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Historical tectonic activity along the eastern segment of the Bassano-Valdobbiadene Thrust: new hints for the seismic hazard assessment of the Venetian Prealps between Vittorio Veneto and Valdobbiadene (eastern Southern Alps, NE Italy)

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Abstract. In the framework of the Italian Seismic Microzonation Project, we investigated the easternmost segment of the Bassano–Valdobbiadene Thrust *Auct.* (i.e. the Vittorio Veneto–Valdobbiadene Thrust) which runs at the base of the Venetian prealpine foothill between Miane, Follina and Cison di Valmarino municipalities (NE Italy). The Bassano–Valdobbiadene Thrust belongs to the SW–NE striking, SE–verging Pliocene–Quaternary front of the eastern Southern Alps which at present, accommodates deformation with velocities of the order of 2–3 mm/yr. Prominent geological and morphological expression (Mt. Grappa–Mt. Cesen–Mt. Visentin anticlines) underlies the Miocene to Present tectonic activity of the Bassano–Valdobbiadene Thrust, however the Quaternary tectonic activity is scarcely constrained. The historical seismicity reveals that few destructive earthquakes ($M \geq 5.5$) hit the Venetian prealpine region, but no significant seismic events affected Follina and the surrounding areas during the last millennium. In order to investigate the recent tectonic activity of this sector of the eastern Southalpine front, we made a morphotectonic survey along the San Pietro and Soligo valleys (i.e. the Vallata valley) and, in correspondence of possible morphotectonic evidence, a series of Electroresistivity Tomography investigations. Following, we dug some paleoseismological trenches across the possible surficial trace of the tectonic structure. The results of our study pinpointed that the Vittorio Veneto–Valdobbiadene Th. is an active fault, capable to generate linear morphogenic earthquakes. Particularly, the paleoseismological analysis highlighted that the last seismic event referable to the investigated structure occurred during the High–Middle Age (13th–14th century CE). The event produced a maximum observed displacement of 32 cm, while magnitude estimates suggest an earthquake of Mw 6.5–6.7. These data provide new important seismotectonic hints, which have to be considered in order to re–evaluate the seismic hazard of the Venetian Prealpine region, characterized by high population and industrial density.

1 Introduction

The assessment of the seismic hazard in a region characterised by low deformation rates, such as the eastern Southern Alps in NE Italy (ESA), is difficult because the recurrence time span usually exceeds the time interval covered by historical records

(Riguzzi et al., 2013; Galli, 2022; Niederstätter et al., 2025). Furthermore, since the front of ESA thrust belt is made by prevailing middle–low–angle blind thrusts (Galadini et al., 2005; Vannoli et al., 2015), most of the related papers based their results on seismological, geophysical and/or geodetic data (Riguzzi et al., 2013), and details on faults seismotectonic behaviour are largely unknown. In particular, the lack of paleoseismological data does not allow us to know source parameters such as short–term slip–rate, displacement per event, mean recurrence interval and maximum magnitude. For example, in the eastern Southern Alps historical seismic Catalogues (e.g. Locati et al., 2022; Rovida et al., 2021; Guidoboni et al., 2018 and 2019; Fig. 1), show for the last millennium only a few scattered earthquakes with M≥6. Among these, scarce are data on the seismogenetic parametrization, and seismic hazard is still calculated by means of probabilistic criteria (Stucchi et al., 2004; Meletti et al., 2008; Visini et al., 2019; Meletti et al., 2021). Conversely, because of the high population density and the high density of industrial settlements, ESA is characterised by a high level of potential seismic risk (e.g. GNDT, 2000). Recently, some compressive tectonic structures located at the front of the ESA have been studied by means of paleoseismological technique: Falcucci et al. (2018), Poli et al. (2021) and Monegato et al. (2023) demonstrated that the paleoseismological study is also applicable in compressive contexts with a low deformation rate such as ESA.

After the destructive 1976 Friuli seismic sequence, NE Italy was the object of many seismotectonic studies on the Pliocene–Quaternary tectonic activity (Zanferrari et al., 1982; Peruzza et al., 1989; Slejko et al., 1989; Castaldini e Panizza, 1991). Moreover, at the beginning of the 2000s, following the publication of the results of the CROP–TRANSALP profile (Castellarin et al., 2006), which highlighted the relationships between Adria and Europe in depth, seismotectonic studies in Veneto and neighbouring regions renewed strong interest. Researches mainly focused on the Montello Thrust, which is considered the main silent tectonic structure located at the external front of the eastern Southern Alps in Veneto (Ferrarese and Sauro, 1998; Benedetti et al., 2000; Galadini et al., 2005, Burrato et al., 2008; Danesi et al., 2015; Chiaraluce et al., 2009; Mozzi et al., 2015; Serpelloni et al., 2016; Romano et al., 2019). Recently Picotti et al., (2022), on the bases of the acquisition of ELF seismic lines and of an accurate reinterpretation of the available geological data, proposed a new structural setting for the piedmont Venetian Plain between Vittorio Veneto and Cornuda, where Montello–Conegliano and Bassano Valdobbiadene Thrusts, represent the major potential seismogenic structures. According to the Picotti et al. (2022) interpretation, the Montello Thrust should extend up to Treviso locality, becoming the possible seismogenic source of the Treviso 778 CE earthquake (Ml 5.8; Imax 8.5) as already supposed by Benedetti et al. (2000).

Conversely, Barba et al. (2013) and Anderlini et al. (2020) focused their seismogenetic attention on the Bassano Valdobbiadene Thrust, reporting for this tectonic structure a seismogenic potential greater than the Montello one.

In this paper, we present the results of a morphotectonic and paleoseismological survey made on the eastern sector of the Bassano–Valdobbiadene Thrust *Auct.* (Castellarin, 1981; Antonelli et al., 1990). Following the results of morphological and geophysical investigations carried out within the Seismic Microzonation Project (Gruppo di Lavoro MS, 2008), we dug some paleoseismological trenches across the possible surficial trace of the Valdobbiadene–VittorioVeneto segment (hereafter VVV), which represents the eastern sector of the Bassano–Valdobbiadene Thrust and runs at the base of the relief between Miane and Cison di Valmarino localities. Here, Earthquake Catalogues (Locati et al., 2022; Rovida et al., 2022; Guidoboni 2018 and

2019) do not show any strong seismic event during the last millennium. The collected data allowed us to reconstruct the Holocene/historical tectonic activity of this segment of the BV Thrust *Auct.*, and to evaluate its capability (*sensu* Gruppo di Lavoro MS, 2008; Linee Guida MS, 2015). The results of our investigations pinpoint that in this sector the Valdobbiadene–Vittorio Veneto Th. is an active fault, capable to generate linear morphogenic earthquakes above the damage threshold (M>5.5). Our data strongly improve the seismic hazard assessment of this sector of the Southalpine region and demonstrate that the number of earthquakes above the damage threshold present in the seismic Catalogues is greatly underestimated, at least for the pre–15th century period.

2 Seismotectonic setting

The study area belongs to the Pliocene–Quaternary front of the eastern Southern Alps, a polyphase S–SE–verging, WSW–ENE striking fold and thrust belt in activity from the middle Miocene onward (Fig. 1). In particular, in the Veneto prealpine thrust belt, ESA progressively developed during the Messinian–Pliocene compressive event (Castellarin et al., 1992; Castellarin and Cantelli, 2000; Fantoni et al., 2002; Caputo et al., 2010). Up to now, the ESA front is undergone to a significant tectonic activity linked to Pliocene–Quaternary Adria indentation (Castellarin et al., 2006) and counterclockwise rotation (Vrabec and Fodor, 2006): in this regard, GPS data show an indentation velocity of about 2–3 mm/yr (Bechtold et al. 2009; Devoti et al., 2011; Cheloni et al., 2014; Serpelloni et al., 2016).

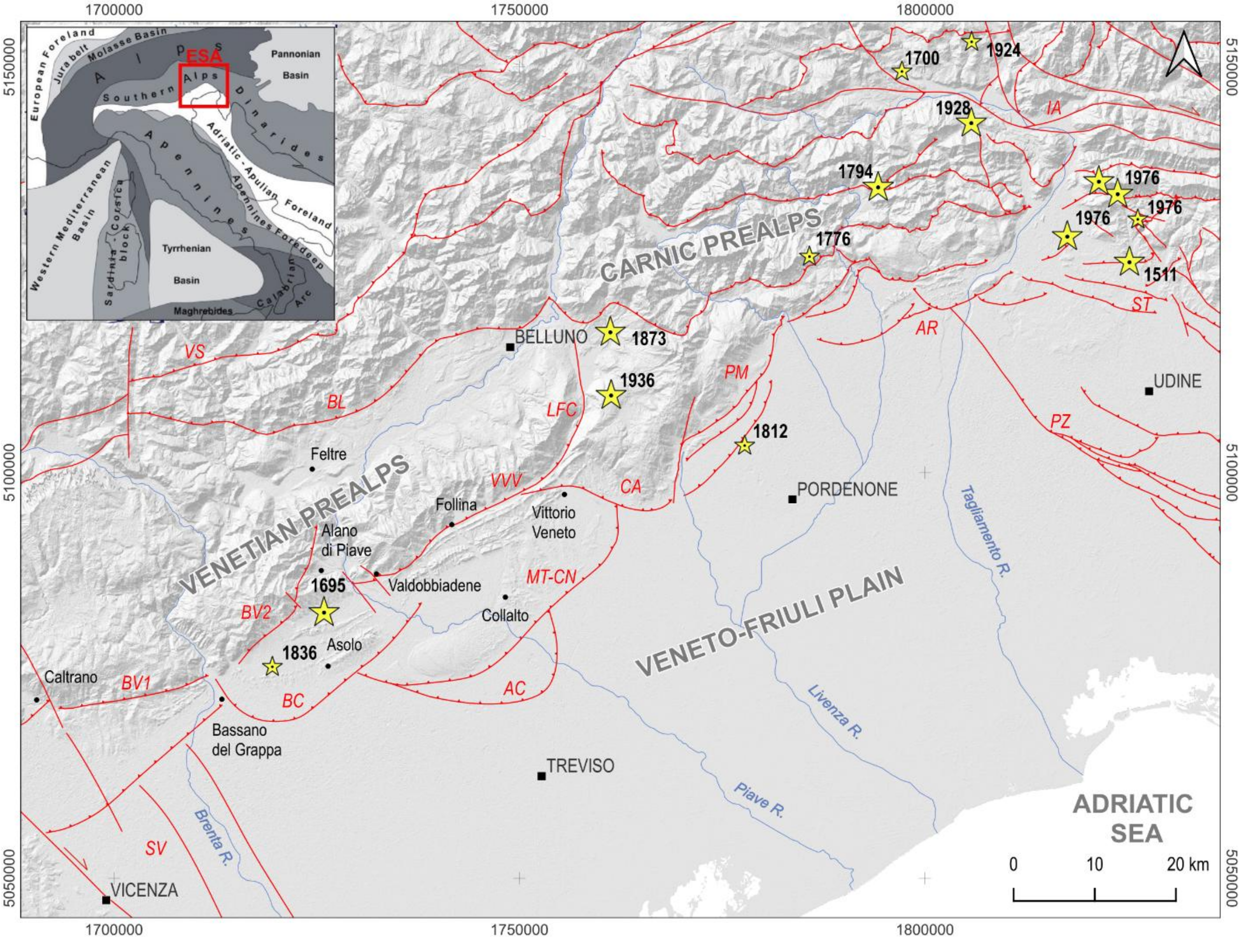

Figure 1: Structural sketch map of the eastern Southern Alps. Yellow stars indicate the historical and instrumental M≥5.5 earthquakes that hit ESA during the last millennium (Rovida et al., 2022). Legend: AC: Arcade Thrust; AR: Arba–Ragogna Th. System; BC: Bassano–Cornuda Th.; BL: Belluno Th; BV1–BV2: Bassano–Valdobbiadene Thrust–System.; CA: Cansiglio Th.; IA: Idrija –Ampezzo Line; LCF: Longhere–Fadalto Cadola Line; MT–CN: Montello–Conegliano Th.; PM: Polcenigo –Montereale Th.; PZ: Pozzuolo Th.; ST: Susans–Tricesimo Th.; SV: Schio–Vicenza Fault–System; VS: Valsugana Th; VVV: Valdobbiadene–Vittorio Veneto Th. Basemap: 30 m resolution ASTER GDEM v2 (NASA/METI, Tachikawa et al., 2011).

During the last millennium, NE Italy was hit by a few M≥5.5 historical earthquakes (Rovida et al., 2022; Fig. 1) showing a widespread seismicity along the ESA front. Conversely, the same data indicate that some of the main potential seismogenetic sources of the ESA front (DISS Working Group, 2025) show lack of activation and therefore they can be considered as silent. From the west to the east, they are: the Schio–Vicenza Fault–System (Zampieri et al., 2021) and the Arba–Ragogna Thrust–System (Galadini et al., 2005; Zanferrari et al., 2008; Poli et al., 2009; Poli et al., 2024).

