Geological Field Trips and Maps

2023
Vol. 15 (2.2)

ISSN: 2038-4947

SOCIETÀ GEOLOGICA ITALIANA
FONDATA NEL 1881 - ENTE MORALE R. D. 17 OTTOBRE 1885

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# LGM glacial and glaciofluvial environments in a tectonically active area (southeastern Alps)

**POST-4 – Post-congress Field Trip of the XXI Inqua Congress "A Mediterranean perspective on Quaternary Sciences", Rome 14th-20th July 2023**

https://doi.org/10.3301/GFT.2023.07

**GFT&M - *Geological Field Trips and Maps***

Periodico semestrale del Servizio Geologico d'Italia - ISPRA e della Società Geologica Italiana
Geol. F. Trips Maps, Vol.**15** No.2.2 (2023), 50 pp., 30 figs. (https://doi.org/10.3301/GFT.2023.07)

# LGM glacial and glaciofluvial environments in a tectonically active area (southeastern Alps)

## POST-4 – Post-congress Field Trip of the XXI Inqua Congress "A Mediterranean perspective on Quaternary Sciences", Rome 14th-20th July 2023

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**Cover page Figure: Overlook of the Friulian piedmont Plain and the Carnic and Julian Prealps from Piancavallo. In foreground the white strip of the Cellina incision and behind, the white strips of the Meduna and Tagliamento rivers cutting the plain (Photo courtesy of L. Rettig).**

ISSN: 2038-4947 [online]

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## INFORMATION



## EXCURSION NOTES



## ITINERARY

# ABSTRACT

**The three-day field trip takes place in the eastern Veneto and Friuli regions, in north-eastern Italy, and it examines the tectono-sedimentary evolution of some of the major river systems of the southeastern Alps in Italy. The evolution of these rivers (Piave, Cellina, Meduna, Arzino and Tagliamento) was strongly influenced by Alpine glaciations and by the ongoing compressive and transpressive deformation of the thrust systems at the front of the eastern Southern Alps, the Alpine sector with the highest deformation rates of continental Europe. During the first day the focus is on the Piave system, the different lobes that interested the palaeoglacier during the Last Glacial Maximum and the activity of the Montello and the Bassano-Vittorio Veneto thrusts. The second day is devoted to the Monte Cavallo area, from the foothills, characterised by late Quaternary activity and important prehistoric sites, to the Piancavallo plateau, where local palaeoglacier reconstruction was made. In the afternoon the trip moves to Meduno, for visiting the tectonic terraces related to the activity of the Maniago-Meduno Thrust. The third day focuses on the Tagliamento end moraine system and outwash plain, with the view of the outstanding sites of the Aonedis fluvial scarp and Pozzuolo tectonic terrace.**

*Keywords:* Eastern Southern Alps, Neotectonics, Last Glacial Maximum, Palaeoglaciers, Alluvial fan.

# PROGRAM SUMMARY

| **Day 1 – The Piave system** | | |
|---|---|---|
| Departure from Venezia-Mestre train station: 8.30 | | |
| Stop 1 | 10.30 – 12.00 | Nervesa d. B.: The Palaeosoils in the Nervesa section along the Piave River |
| Stop 2 | 13.30 – 15.00 | Follina: Holocene/Historical tectonic activity of the Valdobbiadene-Vittorio Veneto Thrust. Morphotectonic and palaeoseismological evidence<br>**Lunch** |
| Stop 3 | 15.00 – 17.00 | Gai-Tarzo: The LGM end moraine system of the Piave in the Soligo Valley |
| Stop 4 | 17.30 – 18.30 | The Vittorio Veneto basin and morainic amphitheatre |
| Arrival to hotel in Vittorio Veneto: 19.00 | | |

| **Day 2 – The western Friulian piedmont plain and the Piancavallo mountain range** | | |
|---|---|---|
| Departure from Vittorio Veneto: 8.30 | | |
| Stop 1 | 09.00 – 10.00 | The sin-tectonic basin of Palù di Livenza |
| Stop 2 | 10.30 – 11.30 | Overlook of the western Friulian piedmont plain from the Piancavallo |
| Stop 3 | 11.30 – 13.00 | The moraines at Pian delle More: reconstructing glaciers in the Monte Cavallo Group during the Last Glacial Maximum<br>**Lunch** |





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| | | |
|---|---|---|
| Stop 4 | 14.00 – 15.00 | The lacustrine sediments from the Caltea valley: insights into palaeo-vegetation and -climate of a pre-LGM interstadial |
| Stop 5 | 16.30 – 18.30 | The tectonic terraces of Meduno |
| Arrival to hotel in Maniago: 19.00 | | |

| | | |
|---|---|---|
| **Day 3 – The Tagliamento morainic amphitheatre and the central Friulian piedmont plain** | | |
| Departure from Maniago: 8.30 | | |
| Stop 1 | 09.00 – 11.00 | The stratigraphy of Friulian piedmont plain in the Tagliamento fluvial scarp of Aonedis |
| Stop 2 | 11.30 – 13.30 | The Tagliamento end moraine system, an overlook from the lateral moraine of Canodusso<br>**Lunch** |
| Stop 3 | 15.30 – 16.30 | Pozzuolo del Friuli tectonic terraces |
| Transfer to Mestre (Venice airport and Venezia-Mestre train station) | | |

## SAFETY

The field trip includes stops that are generally easily accessible. Some stops are close to roads and some risks are due to traffic; high-visibility jackets must be dressed. Hiking boots and comfortable clothing are necessary. Outcrops are close to villages and towns where shops and pharmacies are present. The area is usually sunny during summertime, but thunderstorms can occasionally occur; for these reasons, sunscreen protection and rain jackets are recommended. For stops away from the cars, valuable personal items have to be kept. General Emergency contact number: 112 (Carabinieri, Police, Ambulance, Firefighters)

## HOSPITALS

**Day 1**: Vittorio Veneto Hospital, Via C. Forlanini, 71, Vittorio Veneto. Tel. +39 0438 665111
**Day 2**: Pordenone Hospital, Via Montereale, 24, Pordenone. Tel. +39 0434 399111
Spilimbergo Hospital, Via Raffaello Sanzio, 1, Spilimbergo. Tel. +39 0427 595595
**Day 3**: San Daniele del Friuli Hospital, Via Trento Trieste, 33, San Daniele del Friuli. Tel. +39 0432 9491
Udine Hospital, Piazzale Santa Maria della Misericordia, 15, Udine. Tel. +39 0432 5521

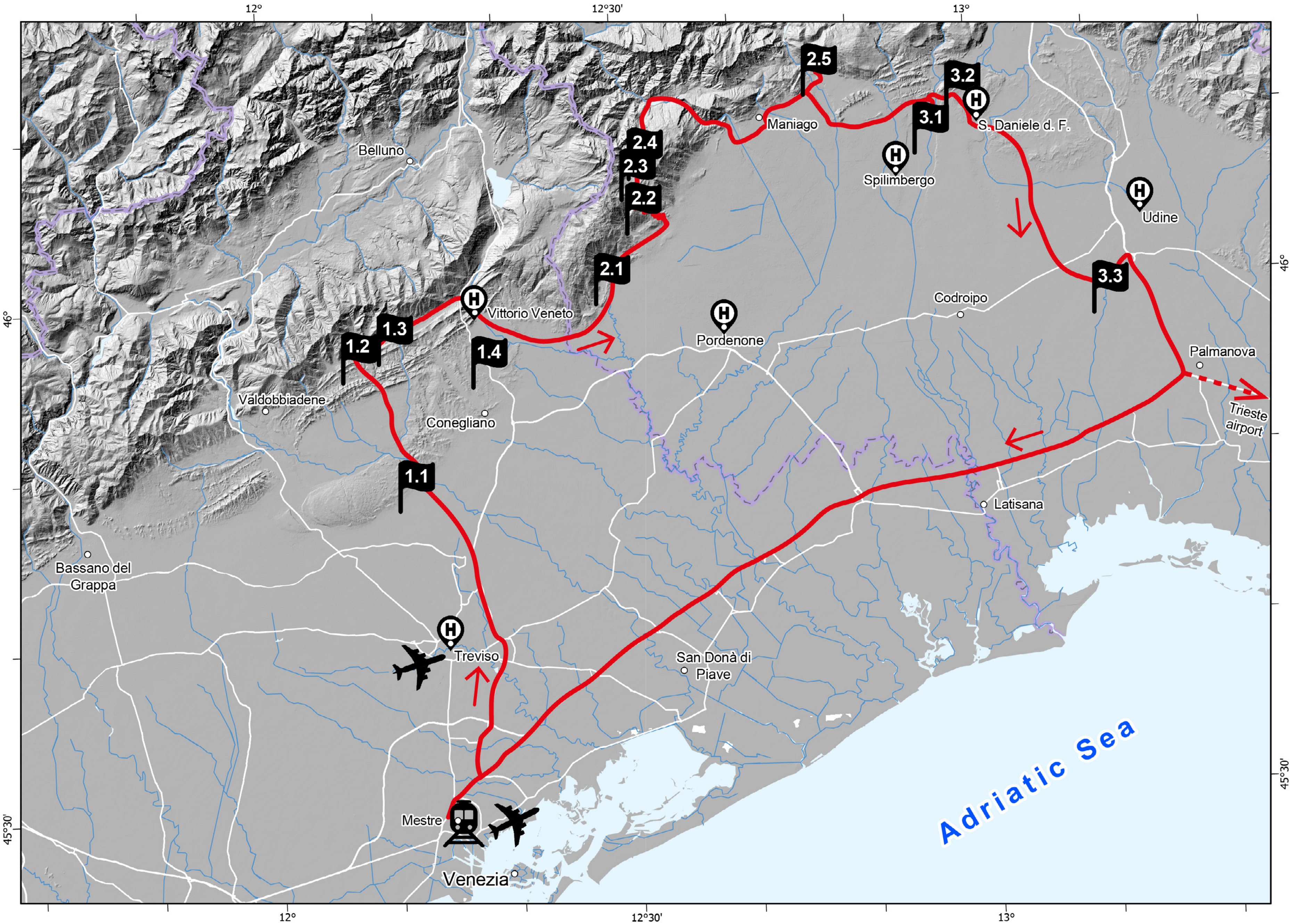


Fig. 1 - Location of the different fieldtrip stops. Facilities and hospitals are marked.

