tricesimo Thrust System, which cuts the Ragogna Thrust (Fig. 1) and is considered the source of the 1976 Friuli earthquake (Patricelli et al., 2022). These two structural elements actually contain the volume of the study area, separating it from the western sector, which is characterized by SW-NE structural trends (Polcenigo-Montereale Thrust System), and from the eastern sector, where the tectonic structures show WNW-ESE striking (Susans-Tricesimo Thrust System). As shown in Fig. 6, the Arba-Sequals and Ragogna Thrust Systems represent the frontal thrust planes of the investigated Carnic prealpine sector and they connect at depth to the MM and TF thrusts, respectively, giving rise to the Active Detachment Thrust (sensu Petricca et al., 2019). This last extends deep up to about 7 km, where it merges the Periadriatic Thrust, underlying the investigated potential volume. Towards the back, the computed potential volume is confined by the Periadriatic Thrust (PE in Fig. 1, Fig. 3): a polyphase regional tectonic structure which is responsible of the overthrusting of the Upper Triassic Dolomia Principale on the Mesozoic and Cenozoic sequences in Friuli (Ponton, 1990; Masetti et al., 1988; Zanferrari et al., 2013).

The identified potential volume (Fig. 11b), is equivalent to 1590 km^3 and corresponds to a seismogenic potential M(V) = 5.9, estimated through the empirical formula of Bath and Duda (1964).

Actually, the low seismic activity of the area registered by instrumental catalogues (ISIDe Working Group, 2007) identifies an important limitation for the validation of the proposed potential volume. The integration of our model with the hypocentral distribution of a sequence would help to test and further investigate the role of the volume boundaries during the seismogenic process.

If considering the historical seismicity of the area, the seismogenic potential estimated is consistent with the seismic potential released during the strongest earthquakes of the last 700 years. Therefore, it can be assessed that the identified crustal volume coincides with the seismic volume activated during the 1776. In this concern, it is important to remark that even though the 1776 event can be considered the characteristic earthquake, it does not necessarily coincide with the maximum expected event, which instead is usually estimated by adding a factor of 0.5 to the characteristic potential (Serva, 1990; Basili et al., 2017 and references therein). Consequently, the identified potential volume is certainly representative of the seismic volume activated during the occurred strongest earthquake, but it could actually constitute only a portion of the maximum potential volume, that is the one associated to the maximum expected event of the study area. However, the magnitude value estimated for the considered potential volume M (V) well fits the Mmax estimation of Petricca et al. (2019) for the eastern Southern Alps, which range from 5.75 e 6.45, and slightly differs from the seismogenic potential estimated from the geometric parameters of the sources, through Wells and Coppersmith (1994) empirical relationships. Particularly, the estimated values of M(V) and M(RA) differ between each other by a factor of 0.2–0.5, while a variation of the order of 0.1 separates M(V) and M(RLD) values. If considering: a) the characteristic seismic potential Mw of 5.8 (1776 earthquake); b) the weak surficial evidence associated to the investigated tectonic structures and c) the higher uncertainty related to the deep geometry of the fault planes (dip and maximum depth), we assess for the M(RLD) estimation, rather than the M(RA), to be more representative of the characteristic seismic potential of this analysed sector of eastern Southern Alps.

7. Conclusions

Thanks to a multidisciplinary approach we investigated the active thrust front of eastern Southern Alps between the Cellina and the Tagliamento rivers. The integration of geological and morphotectonic field data with geological cross sections allowed us to reconstruct the polyphasic evolution of this sector of the Carnic prealpine border, highlighting the persistent Pliocene-Quaternary tectonic activity of the frontal Meduno-Maniago, Toppo-Forgaria, Arba-Sequals and Ragogna Thrust Systems.

Here the evolution of the external front of the eastern Southern Alps was strongly controlled by the deep structural high of the Friulian Carbonatic Platform linked to the Paleogene front of the External Dinarides, which extends with a NW-SE trending in the Friuli plain.

The structural high affected the propagation of the Neogene-Quaternary front defining two distinct structural sectors: a western one, located in the footwall of the Dinaric front (Meduno-Maniago and Arba Sequals Thrusts), and an eastern sector, in the hangingwall of the Dinaric front (Toppo-Forgaria and Ragogna Thrusts). Both the lateral ramps of Toppo and Ragogna developed on the deep inherited structure.

The identified potential volume is contained among Arba-Sequals and Ragogna Thrusts at the front, the Polcenigo Montereale and Maniago-Meduno step-over zone at the west, the Susans-Tricesimo Thrust at the east and Periadriatic Thrust at the back. Within this volume, the inheritances affect seismogenesis separating four distinct seismogenic structures and representing a segment boundary, which affects the rupture propagation process and limits the maximum seismogenic potential associated to the single sources.

The proposed model is consistent with the strongest seismicity that affected the study area in the last 700 years.

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CRediT authorship contribution statement

M.E. Poli: Writing – original draft, Visualization, Supervision, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **G. Patricelli:** Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **G. Monegato:** Writing – review & editing, Investigation. **A. Zanferrari:** Writing – review & editing, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The interpreted industrial seismic lines are property of ENI-Exploration and Production.

Geologic and morphotectonic data are available at the page CARG Project – Geologic and geotematic cartography of the ISPRA website: https://www.isprambiente.gov.it/Media/carg/friuli.html.

The 1 m DTM derived from the LiDAR relief conducted by the Protezione Civile during 2006–2010 are available on the Regione Autonoma Friuli Venezia Giulia website: https://irdat.regione.fvg.it/CTRN/ricerca-cartografia/.

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