In particular, during the last millennium no significant earthquake was recorded by the DBMI Catalogue (2022) for the Bassano–Valdobbiadene Thrust–System: the 25 February 1695 Asolano earthquake (Imax X MCS, Mw 6,4) is referred to the Bassano–Cornuda Th. (Galadini et al., 2005), while the Cansiglio earthquake (18 October 1936, Imax VIII MCS, Mw 6,0) is referred to the Cansiglio Th. (Sirovich and Pettenati, 2004; Galadini et al., 2005; Burrato et al., 2008). Concerning the 27 March 1873 Alpago earthquake (Imax X MCS, Mw 6.3), Galadini et al. (2005) indicated the Polcenigo–Monterale Th. as the seismogenic source, even if the activation of transpressive structures of the Longhere–Fadalto–Cadola (Costa et al., 1996), i.e. the left lateral closure of the Bassano–Valdobbiadene thrust along the Fadalto valley, cannot be ruled out.

During the last thirty–five years in the Venetian prealpine area between Vittorio Veneto and Bassano del Grappa, the Italian Seismological Instrumental and Parametric Data–Base (ISIDE http://terremoti.ingv.it/) shows a moderate to low seismic activity. In particular, the temporary seismic network installed from 1 January 2012 until 31 October 2017 by OGS at the storage plant in Collalto (TV) (Romano et al., 2019) recorded the hypocentral parameters of 1635 earthquakes with local magnitude (ML) ranging between −0.8 and 4.5 that affected the area between Asolo and Vittorio Veneto.

Concerning the structural setting of the area, we refer to the interpretation proposed in the CROP–TRANSALP Project (Castellarin et al., 2006), that at the beginning of the 2000s reconstructed the crustal setting of the European and Adriatic lithosphere. The southernmost portion of the TRANSALP seismic profile crossed the Veneto region from the Dolomites to the Venetian piedmont Plain, highlighting the outermost front of the eastern Southalpine Chain (Bertelli et al., 2003; Castellarin et al., 2006). Here crustal seismic investigation identifies two main S–verging thrust–systems: the Montello Thrust (with its antithetic Longhere back–thrust; Zanferrari, 1973) and the Bassano–Valdobbiadene Th. *Auct.* (Castellarin et al., 1981, Antonelli et al., 1990, Doglioni, 1992; Bertelli et al., 2003; Castellarin et al., 2006).

Concerning the Montello Th., Ferrarese and Sauro (1998), Benedetti et al. (2000) and Picotti et al. (2022) demonstrated that the homonymous karstic relief, which rises about 150 m above the LGM high piedmont plain, formed as a result of the tectonic activity of the buried Montello Th. Due to the progressive tectonic uplift induced by the fault activity, the Piave River first originated a series of terraces with convex geometry and then it moved eastwards, toward the Soligo valley. According to Benedetti et al. (2000), terraces would have originated during the last 30 ka, while the abandonment of the paleo–riverbed by the Piave River would have to be referred to a time interval between 8 and 14 ka ago. Conversely, Mozzi et al. (2015), on the basis of new geological and morphotectonic field data, attributed to the Piave fan in Montebelluna an age of deactivation between 37 and 26 ka ago (i.e. during the MIS 2). These data strongly modify the vertical slip rate calculated by Benedetti et al. (2000) for the last 121 ka.

Although the Montello Th. has a seismogenic potential estimated around Mw 6.5 (Galadini et al., 2005, Burrato et al., 2008, DISS WG, 2025), it does not show any strong associated historical earthquakes. Benedetti et al. (2000) hypothesized that the Montello Th. was the causative source of the 778 CE Treviso (Me 5.8, Io VII–IX), the 1268 CE (Me 5.4; Io VIII MCS) and the 1859 CE (Me 5.2; Io VII) earthquakes (Guidoboni et al., 2019). Recently, after revising geological, geophysical and stratigraphical data, also Picotti et al. (2022) attribute the 778 AD Treviso earthquake to the Montello Thrust activity.

The analysis of the recorded events by the temporary seismic network installed at the storage plant in Collalto (Romano et al., 2019), made it possible to model the surface of the frontal structures at depth, confirming that at present the Montello Th. moves mainly for creeping (Picotti et al., 2022), as previously suggested also by the rheological modeling of Barba et al. (2013) and by the strain–rate observations of Serpelloni et al. (2016), which infer a limited interseismic locking for the Montello Th.

The second main structural element along the southern edge of the Venetian Prealps, is the so–called Flessura Pedemontana (Castellarin, 1981), a S–verging anticline which extends from Caltrano (VI) to Vittorio Veneto (TV) for about 90 km, involving the Mesozoic basinal succession of the Belluno Basin. Accordingly, the Mt. Corno–Mt Grappa–Mt. Cesen–Mt. Visentin anticline would have been originated by the Miocene–Pliocene tectonic activity of the S–verging Bassano–Valdobbiadene (BV) blind Thrust (Antonelli et al., 1990; Barbieri and Zampieri, 1992; Carraro and Grandesso, 198; Caputo and Bosellini, 1994; Costa and Doglioni, 1996; Picotti et al., 2022). Conversely, Doglioni (1992) described the BV–Th. as a compressive structure propagating toward the surface, giving rise to a triangle zone generating a southward dipping monocline in the Venetian foothills between Bassano and Vittorio Veneto (Zanferrari et al., 1980; Castaldini & Panizza, 1991, Doglioni 1992; Bertelli et al., 2003, Galadini et al., 2005; Castellarin et al., 2006).

Castellarin (1981) and Antonelli et al. (1990) segmented the BV Th. into three main segments: Caltrano–Bassano del Grappa (BV1), Bassano del Grappa–Alano di Piave (BV2) and Valbobbiadene–Vittorio Veneto (VVV, Fig. 1). Moreover, according to Costa & Doglioni (1996), in the easternmost portion, the Bassano Valdobbiadene Th. gives rise to a left lateral ramp (the Longhere–Fadalto–Cadola line, LFC in Fig. 1), which reuses the Mesozoic inherited paleogeographic/rheological slope located between the Friuli Carbonate Platform in the east and the Belluno Basin in the west (Masetti et al., 2012; Bosellini et al., 1981). Concerning the Quaternary tectonic activity of the BV Th., Zanferrari et al. (1980) identified a weak rising of the segmented “Flessura Bassano–Valdobbiadene” since the Piacenzian. According to the same Authors, deformation acme began from the Gelasian and lasted throughout the whole Pleistocene, with an average uplifting between 0.5 and 1 mm /yr. In particular, Zanferrari et al. (1982) specified that BV Th. tectonic activity also continued during the Uppermost Pleistocene–Holocene interval. Castaldini and Panizza (1991) inserted both the BV Th. and the Bassano–Montebelluna–Conegliano line (both non–segmented tectonic features) among the active faults of the Venetian prealpine area, highlighting their post–LGM and Holocene activity, respectively.

Recently, Picotti et al. (2022) revised geological and geophysical data of the Venetian Prealps north of Treviso, and proposed a new structural model of the area, where the Bassano–Valdobbiadene (BV) and the Montello Th. (MT) account for the active shortening at the front of the Southern Alps. In particular, the Montello Th. extends up to Treviso, thus potentially becoming the source of the 778 CE earthquake. Moreover, according to the same model, the Bassano–Valdobbiadene and the Cornuda–Bassano Thrusts would form the same buried compressive structure segmented by a NNW–SSE high angle fault along the Piave valley. Deformation at surface is also accommodated by a back–thrust that extends along the Vallata between Longhere and Valdobbiadene up to Asolano area, i.e. the Castelcucco and Longhere backthrusts respectively in Braga (1970) and Zanferrari, (1973).

Concerning the seismic potential Barba et al. (2013), based on the observed horizontal GPS and terrestrial vertical leveling data, highlighted that in the prealpine Venetian area, the structure with the greatest seismogenic potential is the BV Th., which appears locked in the interseismic time. Anderlini et al. (2020), by means of an interseismic fault model constrained by InSAR, GPS and levelling rates, confirmed that the BV Th. is a locked structure capable of generating a potential M>6.5 earthquake.

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3 Methods

As suggested by Gruppo di Lavoro MS (2008) and Commissione Tecnica per la Microzonazione Sismica (2015), we used a multidisciplinary approach to realize the present seismotectonic study. First, in order to identify the morphological anomalies potentially linked to recent tectonic activity (i.e. offset of geomorphic markers, breaks in slope, tilted surfaces, drainage anomalies, land–surfaces suspended over the present valley bottom), we analyzed the 1 m digital elevation model (DEM) of the area, constructed by means of the LiDAR technology, and gently supplied by the Treviso Provincia.

Therefore, geophysical surveys (Electric Resistivity Tomography – ERT) were used to image the shallow subsurface and to identify resistivity anomalies at depth possibly related to tectonic discontinuity. Such surveys are usually carried out using a large number of electrodes, 25 or more, connected to a multi-core cable. A laptop microcomputer together with an electronic switching unit is used to automatically select the relevant four electrodes for each measurement. At present, field techniques and equipment to carry out 2-D resistivity surveys are fairly well developed. To obtain a good 2-D picture of the subsurface, the coverage of the measurements must be 2-D as well. The type of array used for this project is the “multiple gradient array”, which shows good definition in both vertical and horizontal directions. Once data have been collected, they were inverted to obtain 2D resistivity sections (the ones reported in this paper). Instrument used was ABEM Terrameter LS2 and inversion software was ZondRes2D.

The correlation among the geophysical transects helped us to define the surficial fault traces. Based on morphological and geophysics results, we selected some trench sites across the possible surface of the Valdobbiadene–Vittorio Veneto Thrust between the municipalities of Miane, Follina and Cison di Valmarino. Trenches’ walls were cleaned and a 1 x 1 m string grid was installed on the straightened walls, to sketch the walls in 1:10 scale. The vertical orthophotomosaics of the walls were created using the Structure from Motion method with resolution between 1 and 5 mm per pixel and precision between 5 and 10 mm of the points on ground.

Radiocarbon dating was performed by BETA Analytic.

4 Quaternary evolution of the study area

At present, the study area belongs to the northern sector of the Soligo Stream catchment, which rises near Revine locality and flows in an about ENE–WSW direction towards the Follina narrow. Here it makes a sharp deviation and receives from the west the San Pietro Stream (Figs. 2 and 3). Towards the north, the Soligo valley is bordered by the main reliefs of the area, i.e. the Mt. Cesen–Mt. Visentin mountain chain, shaped in the Mesozoic sequences of the Belluno Basin (Costa and Doglioni, 1996). Conversely, towards the south, reliefs are carved in the terrigenous Paleogene sequences of the Belluno Flysch and Neogene Southalpine Molasse (Massari et al., 1990; Stefani et al., 2007).

From a structural point of view, both the San Pietro and the Soligo Valleys settled on the S–verging, WSW–ENE trending Bassano–Valdobbiadene Thrust *Auct.* which, during the Neoalpine compressive tectonic phase ($\sigma 1$ about NW–SE), inverted the about NE–SW trending Mesozoic extensional fault–system bordering the Friuli Carbonate Platform toward the Belluno Basin, and overlapped the Mesozoic sequences on the Paleogene and Neogene sequences of Flysch and Southalpine Molasse.

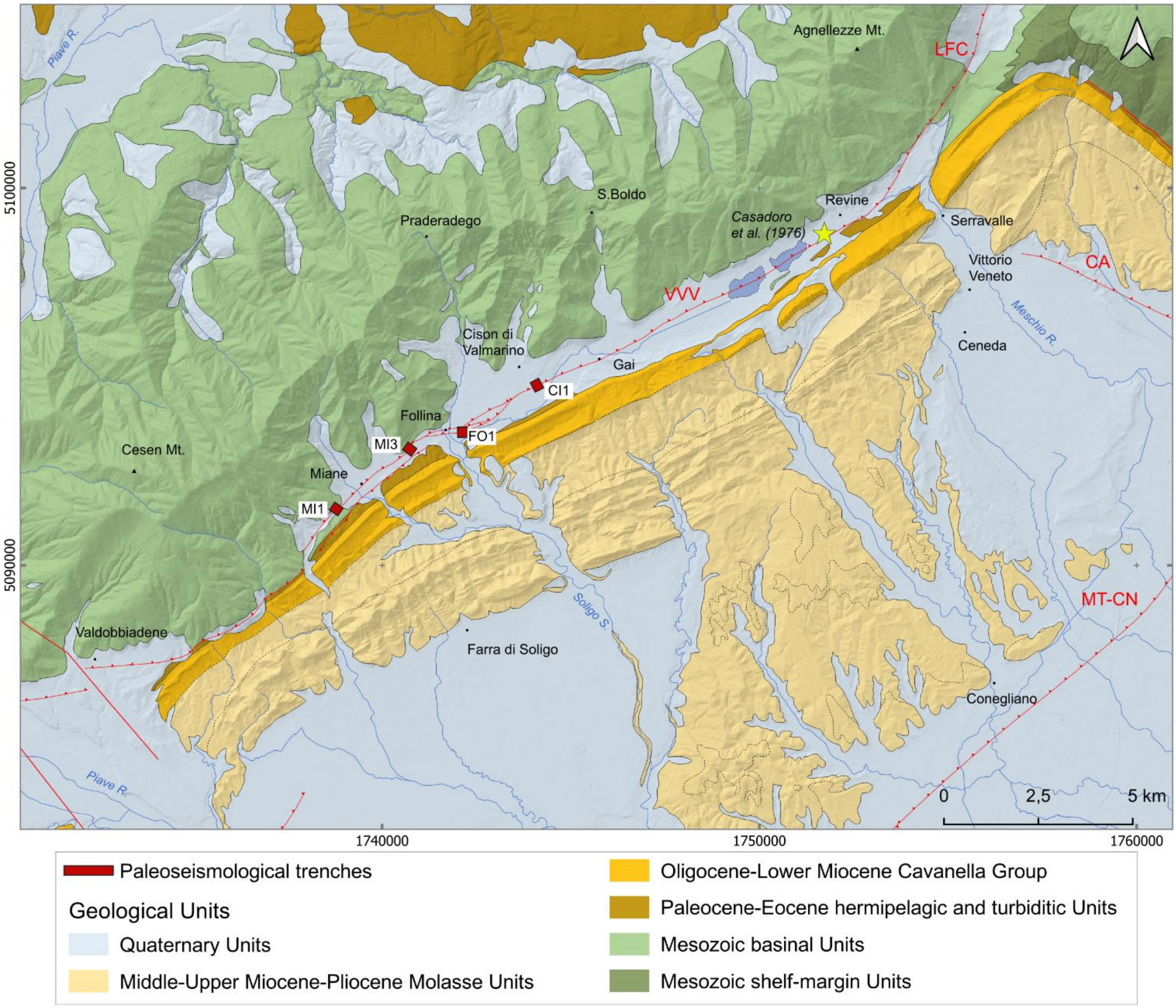

Figure 2: Geological sketch of the study area, where the Valdobbiadene–Vittorio Veneto Th. (VVV) develops (modified after Carta Geologica delle Tre Venezie alla scala 1:100000, Fogli 38 Conegliano – 37 Bassano del Grappa – 23 Belluno; Carta Geologica d'Italia alla scala 1:100000, Foglio 22 Feltre; Antonelli et al., 1990). Faults: CA: Cansiglio Th., LFC: Longhere–Fadalto–Cadola Line, MT-CN: Montello-Conegliano Th. Basemap: TINITALY/1.1 (INGV, Tarquini et al., 2023).