# ACCOMODATIONS

Many options for hotel, B&B and farm-house accommodations are available around Vittorio Veneto and Spilimbergo; they can be booked from websites dedicated to hotel reservations.



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## REGIONAL TECTONIC FRAMEWORK AND EVOLUTION

The investigated area belongs to the Pliocene-Quaternary front of the eastern Southern Alps (NE Italy) and is located at the border between the Venetian and Carnic Prealps and the adjoining piedmont plain ascribed to the Last Glacial Maximum (LGM, 26.5-19 ka, Clark et al., 2009) (Fig. 1). The Pliocene-Quaternary front of the eastern Southern Alps (ESA) is arranged in a set of arcuate SW-NE trending thrust-segments (Fig. 2) whose termination is located where faults are crossed by a transverse structure (e.g., a transfer fault) or where deformation decreases due to the presence of another thrust segment with an en-echelon relationship (Galadini et al., 2005). The Southern Alps develop along the northern margin of the Adria microplate and represent the S-verging, back fold-and-thrust belt of the Alpine chain (e.g., Schmid et al., 2004), from which they are separated by the Periadriatic Lineament (Schmid et al., 1989, PL in Fig. 2). Toward the west, ESA are bordered by the Schio-Vicenza fault-system, accommodating a complex left lateral strike-slip activity (Zampieri et al., 2021). Eastwards, close to the Italian-Slovenian boundary, ESA are cut and displaced by the NW-SE trending dextral Dinaric strike-slip fault system, responsible for destructive historical and instrumental seismicity that hit W-Slovenia and NE-Italy (Atanackov et al., 2021). At present, Venetian and Carnic Prealpine areas are characterised by a dominant dip-slip motion accommodated by the SE verging, NE-SW striking fold and thrust belt (Castellarin and Cantelli, 2000). At the transition between these two structural domains, the Alpine and Prealpine Julian regions define a compressional domain with a strong oblique component (Falcucci et al., 2018; Poli and Zanferrari, 2018; Patricelli and Poli, 2022).

After a long history of rifting and subsidence during the Mesozoic (Masetti et al., 2012), ESA experienced compressive tectonics during the latest Mesozoic and Cenozoic, when they were affected by two main tectono-sedimentary phases: the Late Cretaceous-late Eocene (Mesoalpine) event and the Middle Miocene-Quaternary (Neoalpine) event (Doglioni and Bosellini, 1987; Doglioni, 1992).

Both in the central-eastern Friuli region and Carnic area, Late Cretaceous-middle Eocene propagation of the External Dinarides represented a fundamental tectonic event, because it caused the progressive drowning of the Cretaceous Friuli Carbonate Platform, the stack of a few thousand metres of turbidites in the foredeep basins (Tunis and Venturini, 1992) and a considerable crustal westward shortening (Doglioni and Bosellini, 1987; Servizio Geologico d'Italia, 2013; Zanferrari et al. 2013).

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 foreland basin slowly spread towards SSW so that the terrigenous carbonate platforms of the Cavanella group reached the present shoreline only during the Burdigalian. Starting from Middle Miocene, ESA was involved into the Neoalpine tectonic event, where two compressional phases can be recognised: the Serravallian-Messinian and the Pliocene-Quaternary events. According to Castellarin et al. (1992), Castellarin and Cantelli (2000), and Fantoni et al. (2002), ESA had their fundamental structural setting during the Serravallian-Messinian tectonic phases, when tectonic stress originated a SE–vergent, SW–NE trending fold and thrust belt. The south-eastward migration of the ESA front gave rise to a foredeep with the depocentre located in the present Prealpine area and northern Venetian-Friulian Plain. The clastic wedge, more than 2000 m thick in Friuli and more than 3000 m thick in the Venetian area (Massari et al., 1986;



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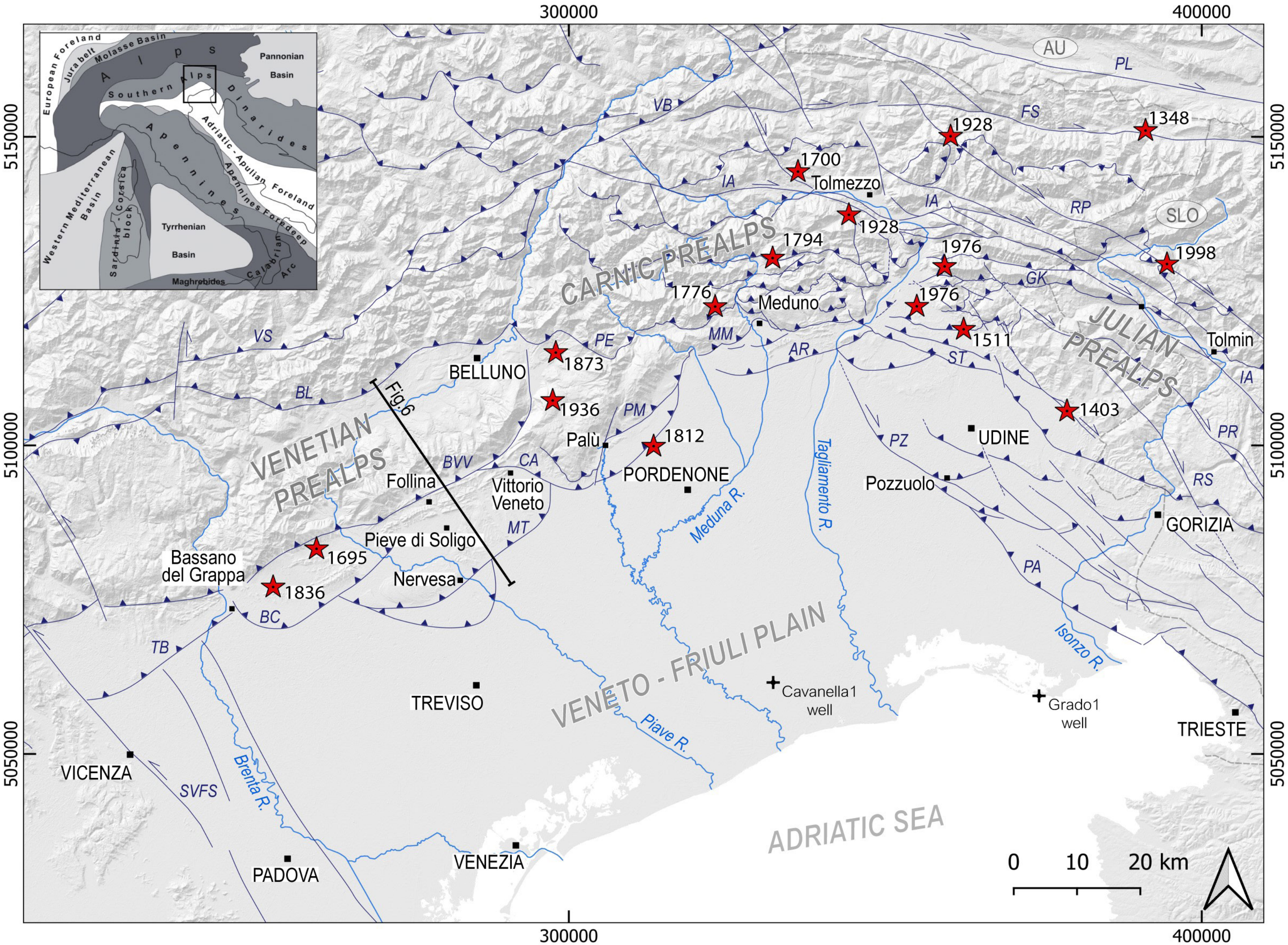


Fig. 2 - Structural sketch map of the eastern Southern Alps in NE-Italy and W-Slovenia. Red stars: historical and instrumental seismicity (Mw > 5.5; Rovida et al., 2022). Legend: AR: Arba-Ragogna Thrust; BC: Bassano-Cornuda Th.; BL: Belluno Th.; BVV: Bassano–Vittorio Veneto Th.; CA: Cansiglio Th.; FS: Fella–Sava Fault; GK: Gemona–Kobarid Th.; IA: Idrija–Ampezzo Fault; 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.; VSVB: Valsugana-Val Bordaglia Th.

Fantoni et al., 2002; Toscani et al., 2016), pinches out very rapidly (only 225 m in the Cavanella 1 borehole; 0 m in Grado 1 borehole; for location see Fig. 1) towards the Serravallian-Messinian peripheral bulge located again near the present shoreline. Foredeep deposition in the WSW-ENE frontal eastern Southern Alps thrust belt largely developed during Neogene in the eastern Veneto and western Friuli areas and stopped in the latest Messinian time. The progressive migration towards the NE of the Messinian-Pleistocene NW-SE Apennines frontal thrust belt (e.g., Caputo et al., 2010) caused the crustal flexure about 15° from central Friuli to the Venice area (Toscani et al., 2016). Moreover, during the Messinian Salinity Crisis, deep incisions of the fluvial valleys developed (Mancin et al., 2009; Monegato and Stefani, 2011; Toscani et al., 2016; Winterberg et al., 2020). The following marine ingression (Ghielmi et al., 2010) did not reach the NE-Friuli plain (Toscani et al., 2016), where continental conditions persisted, but affected the Messinian palaeovalleys up to the present pre-Alpine border. In the Messinian Tagliamento palaeovalley near Osoppo, a marine Gilbert 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 Venetian Prealpine area: Cornuda (Venzo, 1977), Vittorio Veneto (Cousin, 1981); Bassano del Grappa (Favero and Grandesso, 1982), Pieve di Soligo (Viaggi and Venturini, 1996).