Moreover, the present morphology of the area is closely linked to the Quaternary glacigenic morphogenic activity of the Piave Glacier. In particular, during the Last Glacial Maximum (LGM), here dated at about 21 ka cal BP (Bondesan, 1999; Carton et al., 2009), the Piave Glacier entirely occupied the Belluno valley toward the north, and formed a second major branch along the Lapisina Valley. In turn, the Lapisina valley branch divided into two smaller tongues toward the south: the first occupied a large part of the present Soligo valley, closing near the Gai end–moraines (Venzo, 1977) (Fig. 3), the second occupied the Vittorio Veneto basin up to the end moraines of Ceneda (Bondesan, 1999). The progressive retreat of the glaciers towards the upper part of the Piave catchments occurred between 18 and 15 ka cal BP (Pellegrini, 2018). The discovery near the Fornaci di Revine locality (yellow star in Fig. 2), upstream of the Gai frontal moraine, of a forest of fossil trunks in a growing position dated at about 16 ka cal BP (Casadoro et al., 1976; Friedrich et al., 1999), confirms that the complete deglaciation of the valley had already begun around 17 ka cal BP (Pellegrini 2018).

During and after the definitive retreat of the LGM Piave Glacier, widespread slope degradation processes were particularly active along the Soligo and Lapisina valleys, probably supported also by active tectonics. From the slopes still bare of vegetation and subject to the action of the washing waters, considerable quantities of landslides and debris were toppled onto the valleys: concerning, we can remember the colossal Fadalto landslide that happened about 15 ka ago (Pellegrini and Surian 1996). The glacial over–excavation basins and the lake basins that had been close to the lateral moraine banks (see for example the Revine lake formed about 16 ka cal BP, Casadoro et al., 1976; Venzo, 1977), or formed by landslide damming (see for example the Lake of Santa Croce) or by alluvial fans, were thus filled by various mass transport phenomena. The presence of telescopic fans along the Lapisina valley (Venzo, 1977) testifies a widespread phase of aggradation up to the Holocene.

4.1 Morphotectonic hints of recent tectonic activity of the Valdobbiadene-Vittorio Veneto Thrust

In order to reconstruct the Upper Pleistocene–Holocene tectonic activity of the VVV Thrust, we made a morphotectonic survey along the San Pietro and the Soligo valleys from Miane to Cison di Valmarino (Fig. 3). For this purpose, we analyzed the 1 m digital elevation model (DEM) of the area, and selected the areas with possible anomalies linked to the tectonic activity. Then we validated these observations by a morphotectonic field survey. The resulted morphotectonic map (Fig. 3) shows widespread river anomalies: most of the tributaries of the Soligo and San Pietro Streams make a series of about NNE–SSW striking water gaps before flowing in the respective major streams. Moreover, in correspondence of the river gaps, along the supposed surficial trace of the VVV Thrust, a series of about WSW–ENE scarps and elongated warping of the topographic surface were observed and mapped. Near Follina, widespread Deep-Seated Gravitational Slope Deformation (DSGSD) and counterslopes characterize the southern slope of Pianezze hill.

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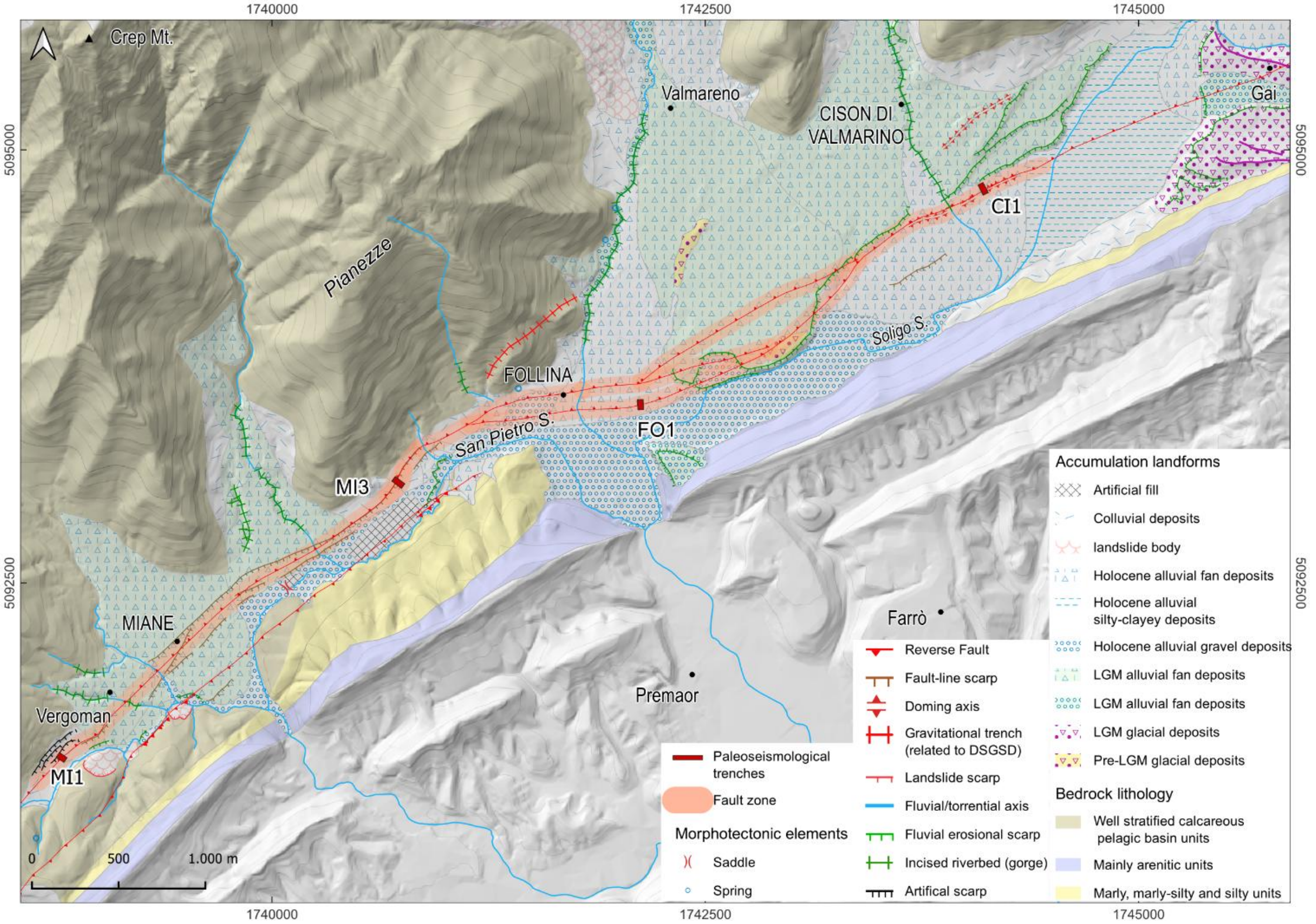

Figure 3: Morphotectonic map of the area between Miane and Cison di Valmarino. The fault zone was mapped based on morphotectonic and geophysical evidence. Red bars are the paleoseismological trenches (CI1, FO1, MI3 and MI1). Basemap: TINITALY/1.1 (INGV, Tarquini et al., 2023).

5 Paleoseismological trenching

Based on geophysical and morphotectonic surveys, we dug four trenches along the supposed surficial trace of the Valdobbiadene–Vittorio Veneto Th. (for location see Figs. 2 and 3).

5.1 Cison 1 trench (Case dalla Libera locality)

The Cison 1 trench was located in the distal portion of the Holocene fan of the Ruio Stream (Fig. 4) which outflows from the southern slopes of the prealpine relieves between Praderadego and San Boldo (Fig. 2).

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Figure 4: Location of the Cison 1 trench near Case dalla Libera. The ERT highlights the anomaly in the resistivity distribution in correspondence of the morphostructural warping. Fault zone derives from the morphotectonic map in Fig. 3. Basemap: 1 m grid resolution LiDAR DTM provided by Provincia di Treviso and 1:10000 topographic cartography from Regione del Veneto.

Carving the Jurassic–Cretaceous units of the Belluno Basin succession, the Ruio Stream generates a series of telescopic fans, the eldest of which is dated back to Upper Pleistocene (LGM according to Venzo et al., 1977). In the innermost portion of the Holocene alluvial fan, gravels are tilted towards the north by approximately 25° (Fig. 4 and Fig.5) suggesting a Holocene tilting.

Figure 5: Holocene back–tilted gravels of the Ruio fan (for location see Fig. 4).

The trench was realized across an ENE–WSW elongated surficial bulge, located in coincidence of the geophysical anomaly detected by ERT survey (Fig. 4). Particularly, the 33 m long excavation reached a depth of 2.5 m from the datum plane, with local deepening up to 3 m depth.

The excavated trench exposed a gravelly succession of alluvial fan (Fig. 6).

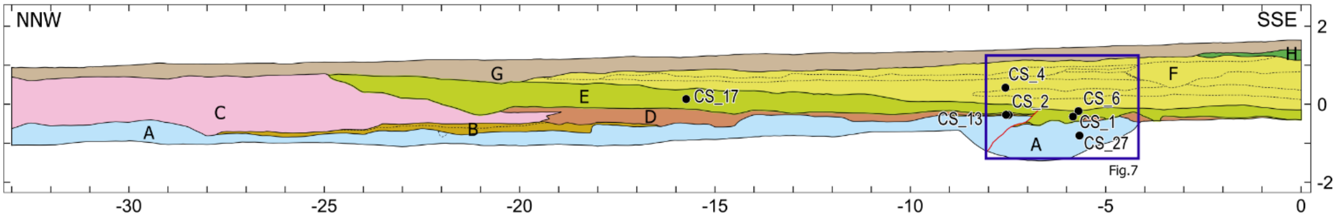

Figure 6: Log of the eastern wall of trench Cison 1 (ortophotomosaic in supplementary material S1). Units from A to E are cut and displaced by a S–verging reverse fault (detail in the text and in Fig. 7). The black circles are the samples dated by Beta Analytic.

The lowermost A Unit (dated at 552–648 cal CE) is composed of gravels with pebbles and cobbles in sandy–silty matrix. The biggest pebbles, mainly made of oolitic limestones, testify a northern provenance (Dolomia di San Boldo Fm.). A Unit is covered by the B Unit made of discontinuous thin organic–rich silt (dated at 1033–1190 cal CE/1160–1264 cal CE), which marks the transition from a high–energy depositional environment towards a low–energy interchannel domain. Upwards, the sedimentary succession is made by a set of fine–to–coarse gravelly channel units (Units C, D and E, this latter dated at 974–

1047 cal CE/1056–1158 cal CE and 1165–1265 cal CE), getting thinner and thinner towards the southern portion of the wall. Unit F (dated 1302 – 1368 cal CE) closes the continental sequence: it represents the distal deposition of the alluvial fan and is made of prevailing sands with thin lenses of gravels.

Concerning deformation, we can note that, between sections –8 and –6, a S–verging, about W–E trending medium angle reverse fault displaces A, B, D and E Units (Fig. 7) but is sealed by Unit F. The estimated vertical throw, measured both on the bottom of Units B and E, is about 21 cm.

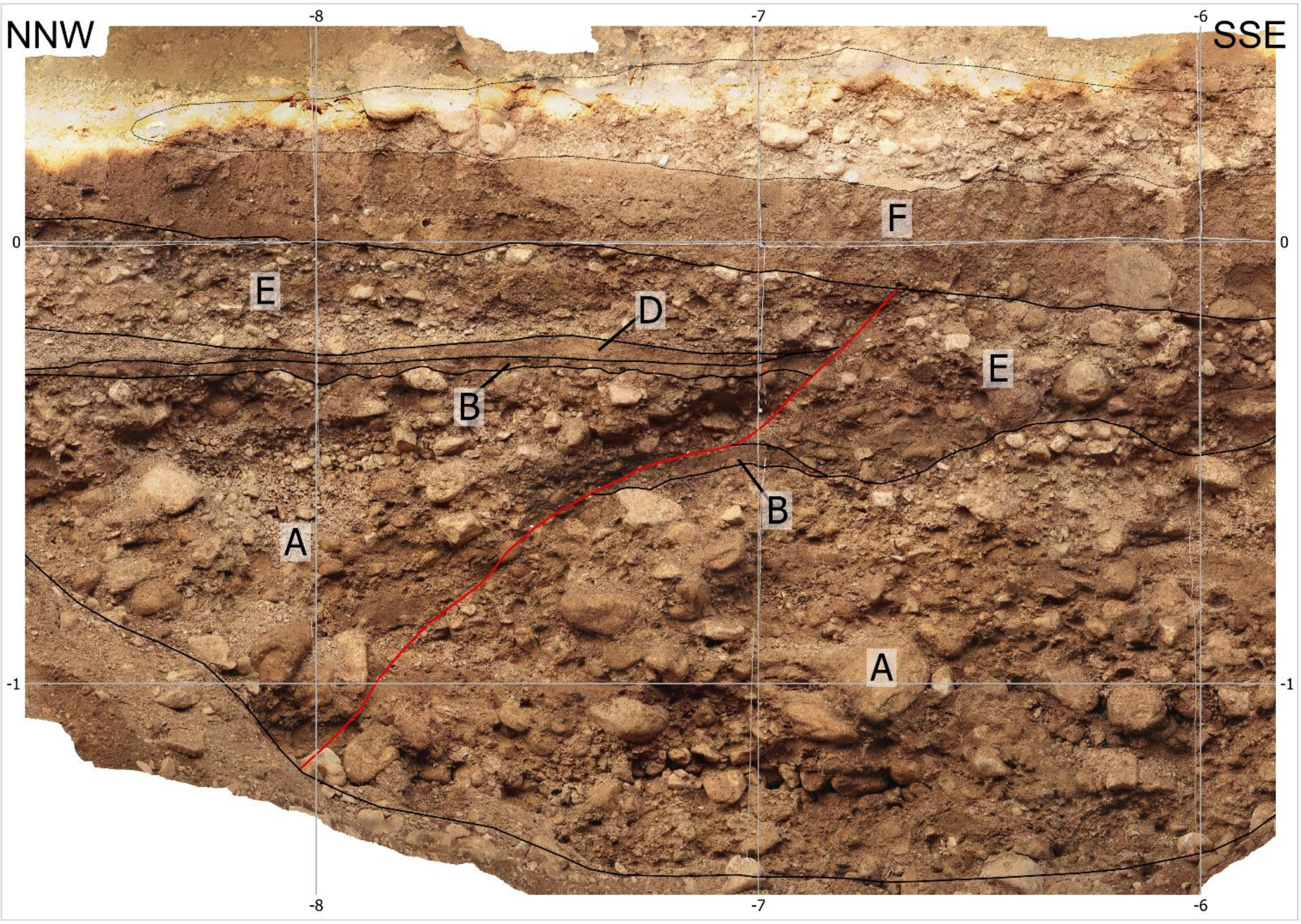

Figure 7: Detail of the fault zone identified in the Cison 1 trench: the thin silty layer (unit B) and the bottom of E unit are cut and displaced of about 21 cm by a S–verging reverse fault. The fault is sealed by unit F dated at 1302 – 1368 cal CE.

Table 1: Detail of the radiocarbon dating performed on the collected samples (calibration curve by Reimer, et.al., 2013 and Reimer et al., 2020 [*]).

SAMPLE	UNIT	DATING	TYPE OF MATERIAL
CS1_27	A	552 – 648 cal CE	organic sediment

CS1_2	B	1033 – 1190 cal CE	charred material
CS1_13	B	1160 – 1264 cal CE	charred material
CS1_1*	E	974 – 1047 cal CE	charred material
CS1_6*	E	1056 – 1158 cal CE	charred material
CS1_17	E	1165 – 1265 cal CE	charred material
CS1_4*	F	1302 – 1368 cal CE	charred material

Based on these observations, it is possible to identify one deformative event (C1) occurred after the deposition of E Unit but before the sedimentation of F Unit. The available datings strictly constrain the chronology of this deformative event, defining a time interval comprised between 1165–1265 cal CE (E Unit) and 1302–1368 cal CE (F Unit).

5.2 Follina 1 Trench (alla Sega locality)

Follina 1 trench was dug at the eastern portion of Follina village ("alla Sega" locality, Fig. 8). From a morphological point of view, the excavation was located on the toe of the Holocene alluvial fan of the Corin Creek, where it joins the Soligo Stream (Fig. 8). The Corin Creek, that at present across Follina in an artificial channel, comes down from the southern prealpine slope of Praderadego gap (Venzo et al., 1977), and its catchment affects the basinal lower Jurassic–Lower Cretaceous formations of the Mesozoic Belluno Basin: Igne Fm., Vajont Limestones Fm., Fonzaso Fm. and Maiolica Fm. (Bondesan et al., 2013).

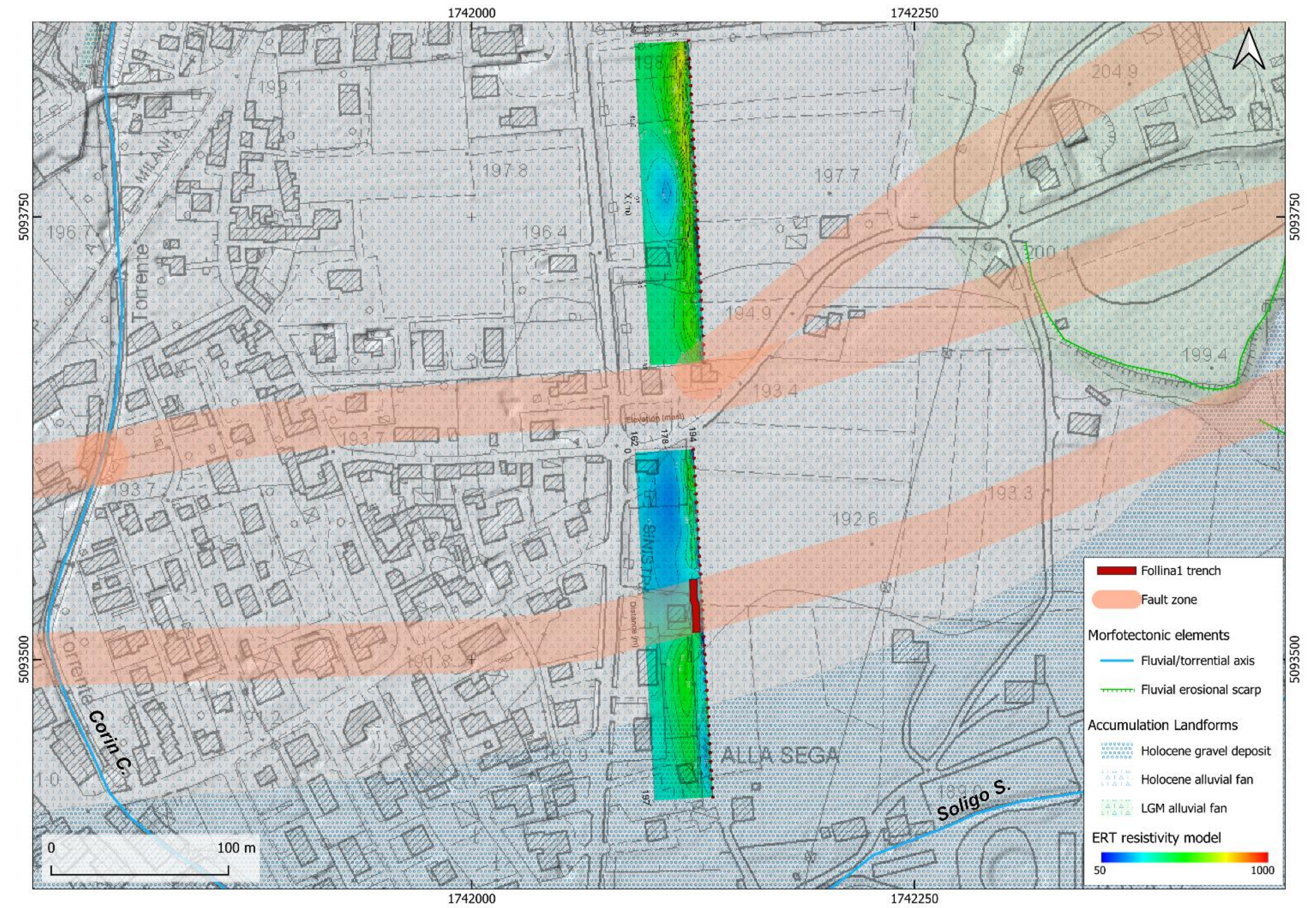

Figure 8: Location of Follina 1 trench near "la Sega" locality. Fault zone derives from the morphotectonic map in Fig. 3. Basemap: 1 m grid resolution LiDAR DTM provided by Provincia di Treviso and 1:10000 topographic cartography from Regione del Veneto.

The trench was dug across the lateral transition of resistivity values showed by the geophysical survey (Fig. 8).

The 25 m long and 2.5 m deep Follina1 trench cut through a continental stratigraphic sequence, related to the Holocene alluvial dynamics. The southern portion of the wall is characterized by lens shaped gravel bodies typical of high–energy torrential fan (A, B and C Units in Fig.9); thin levels of sands and sandy silt characterised B Unit. The composition of the gravels (mostly limestone, dolostone and cherty limestone), which are generally well rounded, confirms the northern provenance of the clasts (i.e. Venetian Prealps) of the A, B and C alluvial Units which are overlaid by the gravelly silt of D Unit. This aspect testifies the persistence of an alluvial environment, revealing the transition from a high energy domain (Corin Creek) towards a lower one that can be attributed to the post-LGM/Holocene Soligo Stream.

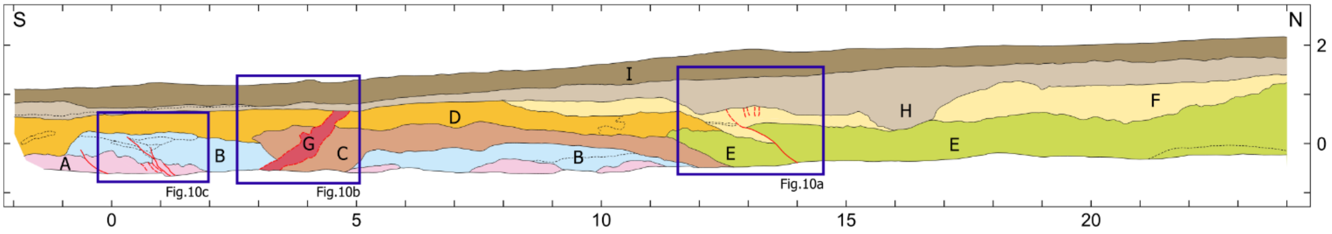

Figure 9: Log of the western wall of the Follina trench 1 (ortophotomosaic in supplementary material S2). The black circles are the samples dated by Beta Analytic, the blue square and the red triangles are the plastic and the bricks that were found in the continental units.

Differently, the northern portion of the trench wall interested a thick gravel body (E Unit) characterized by a sub–horizontal attitude. The sub–rounded to rounded carbonatic clasts are often coated with Fe/Mn oxides, more abundant in the shallower portion of the unit. On top of the gravels, an erosional surface separates the Unit E from the 1 m thick body of sands and locally, gravelly sands (Unit F). All the stratigraphic sequence is overlaid, through an erosional surface, by a silty body with pebbles (Unit H). Because of the abundant presence of bricks and plastics, Unit H certainly represents an anthropogenic unit, sealed by the ploughed soil (Unit I) (Fig. 9).

The stratigraphic succession at whole revealed a historical age, spanning from 1221–1016 cal BCE for the deepest body (Unit B), to 1666–1783 cal CE for the shallowest deposits (Unit H) (Table 2).

Table 2: Detail of the radiocarbon dating performed on the collected samples (calibration curve by Reimer, et.al., 2013 and Reimer et al., 2020[*]).

SAMPLE	UNIT	DATING	TYPE OF MATERIAL
1FO/10	B	1221–1016 cal BCE	charred material
1FO/7	B	1265–1053 cal BCE	charred material
1FO/19*	D	645–706 cal CE	charred material
1FO/27	E	662–774 cal CE	organic sediment
1FO/21	F	1262–1309 cal CE	charred material
1FO/22	H	1666–1783 cal CE	charred material

Concerning the tectonic activity, two distinct deformational zones were detected along the Follina 1 trench (Figs. 9 and 10).

- In the central portion of the wall (between sections 12 and 14, Fig. 9 and Fig. 10a), both the gravels of Unit E (662–774 cal CE), and the overlying sands of Unit F (1262–1309 cal CE) are displaced by a N115° striking, middle–angle reverse plane. The vertical displacement is of about 32 cm. The fault plane is sealed by Unit H, which representsthe subsequent anthropogenic infill deposited between the 17th and 18th centuries (1666–1783 cal CE). This vertical displacement can be correlated to a coseismic event.