## The LGM landforms and the evolution of the Venetian-Friulian Prealps and Piedmont plain

During the Last Glacial Maximum, the European Alps hosted a large ice cap characterised by large piedmont lobes at the outlet of the major trunk valleys (Ivy-Ochs et al., 2022 and references therein). The chronology of the phases of glaciers' advance and withdrawal is well-constrained (Fig. 3) thanks to several papers published in the last decades (Ivy-Ochs et al., 2022 and references therein): a first spread of the glaciers took place at about 26-24.8 ka; a second important advance, with glacier lobes of similar size, occurred after a short withdrawal and is well constrained in the southeastern sector at about 23 ka; a third advance, with glacier fronts confined into the end moraine system, took place at about 20-19 ka. The downwaste of the glaciers occurred after 18.5 ka (Ravazzi et al., 2014; Rossato and Mozzi, 2016; Wirsig et al., 2016). Before the Bølling/Allerød interstadial, a short re-advance of the Alpine glaciers is constrained at about 16 ka (Ivy-Ochs et al., 2023 and references therein).

In the southeastern sector of the Alps (Fig. 3), the main glacier network was related to the Piave, Tagliamento and Isonzo catchments. They developed valley glaciers with frontal snouts in the lower valleys (western Piave and Isonzo) and piedmont lobes (eastern Piave and Tagliamento). The chronology of the glacier evolution is well constrained for the Tagliamento (Monegato et al., 2007; Fontana et al., 2014a) and coupled with palaeoclimatic data (Pini et al., 2009) and models (Del Gobbo et al., 2023). This glacier developed a wide piedmont lobe at the valley outlet and formed a large outwash system (Fontana et al., 2010, 2014a) with a characteristic evolution of downstream migration of the coarse-grained deposits from the LGM climax to the progressing withdrawal of the glacier front (Fontana et al., 2008, 2014b, 2019).

The Piave glacier (Fig. 3) was split into several ice streams crossing the Venetian Prealps (Carton et al., 2009): 1) to the west, it joined the Cismon and Brenta glaciers in the Valsugana (Fig. 3; Rossato et al., 2018); 2) a second stream flowed in the modern Piave valley till Quero,

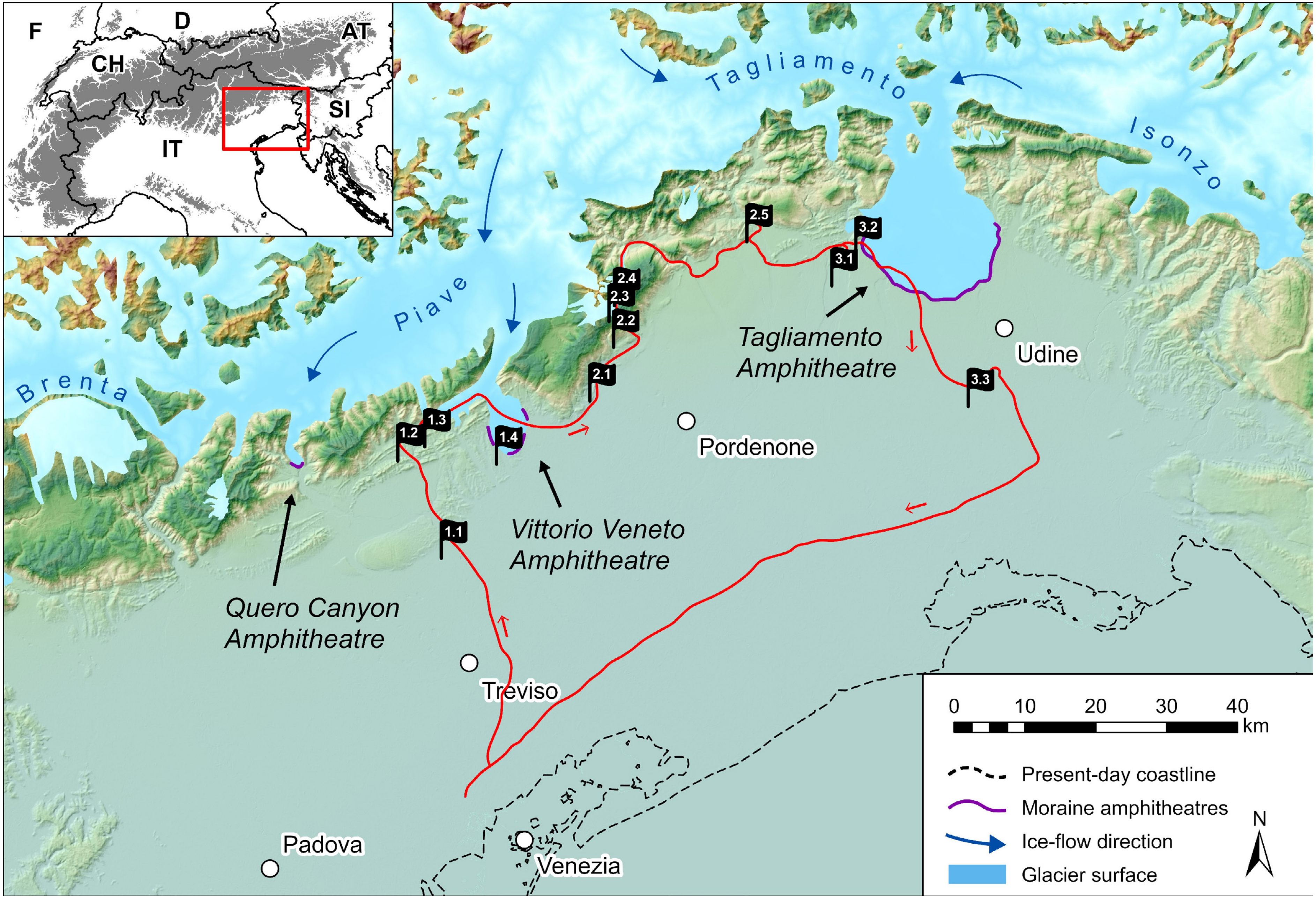


Fig. 3 - Topographic map of the southeastern fringe of the European Alps, showing the mountain ranges and the glacier extent during the LGM (mod. after Ehlers and Gibbard, 2004) in which is marked the trip with the stops.

where it formed a small morainic amphitheatre (Venzo, 1977); 3) a third track of the glacier flowed across the Lapisina valley and split into two branches, one flowing along the Soligo valley forming frontal moraines at Gai and Tarzo (Venzo, 1977), and another crossing the Serravalle narrow and forming the Vittorio Veneto frontal moraine system (Venzo, 1963; Bondesan et al., 2002). These different snouts fed different outwash megafans spreading in the central Venetian Plain (Mozzi, 2005; Fontana et al., 2008, 2010).

The Isonzo glacier was confined into its catchment and had a frontal sector at Most na Soči (Monegato et al., 2015; Jamšek Rupnik et al., 2021) and a secondary lobe in the upper Natisone valley. The Isonzo outwash streams formed the megafan from the outlet in Gorizia and the Natisone alluvial fan (Fontana et al., 2008, 2019).

In the pre-Alpine belt from the Piave to the Isonzo sector, several small and isolated glaciers developed during the LGM (e.g., Carraro and Sauro, 1979; Baratto et al., 2003; Monegato, 2012; Žebre et al., 2014; Rettig et al., 2021; 2023). Absolute dates are not available for these small systems, but they can be ascribed to the LGM thanks to their connections with the major ones through the outwash deposits, and rarely with partial merging of the glaciers (Rettig et al., 2023). Thanks to their relatively simple geometry, these small glaciers permitted their reconstruction that lets to an accurate estimate of their Equilibrium Line Altitude (ELA), which can be used as palaeoclimate proxy. The Carnic Prealps are characterised by three major catchments related to the Cellina, Meduna and Arzino rivers. Only the Cellina valley hosted valley glaciers (Fig. 3), while the other valleys were ice-free during the last glaciation, as well as the Torre, Cornappo and Natisone valleys in the Julian Prealps. In the Cellina and Meduna catchments, the outwash from the mountain glaciers built large alluvial fans (Avigliano et al., 2002a). The Arzino and Torre valleys were dammed by the Tagliamento glacier (Zanferrari et al., 2008b, 2013), and the Cornappo valley was blocked by the growing of the Torre megafan (Fontana et al., 2008).

The deglaciation phase in a hilly piedmont area produced a landscape rich in lacustrine/palustrine environments, like those of Revine in the Soligo valley (Casadoro et al., 1976), or the several ponds in the Tagliamento end moraine systems (Casadoro et al., 1976; Marocco and Vaia, 1991; Monegato et al., 2007). The lacustrine/palustrine environment of the Palù di Livenza was persistent through the LGM and the Holocene.

The Venetian-Friulian Plain was characterised by a strong phase of deposition from ~30 to 20 kyr (e.g., Fontana et al., 2010; Rossato and Mozzi, 2016; Hippe et al., 2018; Marcolla et al., 2021); subsequently, the sedimentary rate lowered and led to apical incision of alluvial systems in the Friulian Plain (Fig. 4). Since the Late Glacial a fast erosional phase affected the whole plain and brought to the formation of deep and wide incised valleys up to the present coast (e.g., Fontana et al., 2008; Mozzi et al., 2013). In the distal sector of the plain, these fluvial incisions were filled by lagoonal and fluvial deposits during the Holocene, because of the marine transgression and highstand (Fontana et al., 2008; 2014b; Ronchi et al., 2021).