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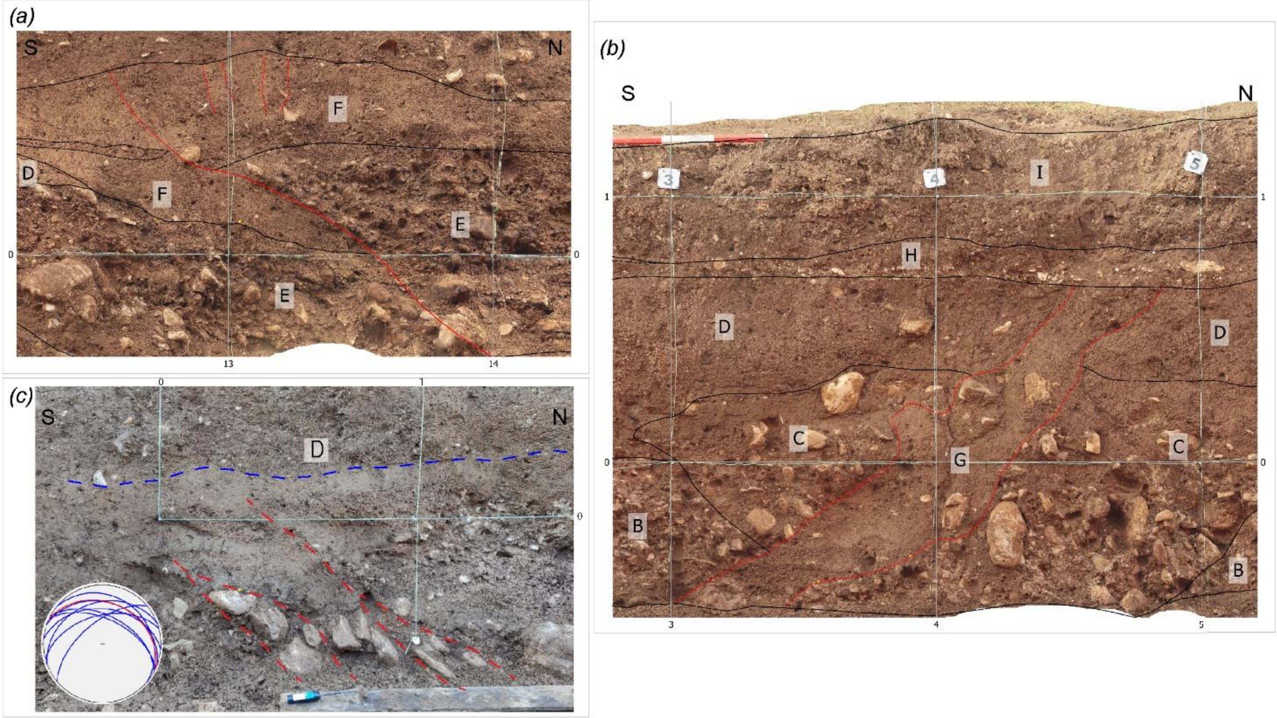

Figure 10: (a) reverse fault plane displacing units E, F and D, sealed by unit H; (b) paleoliquefaction dike filled by massive sands crossing units B, C and D units; (c) aligned clasts marking the S–verging shear zone in the southern portion of the wall affecting units A and B and stereographic plot of the measured shear planes with a mean value of 25/30.

- The southern portion of the wall (sections 3–5, Fig. 9 and Fig. 10b) is characterized by the presence of a massive sandy body (Unit G) which cuts both the gravelly debris bodies (B and C Units) and the overlying silty gravels (Unit D), but is sealed by the Unit H. The genesis of the G Unit could be referred to liquefaction phenomena induced by seismic shaking. In this regard, it is worth to remark that the proximity of the Soligo Stream allows defining the depth of the water table in the study area at about 5–6 m depth from the datum plane. Moreover, the presence of local perched aquifers at shallow depth is documented.
- In the southernmost portion of the wall, between sections 2 and –1 (Fig. 9 and Fig. 10c), the boulders of Unit A are imbricated towards the south: this arrangement could be related to the southward alluvial outflow of the Corin Creek. However, the imbrication planes visible in A Unit define a series of *s/c* structures which affects also the B Unit. These detected geometries could be associated to another tectonic event related to the Valdobbiadene–Vittorio Veneto Thrust or to a secondary effect linked to the seismic shaking, probably referred to the liquefaction event registered by sand body of G Unit.

The analysis of the Follina 1 trench shows that the coseismic activation completely involved the continental succession, except for Unit H dated back to the 17th–18th century. Two possible tectonic events could be identified:

- the first and older (F2) involved both A and B Units, but is sealed by D Unit. On this evidence, we suppose that this first seismic event, happened after the deposition of Unit B (1265 – 1016 cal BCE) and before the sedimentation of Unit D (645–706 cal CE);
- a second more recent seismic event (F1) produced coseismic rupture and displaced Units E, D and F. However, since the Unit H is not affected by deformation, F1 must have occurred after the deposition of Unit F (1262–1309 cal CE), but before the development of Unit H (1666–1783 cal CE). The vertical offset of this coseismic event is of the order of 32 cm. FO1 caused also secondary effects as liquefactions, with the intrusion of a sand body (Unit G).

5.3 Miane 3 Trench (via Giorgione)

The Miane 3 trench was dug in Giorgione Street (Miane municipality, Fig. 11). The site is located on the left of the San Pietro Stream, where the San Pietro alluvial fan merges with the colluvial fans covering the southern slope of the carbonatic massif. The mountain slope is composed of the Jurassic–Cretaceous Belluno Basin lithological units: Maiolica, Rosso Ammonitico and Vajont Limestones (Venzo, 1977; Bondesan et al., 2013). Particularly, the trench crossed a well–expressed morphological scarp, which affects the small colluvial fan on the left side of the San Pietro valley (Fig. 12). The about 2 m high scarp extends towards the east and the west with a WSW–ENE trending, for a total length of about 2 km, crossing densely populated areas.

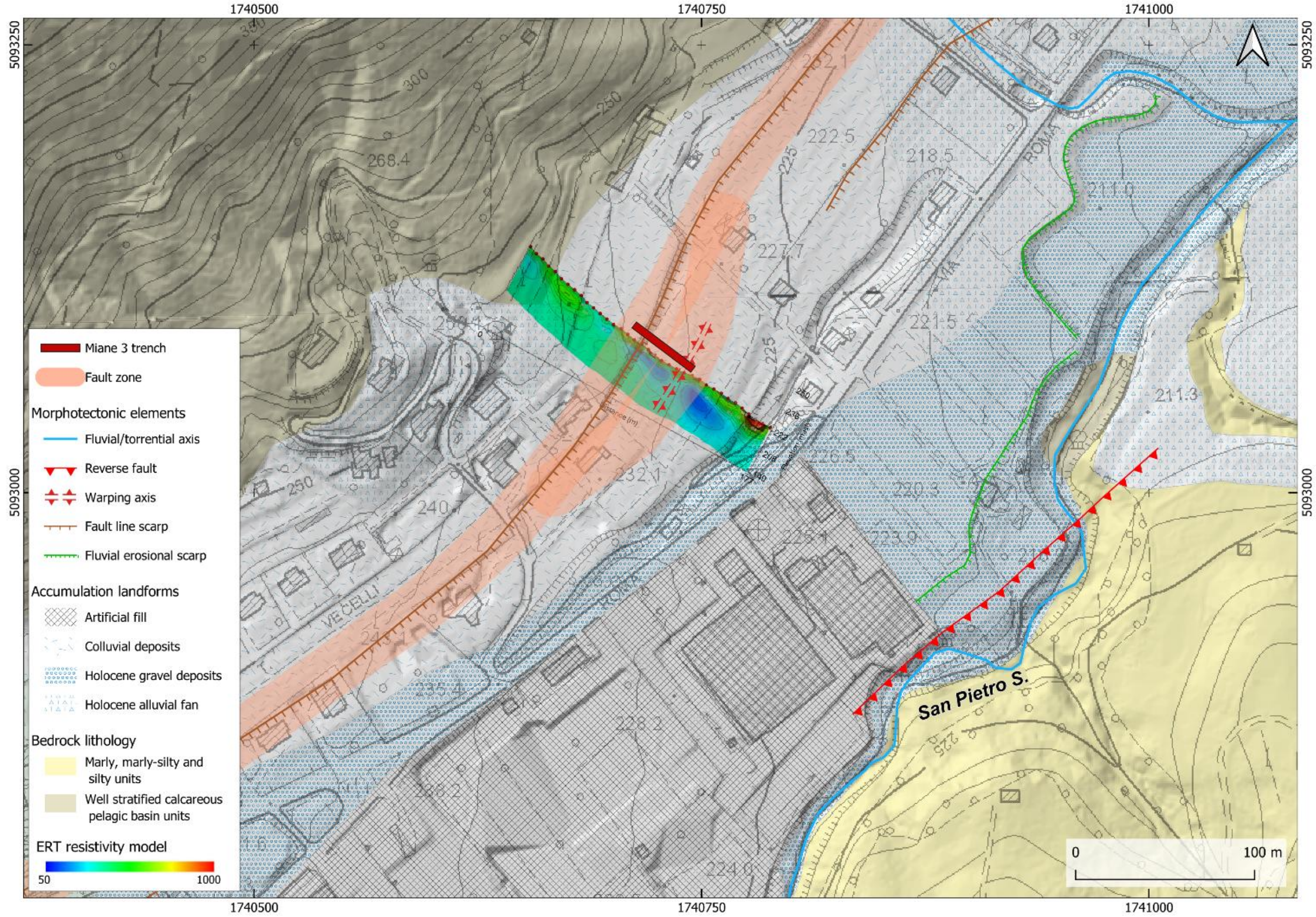

Figure 11: Location of Miane 3 trench (Via Giorgione, Miane locality). The ERT highlights some anomalies in the resistivity distribution in correspondence of the morphological scarp. Fault zone derives from the morphotectonic map in Fig. 3. Basemap: 1 m grid resolution LiDAR DTM provided by Provincia di Treviso and 1:10000 topographic cartography from Regione del Veneto.

Figure 12: The morphological scarp across which Miane 3 trench was excavated.

The excavated trench exposed a continental stratigraphic succession (Fig. 13) composed of colluvial body (A Unit) covering a basal silty gravel representing a heavily altered paleosoil (P Unit: Munsell colour 7,5YR 5/4). On top of the A Unit, a gravel body of distal alluvial fan (B Unit) with thin sandy lenses, is present. Both the geometry and the clasts composition reveal the local provenance of the deposit coming from the southern mountain slope. Unit C, that is a debris body of poorly sorted coarse gravelly in silty matrix, locally covers the B Unit by means of an erosive surface.

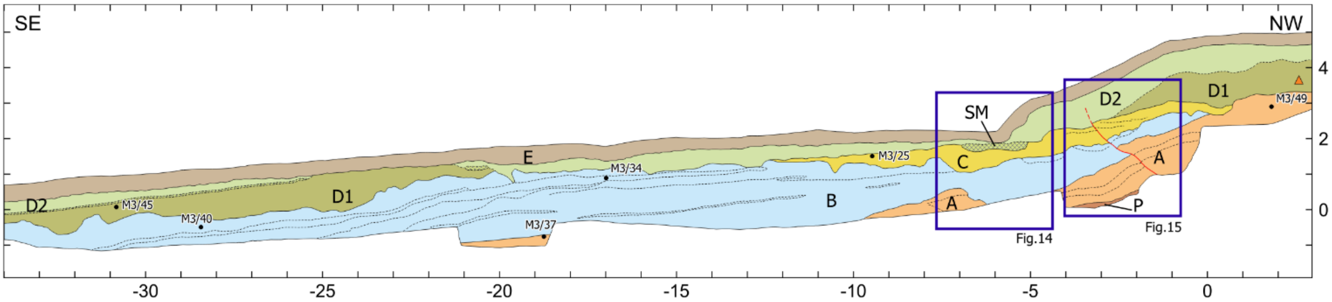

Figure 13: Log of western wall of Miane 3 Trench (ortophotomosaic in the supplementary material S3). The black circles are the samples dated by Beta Analytic, the red triangles are the bricks. Blue rectangles are Figs. 14 and 15.

Upwards, D Unit that presents reddish bricks, is composed by a basal sandy gravel D1 Unit and an upper chaotic D2 Unit, with coarse sharp gravels in sandy matrix. D Unit is characterised by anthropogenic artefacts. In particular, between –7 and –5 sections, carved on C Unit, we identified a 20–30 cm thick well–organized collection of prevailingly sub–rounded and often well–altered carbonatic pebbles covered by 3–5 cm thick, compacted layer of fine gravel in silty–clayey matrix (SM Unit). According to dr. M. Zanchetta (personal communication), SM Unit is probably referable to the pre–Roman Age "Strada Maestra", that connected Valdobbiadene to Serravalle during the Bronze Age. Moreover, in the southern portion of the trench (–34/–25 sections) a thin well organized fine gravels level probably of anthropogenic origin, separates D1 from D2 Units. The ploughed soil (F Unit) overlies the whole stratigraphy all along the excavated wall (Fig. 13).

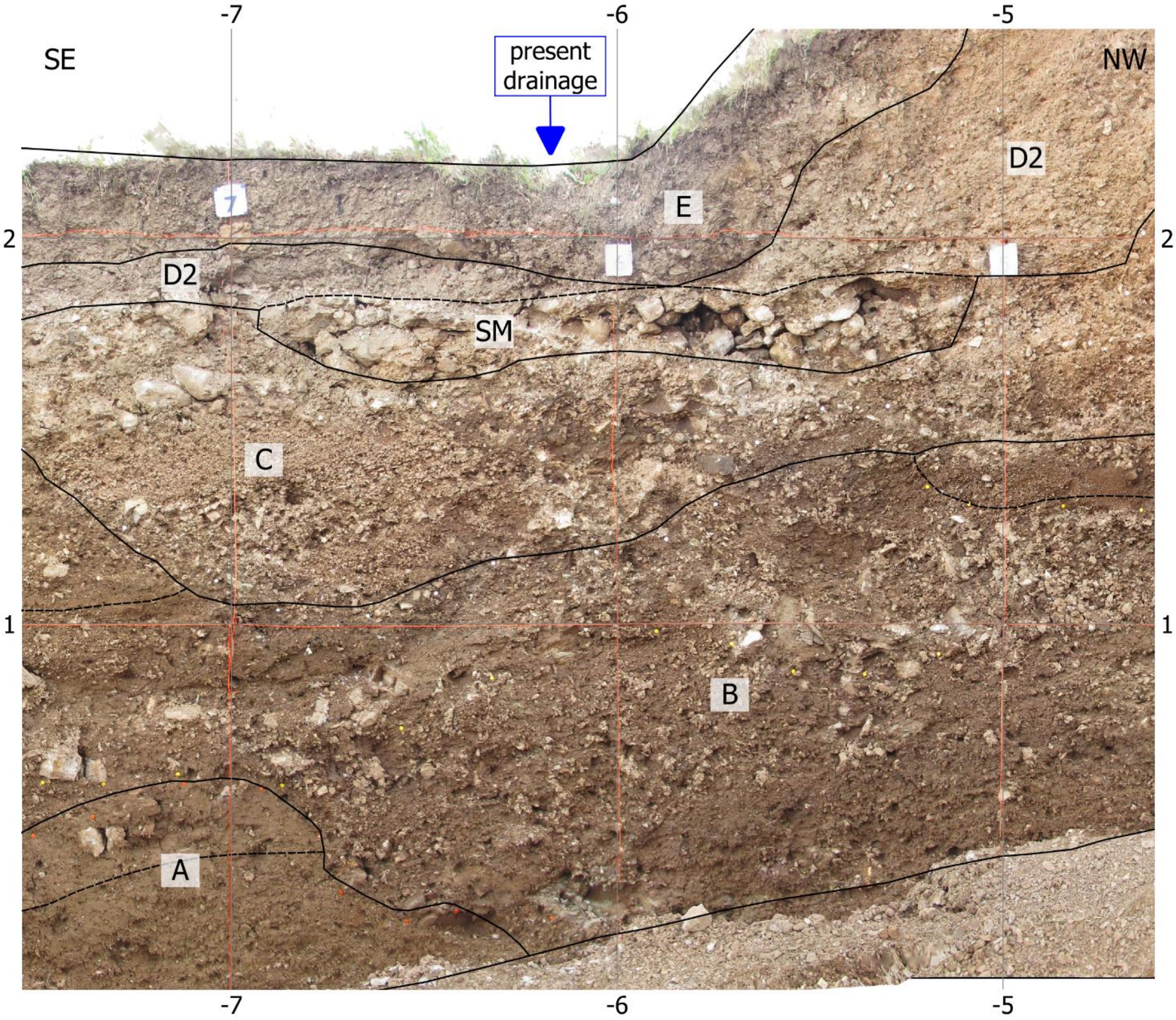

Figure 14: Detail of the Miane 3 western wall showing the anthropogenic artefact: the pre–Roman Strada Maestra (dr. M. Zanchetta personal communication).

Concerning the age of the continental succession (Table 3), the dating samples related to A and B Units showed an age between 4783–4351 cal BCE. C Units deposited between 3770 and 3653 cal BCE, while D1 Unit is dated 2504–2399 cal BCE. Concerning D2 Unit, we suppose that it deposited during or post the Bronze Age (here dated at 2300–1000 CE, Bonetto et al., 2009), since it overlays the pre–Roman Strada Maestra Unit (SM).

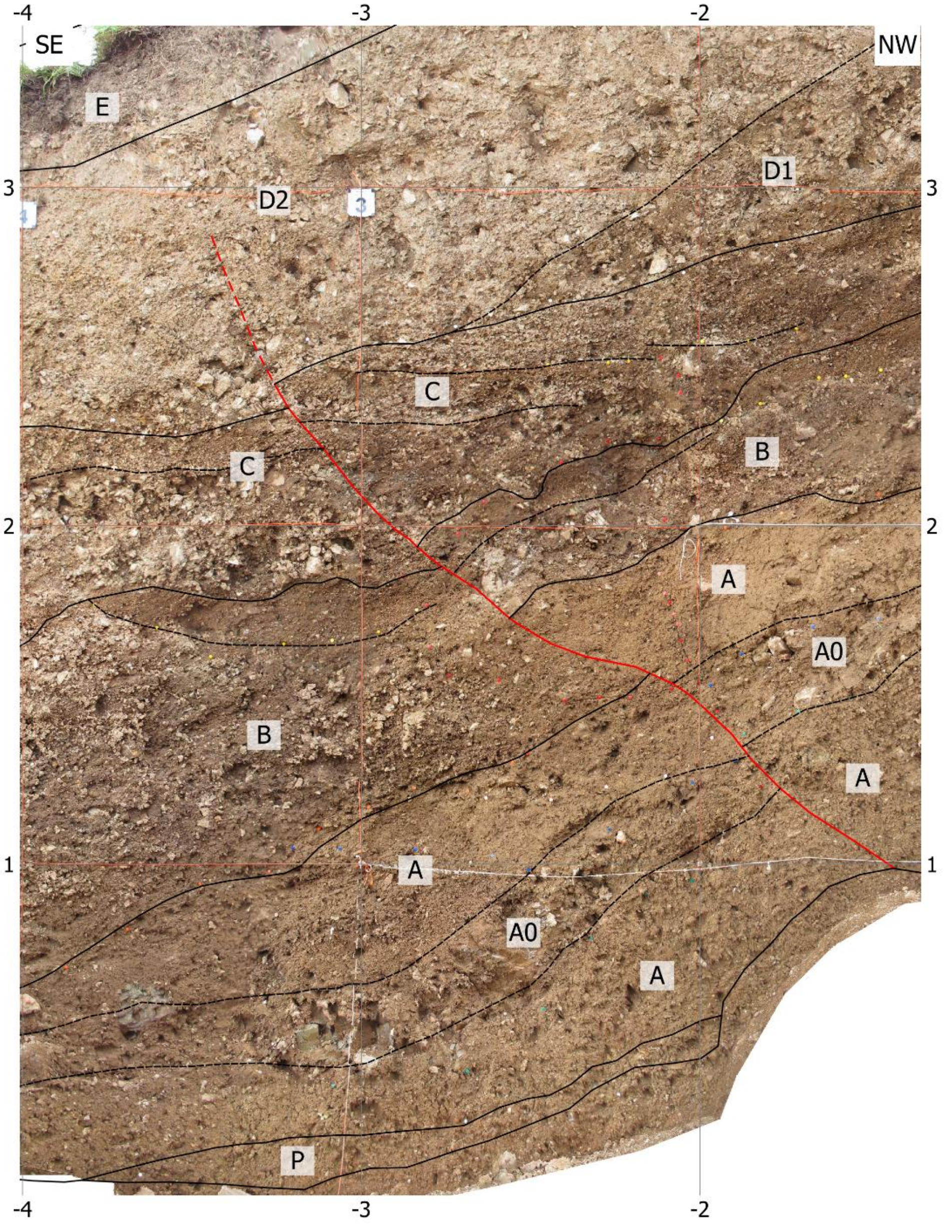

Figure 15: Western wall of the Miane 3 trench: detail of the portion located between –1 and –4. The Az, A0, A, B and C units are displaced by a medium–angle, S–verging reverse fault.

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Table 3 – Detail of the radiocarbon dating performed on the collected samples (calibration curve by Reimer et al., 2013).

SAMPLE	UNIT	DATING	TYPE OF MATERIAL
M3/37	A	4783 – 4605 cal BCE	organic sediment
M3/49	A	4453–4349 cal BCE	organic sediment
M3/40	B	4554–4445 cal BCE	organic sediment
M3/34	B	4461–4351 cal BCE	organic sediment
M3/25	C	3770–3653 cal BCE	organic sediment
M3/45	D1	2504–2399 cal BCE	organic sediment

The excavated trench exposed the about 25 m wide deformation zone (Fig. 13), in particular we identified the following features:

a) between sections 0 and –8 the morphological scarp coincides with an E–W trending, S–verging medium–angle reverse fault which displaces all the stratigraphic sequence up to the ploughed soil.

b) Between sections –35 and –19 A, B, and D sedimentary Units are gently warped: deformation seems to involve the topographic surface which forms a gently curvature in correspondence with the fold, probably related to the presence of a minor frontal splay (Fig. 13).

Regarding the interpretation of the Miane3 trench, both the longer stratigraphic interval exposed, and the different vertical displacement values measured on the bottom of the stratigraphic units agree for an articulated deformation and seismic history of the fault plane. For this reason, we restored the trench wall log and successively validated the restoration through the forward model construction in 3D Move (Fig. 16).

The interpretation of the wall shows that the shallower D2 and C Units registered a comparable displacement. Differently, the offset characterizing the bottom of Unit B is higher (Fig. 16a). In this regard, it is important to remark that if considering the similar age of B and A Units, it is reasonable to assume that both Units registered the same seismic history. During the restoration, the first step consisted of removing the deformation of the bottom of D2 Unit associated to the M2 identified event. This stage allowed to restore a vertical slip ofabout 7 cm on both the bottom of D2 and C Units, and highlighted some residual displacement on the bottom of B Unit (Fig. 16b). In the second step we restored the displacement of a previous event M3 by removing 13 cm vertical offset on B and A Units (Fig. 16c). At this point, the offsets of the stratigraphic horizons were restored. However, if considering the standard value of about 15° for the original dip slope, some folding deformation is still detectable within A and P Units. Moreover, the upwarping affecting the entire stratigraphic succession in the southern sector of the wall (sections −35 to −19) should also be considered.

Based on these statements, the restoration of the Miane 3 wall allowed us to reconstruct the seismic history of the site:

- a first, older event (M3) involving P, A and B Units occurred before the deposition of C Unit. During this event the fault probably ruptured at surface causing the formation of a topographic scarp (Fig. 16d). Following the coseismic stage, erosion processes and the deposition of C Unit removed the fault offset (Fig. 16e);
- a successive M2 earthquake occurred after the deposition of D2 Unit, thus involving also the anthropogenic artifact SM of the pre–Roman age (Fig. 16f). In this case, because the fault plane propagates up to the base of the ploughed soil, no additional upper chronological constraints are available for the timing of this seismic event;
- the presence of folding deformation affecting the entire stratigraphic succession, including the present–day topographic surface, indicates that the site has recorded additional deformation beyond the coseismic displacement identified along the fault plane. Although the available data do not permit a more precise characterization of this deformation, it is plausible to hypothesize the presence of a frontal blind reverse fault that, if activated in relatively recent times (M1), may have produced the observed folding of the youngest units up to the ground surface.

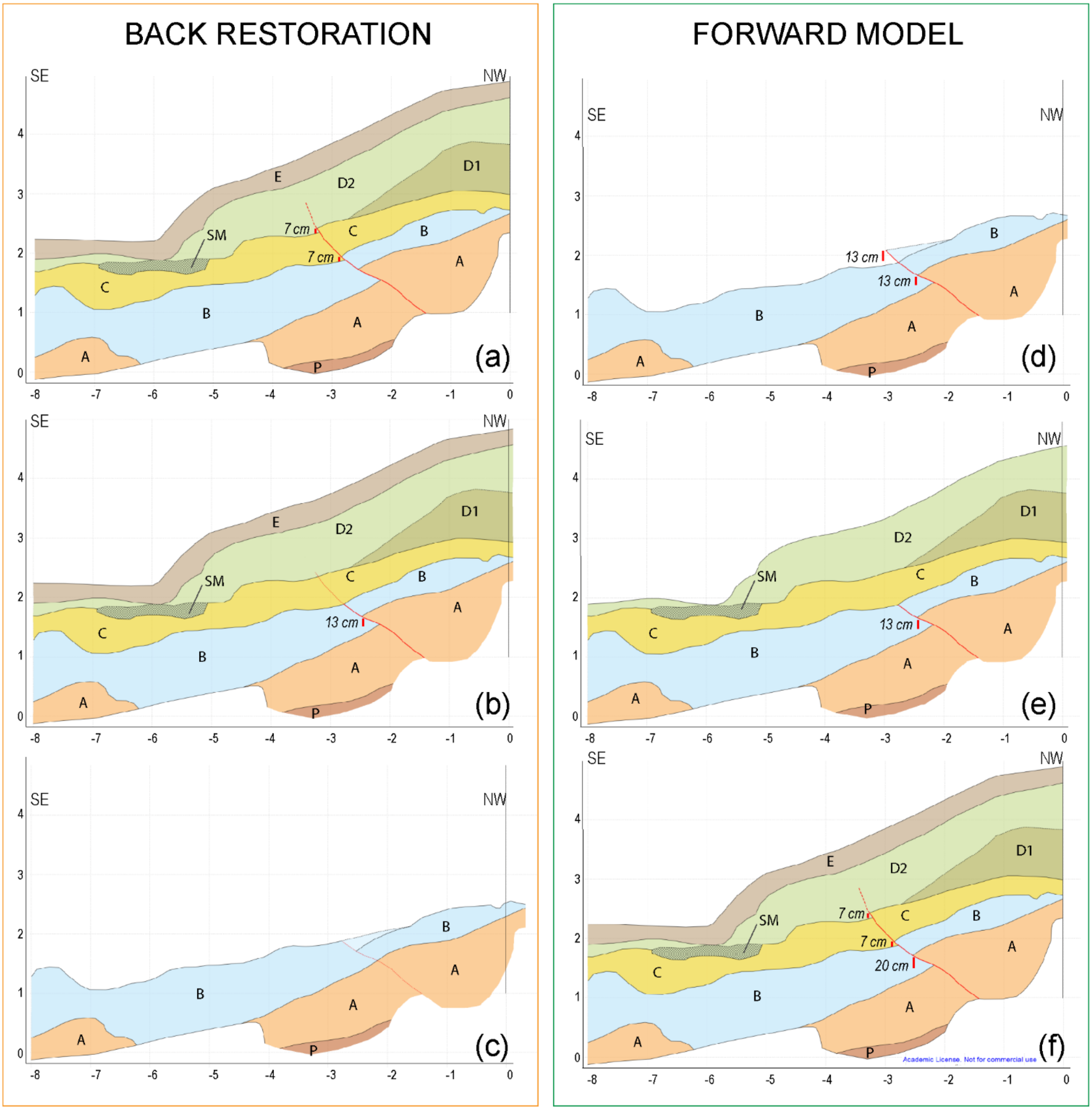

Figure 16: Miane 3 log restoration and forward model.