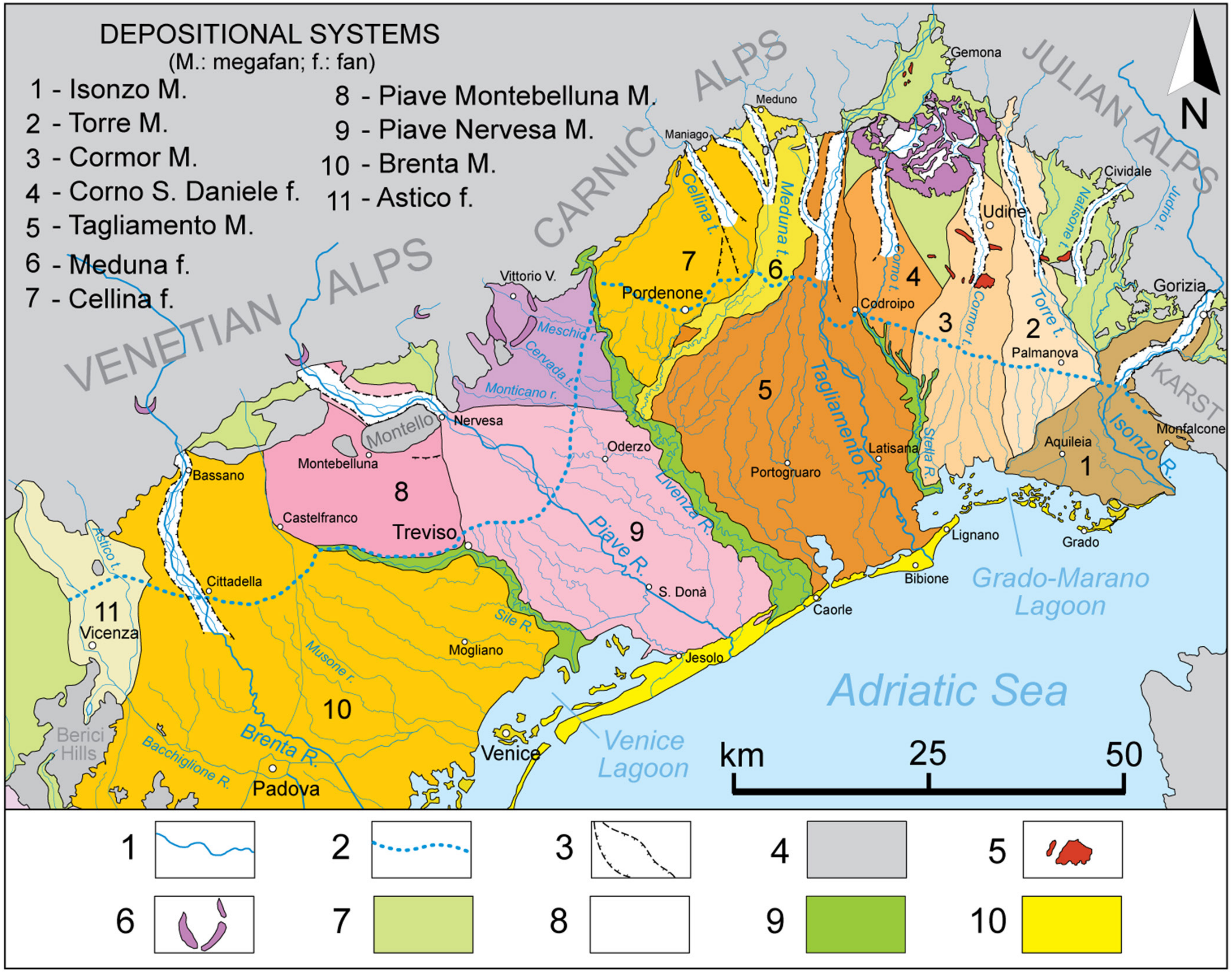


Fig. 4 - Scheme of the large alluvial fans and megafans along the southern side of the Alps (modified from Fontana et al., 2014b). Symbols: (1) river, (2) upper limit of the spring belt, (3) fluvial scarp, (4) mountain and hill, (5) tectonic terrace, (6) moraine amphitheatre, (7) undifferentiated LGM deposit, (8) post-LGM fluvial deposit within incision, (9) alluvial unit related to major groundwater-fed rivers, (10) Holocene coastal deposit.



https://doi.org/10.3301/GFT.2023.07

# DAY 1

## Stop 1.1 - The Palaeosoils in the Nervesa section along the Piave River

**Coordinates: Lat. 45°49’42”N, Long. 12°12’42”E**

The Piave River flows on the bedrock made of Messinian to Lower Pleistocene conglomerates (Picotti et al., 2022) in the Nervesa water gap. At the apex of the LGM Nervesa megafan (Fontana et al., 2008) the river used to cross the tip-line of the Montello thrust (Fig. 5) that represents the outermost fault of the ESA in this sector (Fig. 6, Benedetti et al., 2000; Galadini et al., 2005; Poli et al., 2021b).
The conglomerates dip towards the south-east (Fig. 7A) ending abruptly at the outcropping of a thick palaeosoil, visible in the eastern sector of the river incision (Fig. 7B). The palaeosoil is cut by coarse glaciofluvial gravel showing the merging of the Piave and Cismon palaeoglaciers. On the right side of the thalweg, these coarse gravels show a deep weathering (Fig. 7C and 7D) with alfisols and thick Bt horizons that are much more developed than the soils of the Nervesa megafan. The fluvial deposits of this latter buried the succession of conglomerates and palaeosoils during the LGM.

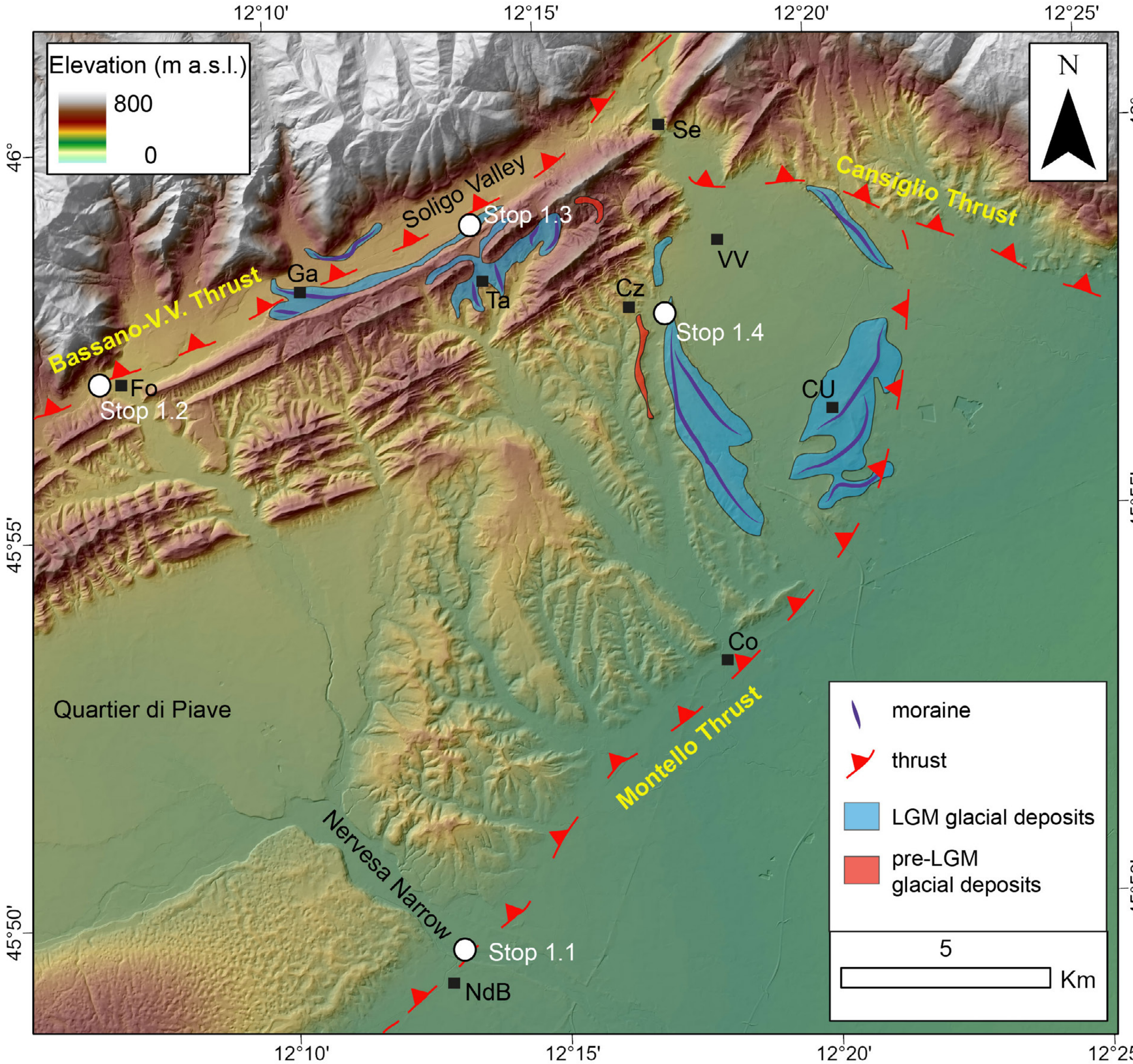


Fig. 5 - Digital elevation model of the Venetian Foothills and piedmont plain with major tectonic features (see Fig. 2). Extent of glacial deposits according to Venzo (1963, 1977). Co: Conegliano; CU: Colle Umberto; Cz: Cozzuolo; Fo: Follina; Ga: Gai; NdB: Nervesa della Battaglia; Se: Serravalle; Ta: Tarzo; VV: Vittorio Veneto.

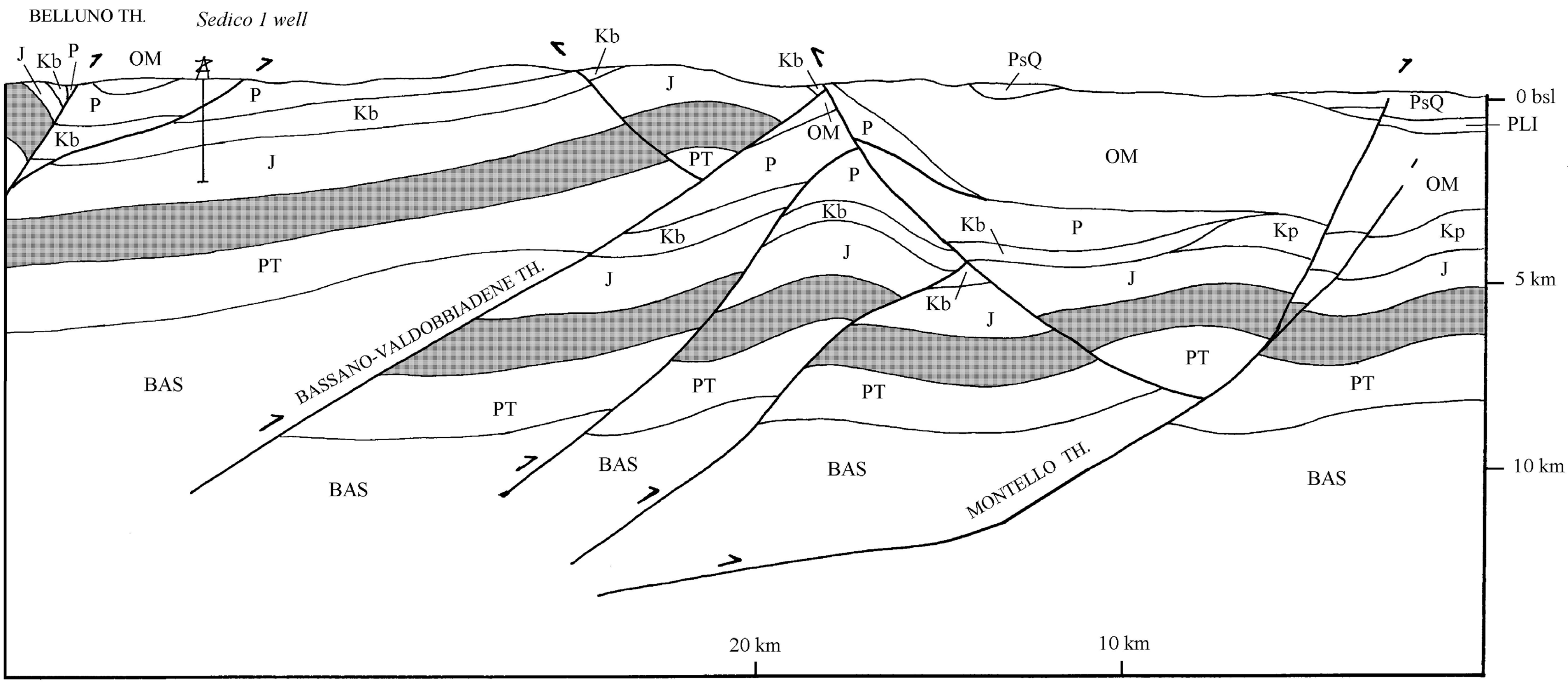


Fig. 6 - Geological section across the southern margin of the eastern Southern Alps (trace in Fig. 2) in the Montello area (Galadini et al., 2005). Legend: PsQ: Upper Pliocene-Quaternary; PLI: Pliocene; OM: Oligocene-Miocene; P: Palaeogene; Kb: Cretaceous (basin); Kp: Cretaceous (platform); J: Jurassic; grey band: Upper Triassic; PT: Permian-Triassic; BAS: magnetic basement (Modified after Galadini et al., 2005).





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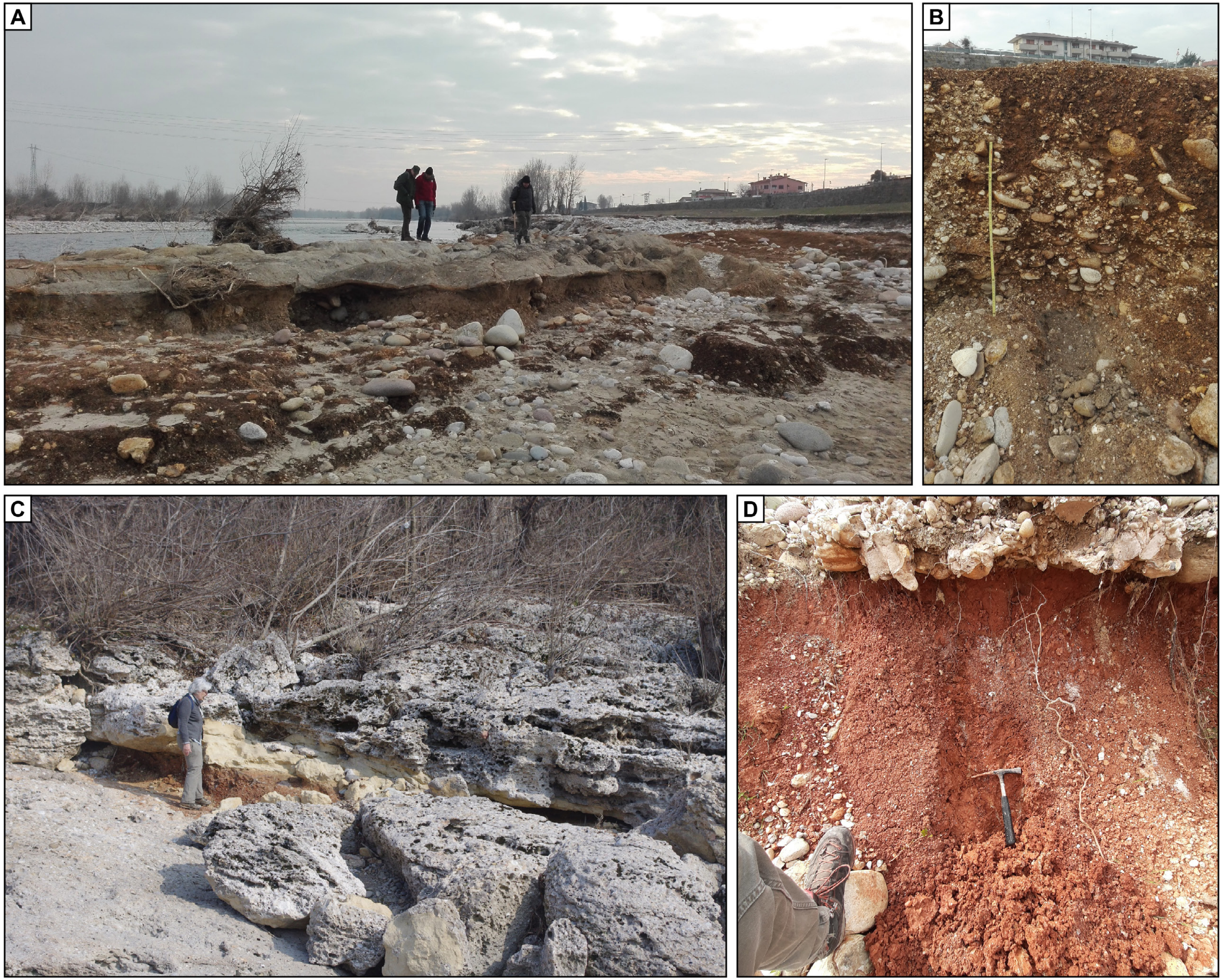


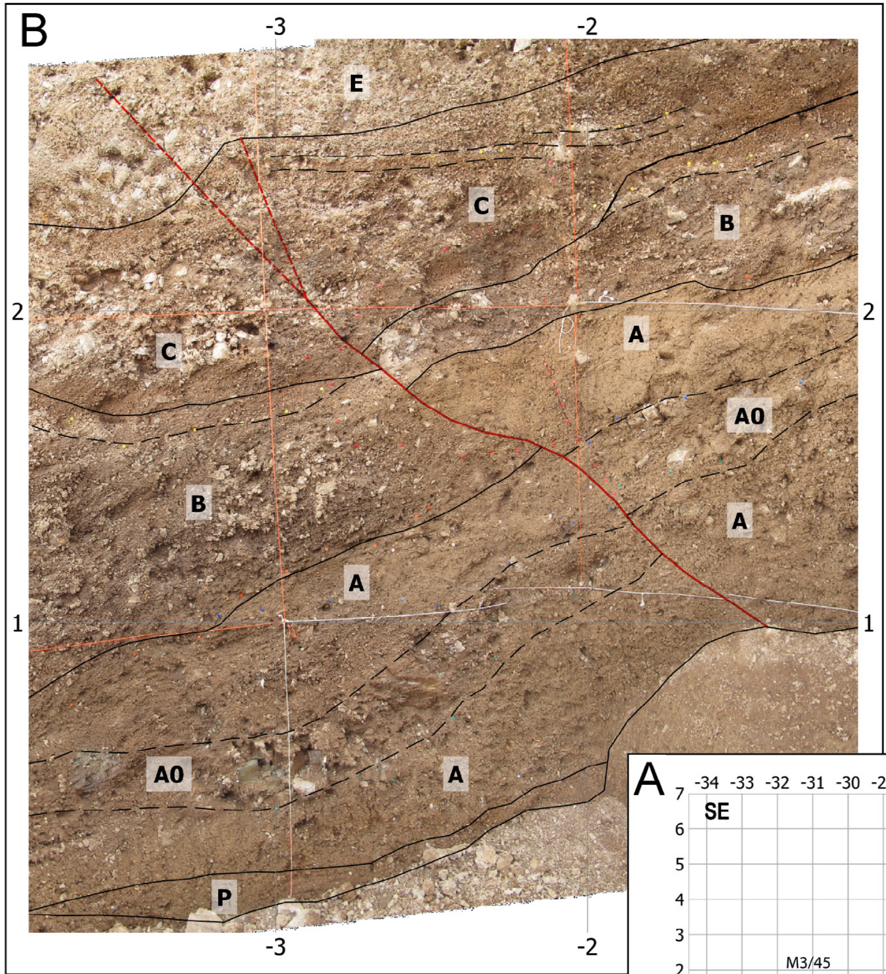

Fig. 7 - Photos of the outcrops related to Stop 1.1. A) the palaeosoil cropping out in the western side of Piave thalweg at Nervesa; B) detail of the palaeosoil; C) Early Pleistocene conglomerates cropping out along the Piave thalweg; D) the palaeosoil cropping out in the eastern side of the Piave section at Nervesa.