5.4 Miane 1 Trench (Vergoman locality)

Trench Miane 1 was dug in the Vergoman area (Municipality of Miane) (see Fig.17), in correspondence of the ERT anomaly, downstream of an about NE–SW striking morphological warping (Fig. 18). The trench reached a length of approximately 22 m, an average depth of 2.5 meters (with local deepening of up to 3 meters) and a width of approximately 2.5 meters.

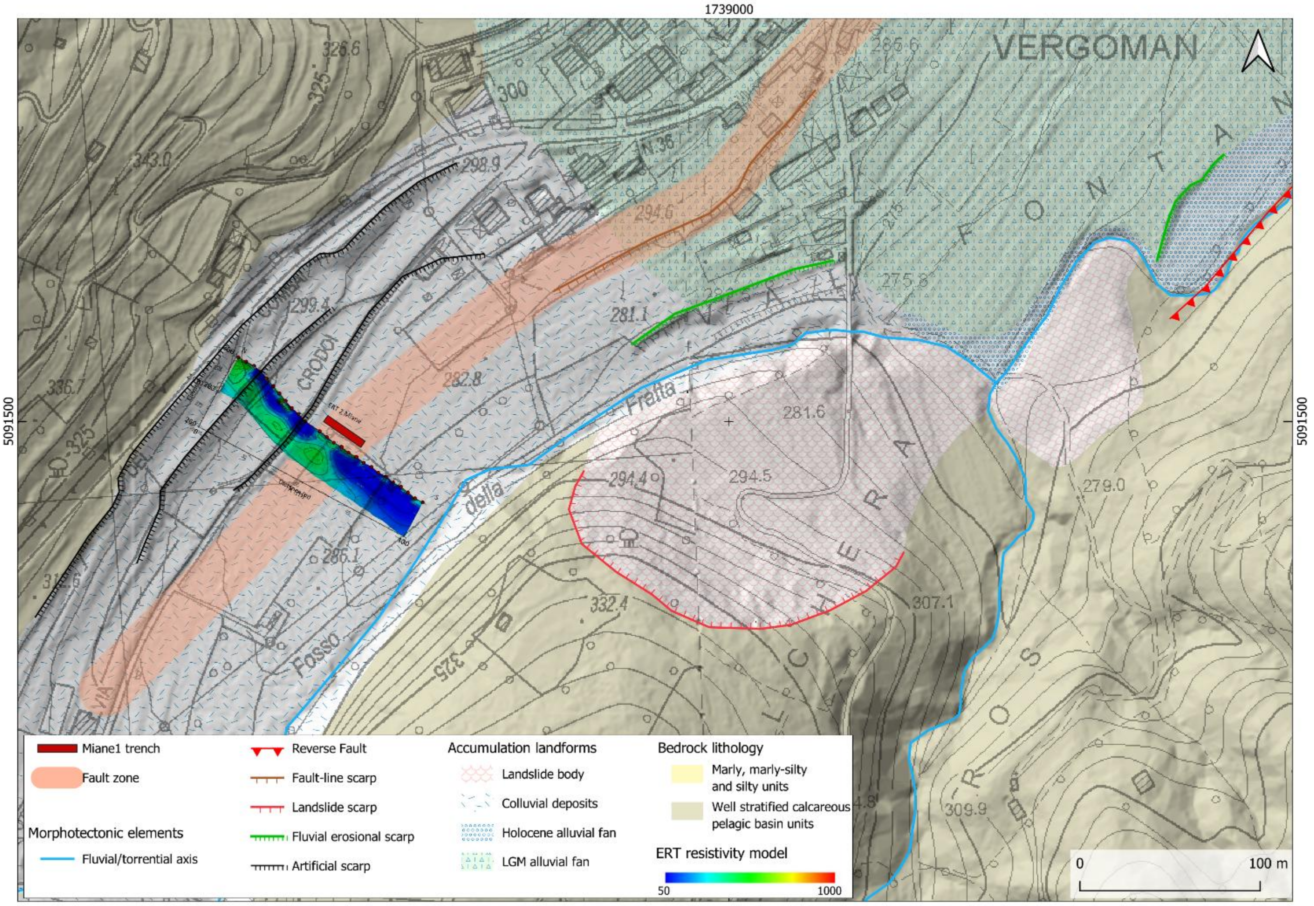

Figure 17: Location of Miane 1 trench, dug in correspondence of a major "anomaly" in the lateral distribution of soil resistivity, downstream a morphological scarp. Fault zone derives from the morphotectonic map in Fig. 3. Basemap: 1 m grid resolution LiDAR DTM provided by Provincia di Treviso and 1:10000 topographic cartography from Regione del Veneto.

Figure 18: Upwarped topographic surface across which the Miane 1 trench was excavated.

The Miane 1 trench investigated a series of local colluvial deposits (Units A, B, C), characterized by an average south dipping stratification (Fig. 19). The colluvial sequence was sedimented between 8490–8308 cal BCE (Unit A) and 4958–4792 cal BCE (Unit C), and is sealed by the anthropogenic D Unit, which, however, was not possible to date given the lack of organic matter even if it contained bricks. The ploughed soil (E Unit) closes the stratigraphic succession. From a deformational point of view, we can observe that the regular stratification of the Units A, B, C is interrupted by a high angle, S–verging fault plane which cuts and displaces them of about 30 cm (minimum displacement). Moreover, toward the north Unit D lies directly on Unit B without the interposition of Unit C, probably eroded by D Unit or never sedimented due to the contemporary tectonic uplift.

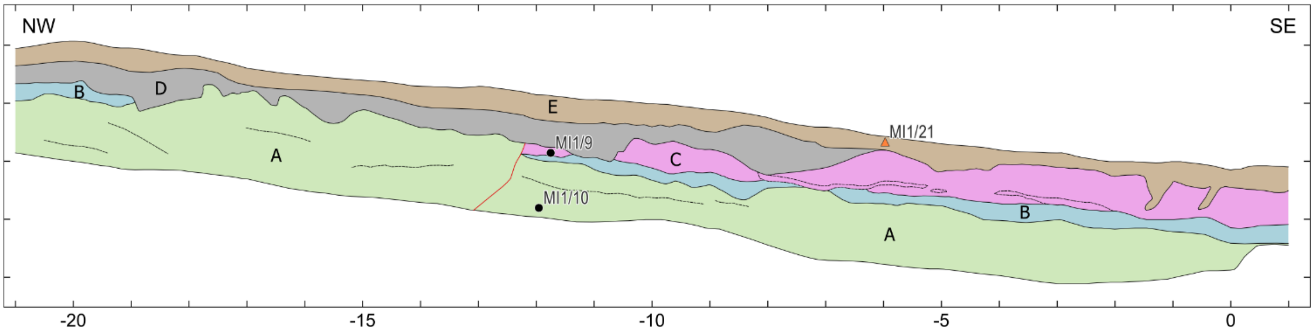

Figure 19: Log of the eastern wall of trench Miane 1 (Vergoman). The lithostratigraphic units are described in the text. (ortophotomosaic in supplementary material S4).

Table 4 –Radiocarbon dating performed by Beta Analytic (calibration curve by Reimer et al., 2013).

SAMPLE	UNIT	DATING	TYPE OF MATERIAL
MI1/10	A	8490–8308 cal BCE	organic sediment
MI1/9	C	4958–4792 cal BCE	organic sediment

Also, Miane 1 trench showed evidence of deformation: in particular, the latest event, which occurred after the deposition of C unit, can be fixed to post 4958–4792 cal BCE. Concerning, we can assess that the minimum displacement of about 30 cm could be referable to a cumulative vertical throw post unit C.

6 Discussion

In the framework of the third level of the Italian Microzonation Project (Gruppo di Lavoro MZS, 2008), we carried out a multidisciplinary study (morphotectonic, geophysical and paleoseismological) in the Municipalities of Cison di Valmarino, Follina, and Miane, in order to reconstruct the recent tectonic activity of the Valdobbiadene–Vittorio Veneto Thrust (eastern segment of the Bassano–Valdobbiadene Thrust *Auct*.) and to define its possible capability (*sensu* Linee Guida FAC, 2015). The Bassano–Valdobbiadene Th. belongs to the Pliocene–Quaternary front of the eastern Southern Alps. It goes for about 90 km from the Astico valley in the west, to the Lapisina Valley in the east. Castellarin (1981) and Antonelli (1990) segmented the Bassano–Valdobbiadene (BV) Th. into a series of minor splays (Fig. 1): BV1 which extends from Caltrano to Bassano del Grappa, BV2 from Bassano del Grappa to Valdobbiadene, VVV from Valdobbiadene to Vittorio Veneto and LFC Longhere–Fadalto Cadola (as in Costa et al.,1996). In particular, the area between Miane and Cison di Valmarino is located inside the Valdobbiadene–Vittorio Veneto (VVV) segment which is about 23 km long. The VVV Th. runs at the base of the Venetian Prealps between Vittorio Veneto and Valdobbiadene giving rise to a prominent anticline (Mt. Cesen–Mt. Visentin anticline) which overlaps the Mesozoic sequences of the Belluno Basin on the Paleogene emipelagites and turbidites (Scaglia and Flysch) and the Oligocene–Miocene Molasse (Doglioni, 1990; Schönborn, 1992). Despite its strong morphological evidence, hints for

Quaternary tectonic activity are scarce and the available field data refer to 1980s–1990s scientific reports (Zanferrari et al., 1982; Castaldini and Panizza, 1991). Moreover, no historical earthquakes with M>5.5 are referred to this tectonic structure during the last millennium. Conversely, the geodetic analysis (Barba et al., 2013; Serpelloni et al., 2016; Anderlini et al., 2020) highlighted that the Bassano–Valdobbiadene Th. could represent the main seismogenic potential source in the prealpine Venetian area.

6.1 Source parameters (last event of activation and displacement per event)

The morphotectonic study carried out between Miane and Cison di Valmarino pinpointed that the Valdobbiadene–Vittorio Veneto segment is an active fault (*sensu* Gruppo di Lavoro MS, 2008) deforming and displacing historical continental deposits up to the surface.

Folding and faulting affect continental deposits dating from 8490–8308 cal BCE (Unit A in Miane 1 trench) to 1262–1309 cal CE (Unit F in Follina 1 trench). Shaking phenomena (i.e. liquefaction) were also observed in the Follina 1 trench where a sand dike cuts sediments dated at 645 – 706 cal CE, but is sealed by Unit H dated at 1666–1783 cal CE.

In Fig 20 we summarized the seismotectonic parameters (last event of activation and displacement per event) estimated for each paleoseismological trench. We correlated them with two main coseismic events: E1 and E3.

- E1: Cison 1 and Follina 1 trenches showed an about E–W striking, S–verging, middle angle reverse fault displacing the historical deposits (A, B, D, E Units in Cison 1 and E, F Units in Follina 1) and reaching the topographic surface existing during the last seismic event. This coseismic event, which should be placed between the 13th and 14th centuries (C1 event in Cison 1 trench and F1 event in Follina1 trench, Fig. 20), matches with liquefaction phenomena observed in Follina 1 trench. It is likely that the surficial warping observed in Miane 3 Trench is referable to the last event E1 which activated also a frontal splay.
- E3: observed only in the Miane 3 trench, occurred between the deposition of Unit B (4554 – 4445 cal BCE/4461–4351 cal BCE) and the onset of the deposition of unit C (3770–3653 cal BCE).

Moreover, both Follina 1 and Miane 3 trenches show a further event (F2 and M2, respectively). In Follina 1 trench, F2 is sealed by D Unit (dated to 645 – 706 cal CE), but involved Unit B (dated at 1221–1016 cal BCE/1265–1053 cal BCE). In Miane 3 trench, M2 event occurred certainly after the deposition of Unit D1 (2504–2399 cal BCE), but, since the bottom of Unit D2 shows the same displacement of C Unit, M2 event is post D2 Unit. However, considering that the anthropogenic manufact (SM Unit) may have been constructed during the Bronze Age (dr. Zanchetta personal communication), it is highly probable that M2 event postdates the anthropogenic manufact and most likely occurred during or post the Bronze Age. Therefore, we can hypothesise that these events are relatable to a single event E2 occurred during or after the Bronze Age but before 645 – 706 cal CE (Unit D in Follina1 trench).