## Stop 1.2 - Follina: Holocene/Historical tectonic activity of the Valdobbiadene-Vittorio Veneto Thrust. Morphotectonic and palaeoseismological evidence

**Coordinates: Lat. 45°57'05"N, Long. 12°06'47"E**

The Bassano – Vittorio Veneto Thrust (BVV in Figure 2) represents the main structural element along the southern edge of the Venetian Prealps: it is composed of three main segments: Caltrano-Bassano del Grappa, Bassano del Grappa-Valdobbiadene and Valdobbiadene-Vittorio Veneto-Fadalto (Figs. 2 and 5). In the framework of the Italian Seismic Microzonation Project (Gruppo di Lavoro MS, 2008) the Valdobbiadene-Vittorio Veneto segment was investigated by means of palaeoseismological trenches. Trench Miane 3 was dug perpendicularly to a morphological escarpment affecting the small colluvial fan placed at the foot of the left slope of the San Pietro valley (Fig. 8). This trench (Fig. 9) exposed a Holocene continental stratigraphic succession affected by a medium-angle S-verging, about E-W striking reverse fault that cuts and displaces Unit P (7,5YR Munsell colour chart; Pleistocene palaeosoil), Unit A (Holocene colluvium), Unit B (Holocene alluvial fan) and Unit C (Holocene debris flow), causing a maximum cumulative vertical throw of about 30 cm. A walking


Fig. 8 - The fault scarp near Miane (Fig. 5 for location) during the trench excavation.



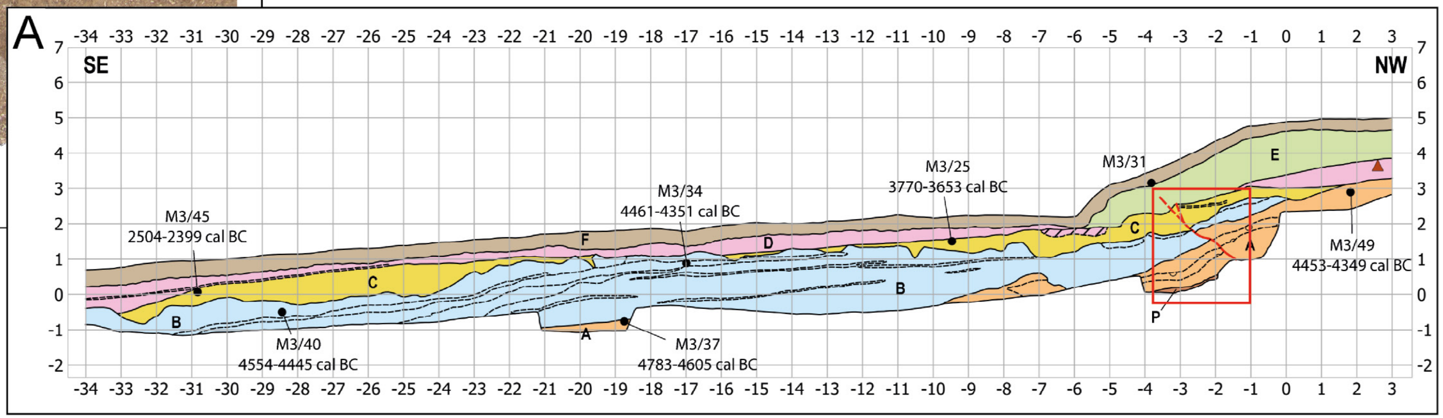




**Fig. 9 - A) Log of trench Miane 3 (Stop 1.2), and B) particular of the shear zone. Legend: Unit P: palaeosoil; Unit A: colluvium; Unit B: alluvial fan; Unit C: debris-flow; Unit D: man-made ground; Unit E: debris-flow; Unit F: soil.**

https://doi.org/10.3301/GFT.2023.07

surface of anthropogenic origin (D1 Unit: "strada maestra") was carved into Unit C. Moreover, A, B, C units are folded in the distal portion of the trench. Palaeoseismological investigations highlighted the seismogenic potential of the BVV, even if no historical earthquake can be linked to this tectonic structure.

## Stop 1.3 - Gai-Tarzo: The LGM end moraine system of the Piave in the Soligo Valley

**Coordinates: Lat. 45°58'05"N, Long. 12°10'38"E**

The upper reach of the Soligo Valley departs from the Lapisina Valley, near Serravalle, and displays a subsequent NNE-SSW trend along the strike of the bedrock, here characterised by the emergence of the BVV Thrust (Fig. 5). The shape of the valley is interrupted at Gai by two ridges, the internal one being more prominent, that were the frontal moraines of a branch of the Piave glacier during the LGM (Figs. 10 and 11). The ice also reached the bedrock ridge to the south, outflowing to the south from the gaps of Tarzo and Nogarolo.
The distribution of these glacial deposits was depicted by Venzo (1977) as shown in Figure 11. Most of these deposits crop out in the southern side of the valley; whereas the northern side is located in the steep slope at the foot of the Prealps and few remnants are preserved.
Weathered glacial and glaciofluvial deposits are located at higher elevations and more external with respect to the LGM limit. These were ascribed to the Riss glaciation (Venzo, 1977) but without chronological data, they can only be generally attributed to the Middle Pleistocene. Notably, downstream of the Gai moraines thick conglomerates with Piave provenance signature crop out; these can be ascribed to a Middle Pleistocene Soligo River or to a glaciofluvial and glacial deposition during an old glacial phase (Dall'Arche and Zanferrari, 1979).
Upstream of the Gai moraines the valley is flat and characterised by palustrine and lacustrine deposits. These were excavated in a clay pit in Revine (Fig. 12); the excavation discovered a flooded conifer forest (larch and pines) that was radiocarbon dated at about 16 ka cal BP

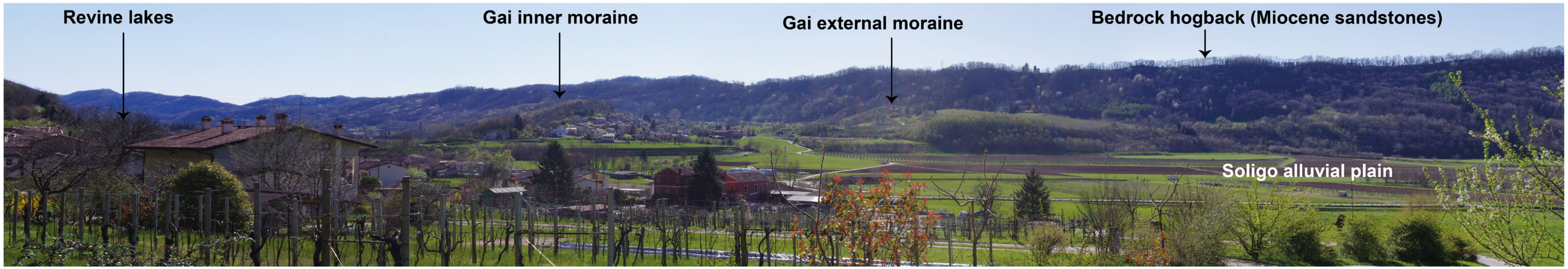



**Fig. 10 - Panoramic view from the North of the Soligo Valley with the frontal moraines of Gai (Stop 1.3).**





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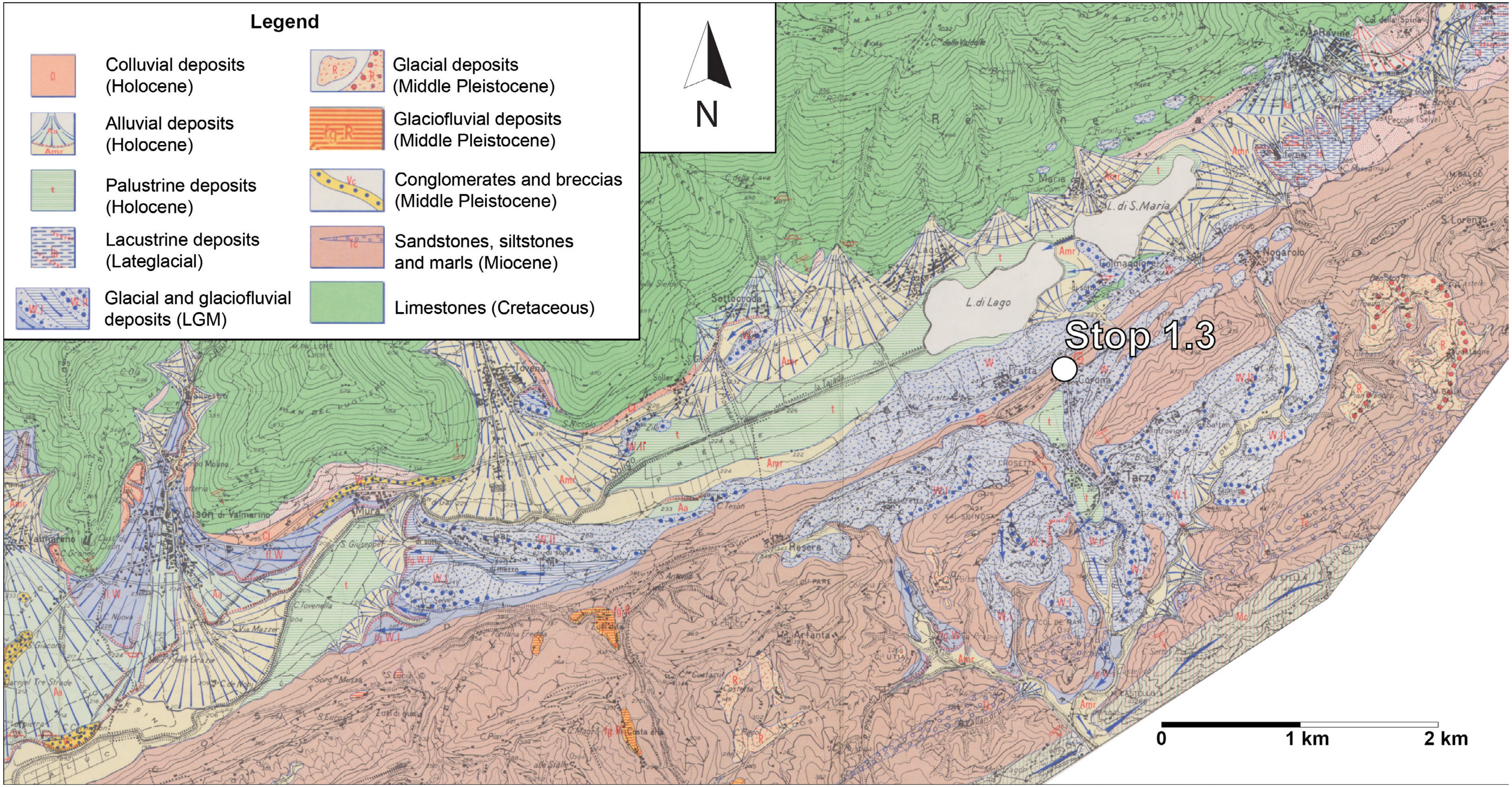


Fig. 11 - Geological map of the Soligo Valley according to Venzo (1977).

(Casadoro et al., 1976; Kromer et al., 1998; Friedrich et al., 1999). The trees were found in life position and yielded information about the palaeoclimate of the phase of forest withdrawal (Ragogna oscillation; Monegato et al., 2007; Ravazzi et al., 2007) before the onset of the Bølling-Allerød Interstadial.

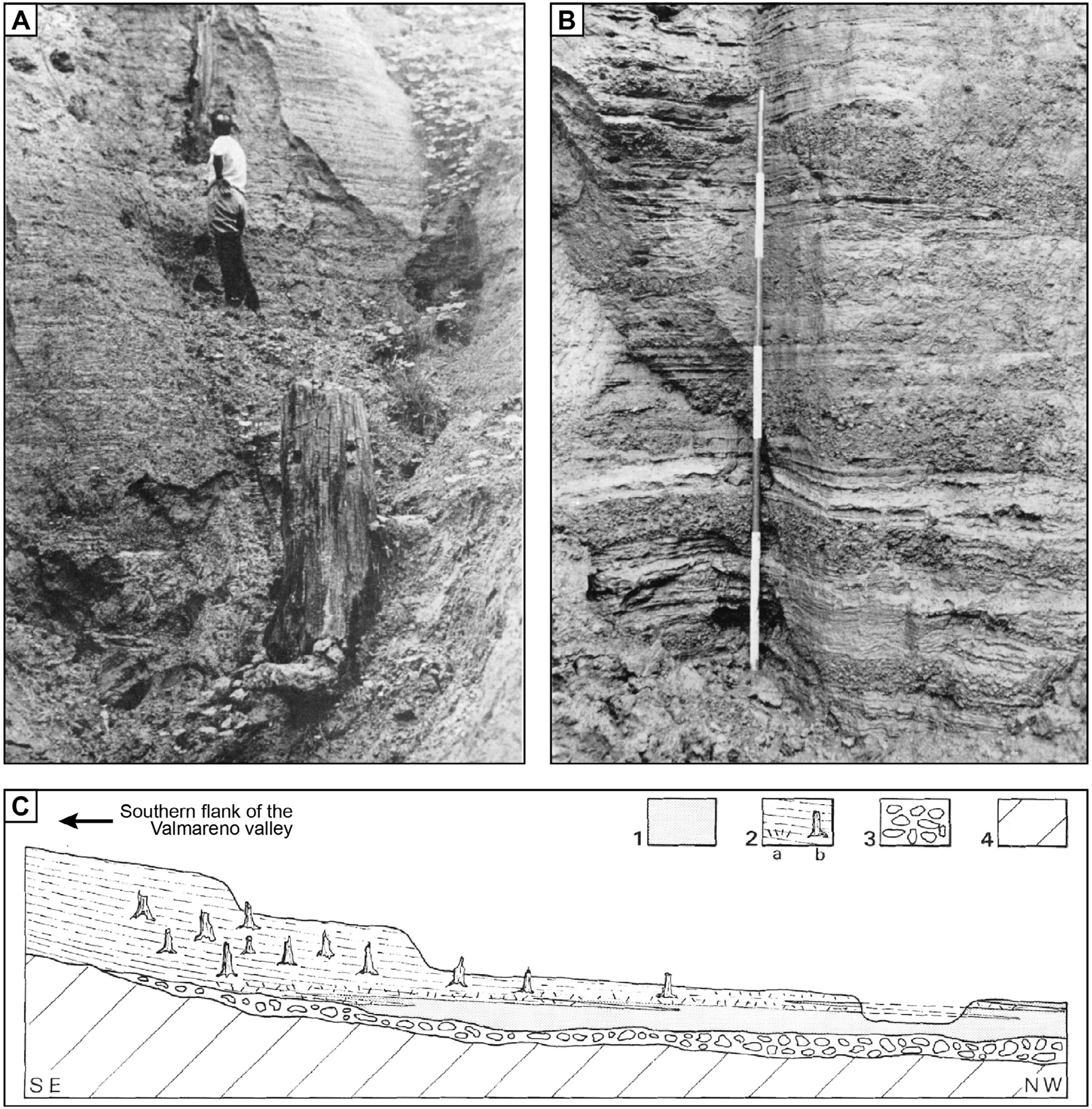


Fig. 12 - A) Photo of the lacustrine deposits of Revine embedding larch trunks in life position (Stop 1.3); B) Detail of the laminated lacustrine deposits; C) Geological sketch of the Revine succession cropping out in the clay pit; legend: 1) Lacustrine deposits; 2) Slope deposits with roots and larch logs in place; 3) Glacial and glaciofluvial deposits, 4) Bedrock (photos and scheme from Casadoro et al., 1976).

## Stop 1.4 - Vittorio Veneto basin and morainic amphitheatre

**Coordinates: Lat. 45°57'22"N, Long. 12°16'52"E**

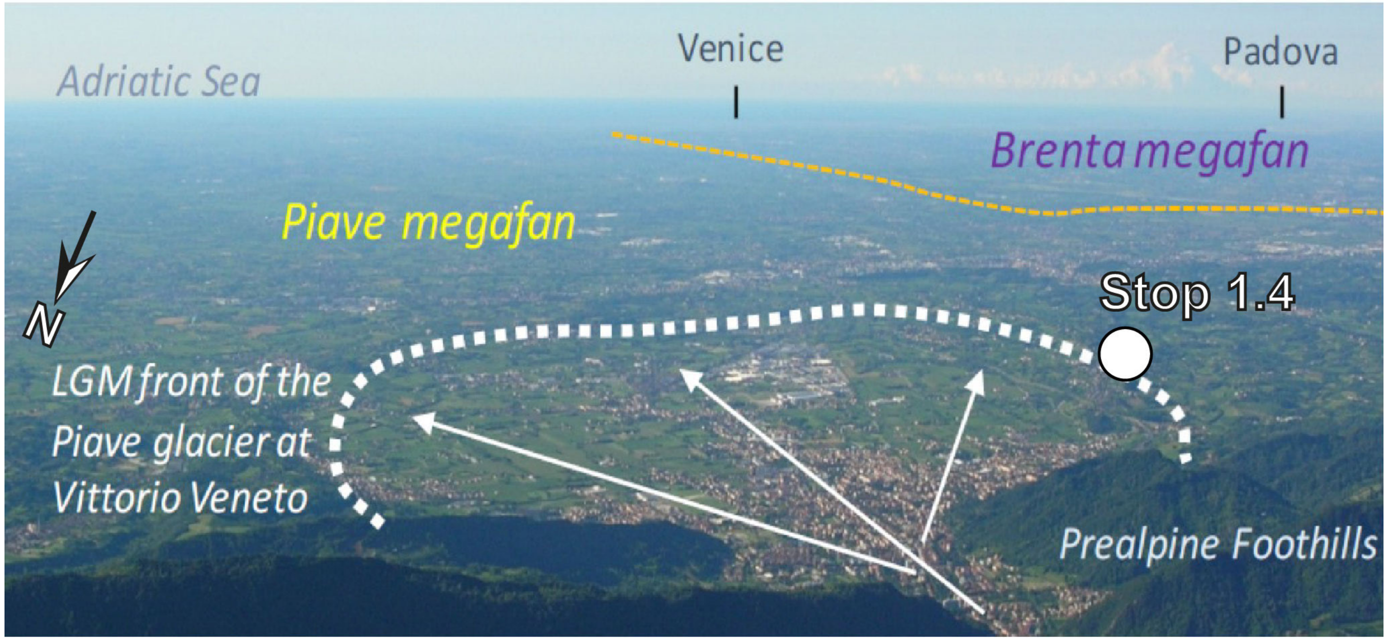


Fig. 13 - Panoramic view of the Vittorio Veneto basin (Stop 1.4) and the Venetian plain from the Prealps.