Finally, concerning the Miane 1 trench, we suppose that the minimum vertical throw of 30 cm that displaced the B–C boundary (dated at 4900–4700 cal BCE) could represent the cumulative displacement of all identified events.

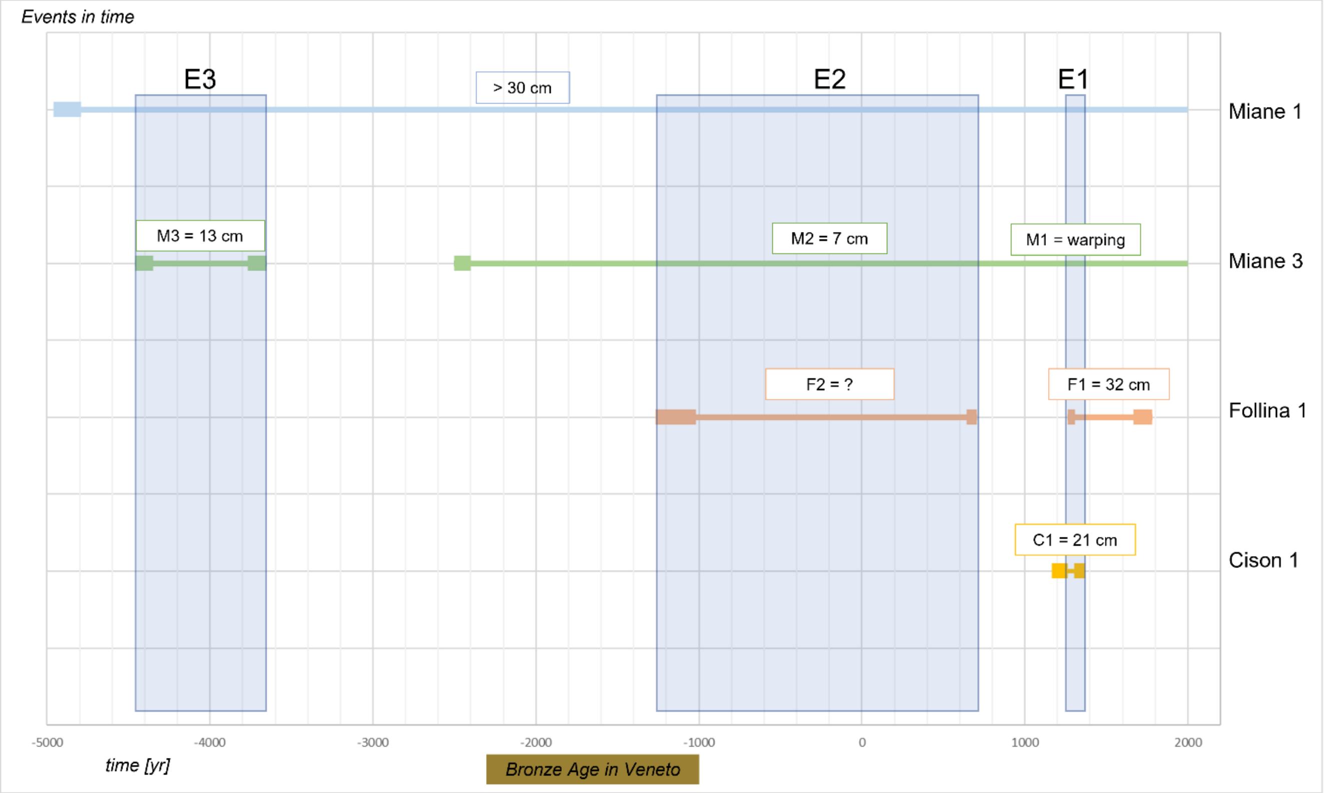

Figure 20: Time distribution of paleoseismic events identified at the trench sites. Shaded intervals represent the inferred age ranges for events E3, E2 and E1. Horizontal bars indicate the temporal constrains obtained at each site, with labels showing the measured vertical displacement associated with each event. Brown interval refers to the Bronze Age in Veneto according to Bonetto et al. (2009).

Regarding the most recent event E1, we can estimate an average displacement (AD) mediating offset values measured in Cison1 and Follina1 trenches. If considering the displacement along the fault plane (slip) in both sites, the slip average displacement (ADs) is of 49 cm, while starting from the vertical offset values, the throw average displacement (ADt) is of 27 cm. Successively, we estimated the magnitude of the E1 event, through the Wells and Coppersmith (1994) empirical relationships (Table 5). Since the equation which relates displacement and magnitude is not statistically valid for thrust faults, we considered the All Type relationships and we estimated magnitude values ranging between Mw 6.5 and 6.7, if considering the throw average displacement (ADt) or the slip average displacement (Ads), respectively.

Table 5 – Seismogenic parameters estimated from the observed average displacement for E1 event in Cison and Follina trench sites through the Wells and Coppersmith (1994) empirical relationship which relates the Average Displacement (both slip and throw) and the Maximum Moment Magnitude for All Type faults.

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TRENCH	RELATIVE EVENT	ABSOLUTE EVENT	SLIP (m)	FAULT DIP ANGLE	THROW (m)	ADt	Mw (ADt)	ADs	Mw (ADs)
Cison1	**C1**	**E1**	0.29	45°	0.21	0.27	6.5	0.49	6.7
Follina1	**F1**		0.69	28°	0.32				

The Mw estimated values certainly exceed the damage threshold of Mw 5.5, and are consistent with the maximum expected magnitude estimated from the length/magnitude empirical relationship (Wells and Coppersmith, 1994): assuming that the structure extending from Valdobbiadene to Vittorio Veneto represents a single seismogenic source, it could be considered a ~23 km–long segment with a maximum seismogenic potential Mw (RLD) of 6.5–6.7 (for Reverse and All Type faults, respectively).

The observed deformational phases and the relative displacement per–event are summarized in Supplementary Material S5.

6.2 Possible historical earthquake

According to the earthquake catalogues (CFTI15, DBMI15, CFTIMed2019) in the area between Valdobbiadene and Vittorio Veneto, no earthquake with M>5.5 was reported at least during the last millennium.

In particular, among the earthquakes that struck the prealpine Veneto area before the 15th century, the only one that could potentially be attributed to the activity of the Valdobbiadene–Vittorio Veneto Th. is the 1268 Trevigiano earthquake (Mw 5.4; Io VIII in Guidoboni et al., 2019). The towns that suffered the most damage were Treviso, where private buildings collapsed and the convent of Santa Cristina was damaged, and Asolo, whose fortress suffered severe damage. The area of damage extended to Padua and Feltre, where, however, the earthquake was only felt but did not cause damage (Guidoboni et al., 2019). Damage distribution indicates a source downstream of the Valdobbiadene–Vittorio Veneto Thrust, likely linked to the Montello–Conegliano–Arcade Thrust–System, as already highlighted and hypothesized by Benedetti et al. (2000) and Picotti et al. (2022).

Therefore, considering the geometry of the VVV Thrust, which deepens toward the north beneath the Mt. Cesen–Mt. Visentin ridge, we can suppose that the main shaking developed along the Belluno valley probably in the area between Feltre and Trichiana.

If we look at the earthquakes that occurred in the Belluno valley (that represents the hanging wall of the VVV Th.) before the 15th century, we observe that they are few and with low macroseismic intensity. In particular, the strongest earthquake reported by the DBMI Catalogue and Guidoboni et al., (2018–19) is the 1348 Alpi Giulie seismic event (Fig. 21) whose epicentre is located near Tarvisio (Rovida et al., 2022) and thus referable to different seismogenic sources. Therefore, the historical 13th-14th century earthquake observed in the Follina area could belong to the “lost” earthquakes that characterize the Italian seismic history prior to the 15th century (Galli, 2002).

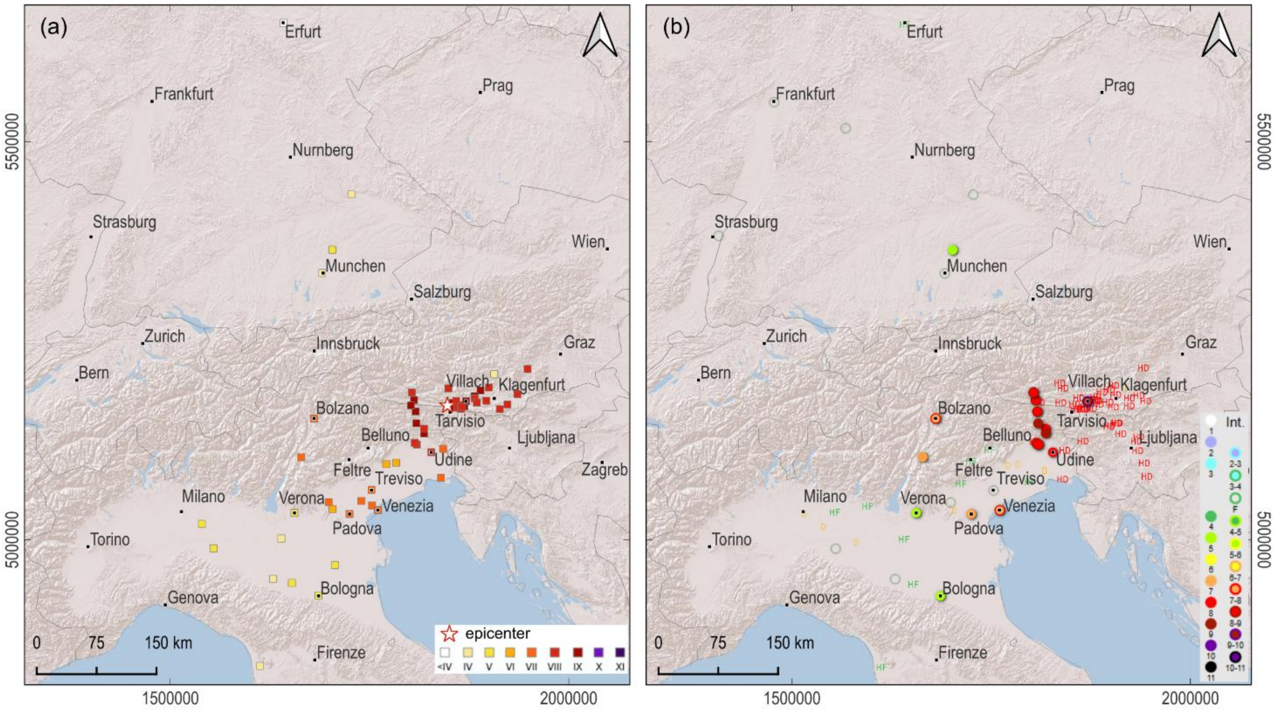

Figure 21: damage distribution of the 1348 earthquake according to Seismic Catalogues: (a) CFTIMed15 (Guidoboni et al., 2019) and (b) DBMI15 (Locati et al., 2021). Basemap: ESRI shaded relief.

7 Conclusions

This multidisciplinary study, pinpointed that:

a) in the municipalities of Miane, Follina, and Cison di Valmarino, the Valdobbiadene–Vittorio Veneto Th. (eastern segment of the Bassano–Valdobbiadene Thrust) is active and capable to generate linear morphogenic earthquakes.

b) On the basis of the collected data we identified 3 coseismic events in the latest 6000 years: E1 (13th–14th century CE), E2 (upper to post Bronze Age), E3 (4500–3600 BCE).

c) The best constrained event E1 shows an average vertical displacement of 27 cm, while the average slip is 49 cm. Based on the empirical relationships of Wells and Coppersmith (1994), the maximum Magnitude ranges between Mw 6.5, if considering the average throw (ADt), and Mw 6.7 if considering the average slip (ADs).

e) As pinpointed by the analysis of historical and instrumental seismicity (CPTI, 2015 and CFTIMed5, 2018), over the last thousand years, the Veneto prealpine area between Valdobbiadene and Cison di Valmarino was not hit by any earthquake above the damage threshold (M≥5.5). The only known earthquake in the Venetian prealpine area dating to a period between the 13th and 14th centuries, is the November 4, 1268 seismic event. However, current knowledge does not allow us to define with certainty either the epicentral location or the macroseismic intensity.

f) Therefore, considering the geometry of the VVV Thrust, which deepens toward the north beneath the Mt. Cesen–Mt. Visentin Mountain ridge and reaches the Belluno Valley probably at the seismogenic depth (7-10 km), we can suppose that the main shaking during the possible 13th–14th century earthquake E1, developed along the Belluno valley probably in the area between Feltre and Trichiana. Since there are no indications of strong earthquakes in that period (Guidoboni et al., 2018 and 2019; Rovida et al., 2022), the historical 13th–14th century earthquake observed in the Follina area could belong to the numerous "lost" earthquakes that characterize the Italian seismic history prior to the 15th century.

Author contributions

MEP: Project administration; funding acquisition
MEP, GPT, GPR, AM: morphotectonic and paleoseismological investigation
AM: software
EF: ERT investigation
MEP and GP: conceptualization, data curation, methodology and writing

Competing interests

The authors declare that they have no conflict of interest.

Disclaimer

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