The piedmont plain forms a wedge into the Miocene-Pleistocene "molasse" with the apex at Serravalle, forming the Vittorio Veneto basin (Figs. 13 and 14A). This sector is encircled by the LGM frontal moraines of the major lobe of the Piave glacier branch flowing along the Lapisina valley (Dall'Arche et al., 1979).

The western and southern moraines lie on the bedrock (Pleistocene conglomerates). Here, the external ridge of Cozzuolo was ascribed to an older glacial advance, likely occurred in the Middle Pleistocene (Fig. 5, Venzo, 1963). The eastern lateral moraine ends at Cappella Maggiore, and its continuity is cut by the Meschio River incision. The area encircled by the moraines is flat due to the intensive alluvial deposition in the Vittorio Veneto basin that started since the Late Glacial and probably lasted up to the beginning of the Holocene. This geomorphological setting is opposite to the classical suit of recessional moraines of other southalpine end moraine systems (see stop 3.2). This part of the plain gently dips from the apex at the Serravalle narrow towards the southeast and it is made of a succession of alluvial and glacial deposits (Fig. 14B and C; Avigliano et al., 2008).

In the Vittorio Veneto basin, the following Quaternary units crop out: a) glacial deposits (Upper Pleistocene). The morainic ridges of the amphitheatre of Vittorio Veneto, and part of the city underground, are formed by glacial deposits of the LGM Piave glacier. Glacial deposits are mostly represented by lodgment and ablation tills and consist of a diamicton of prevailing gravels with pebbles and blocks; b) coarse alluvial deposits (Upper Pleistocene - Holocene). The Quaternary fillings of the Vittorio Veneto basin up to the surface are prevailing made of fluvial and glaciofluvial deposits of the Piave glacier and alluvial deposits of local streams. Alluvial deposits consist of prevailing sandy gravels with

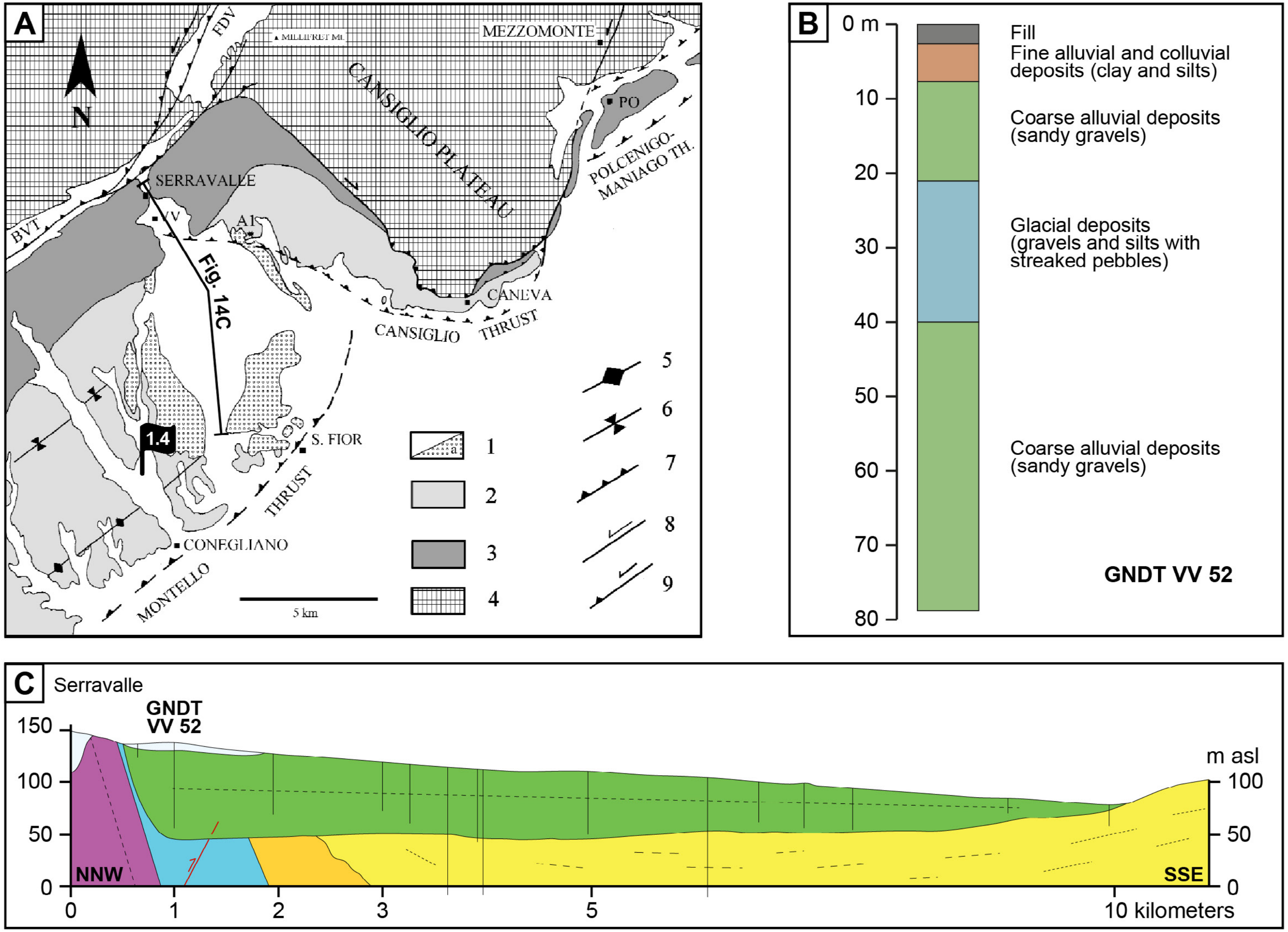


Fig. 14 - A) Geological sketch map of the Vittorio Veneto area (Stop 1.4). Legend: 1) Quaternary deposits; 1a) moraines of the Vittorio Veneto glacial tongue; 2) Conegliano complex (clays, sands, conglomerates; Middle-Pliocene – Lower Pleistocene); 3) Southalpine Molasse (upper Oligocene-Miocene); 4) carbonate successions (Jurassic-Cretaceous), Scaglia Rossa Fm. (Upper Cretaceous - lower Eocene), marly-arenaceous flysch (Eocene); 5) anticline; 6) syncline; 7) thrust; 8) strike-slip fault; 9) transpressive fault; A1: Anzano 1 well; BVT: Bassano-Vittorio Veneto thrust; PO: Polcenigo, FDV: Fadalto valley. B) Simplified lithological log of GNDT_VV52 borehole near Serravalle. C) Cross section of the Vittorio Veneto Basin (trace in Figure 14A); the hypothetical trend of the buried "geological" bedrock is derived from borehole stratigraphies (marked VV). Pre-Quaternary bedrock: violet: lower Cavanella group and Monte Baldo fm. (Lower-Middle Miocene); blue: Tarzo marl (Serravallian); orange: Vittorio Veneto sandstone and Montello conglomerate (Tortonian-Messinian); yellow: Conegliano complex (Pliocene - Lower Pleistocene); green: gravelly or sandy-gravelly body; grey: clay, silt and sand (Middle Pleistocene – Holocene). Note that in the SSE end of the profile, the Miocene bedrock rises up because of Montello thrust activity. Heavy dark lines indicate the water table (mod. after Avigliano et al., 2008).

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pebbles and discontinuous conglomerate levels; c) fine alluvial and colluvial deposits (Pleistocene – Holocene). They crop out at the base of the relief and are characterised by prevailing silt and clay layers interbedded with thin gravel levels. A logging borehole (Fig. 14B) drilled in the urban area of Vittorio Veneto (Serravalle) reached the maximum thickness of Quaternary infill (more than 80 m, Fig. 14B from Avigliano et al., 2008).

The LGM Vittorio Veneto amphitheatre consists of three major moraine complexes. The outermost one extends as far as 8 km from the valley mouth at Serravalle and corresponds to the maximum expansion of the glacier (Fig. 5). An intermediate position of the glacier front is suggested by a moraine complex that is located some hundreds of metres at the back of the most external ones. The younger and inner moraine system extends with a typical arched form to a maximum distance of about 6 km from the valley mouth. A tree trunk was found during the excavation of a building lot about 200 m north of the main moraine ridge at Colle Umberto, i.e., in the inner side of the moraine (Bondesan et al., 2002; Carton et al., 2009). This tree was located at a depth of 4 m from ground level, embedded within a sequence of glaciofluvial sediments in turn covered by a glacial diamicton. The layers appear to have been deformed by glaciotectonic phenomena. The trunk was radiocarbon dated 20.6 – 22.2 ka cal BP (recalibrated with IntCal20 curve). This last glacial advance in the Vittorio Veneto amphitheatre is likely correlated to the second maximum advance recorded in the Tagliamento system (i.e., after 23 ka cal BP; see stop 3.2; Monegato et al., 2017).

Vittorio Veneto is located in a basin where, from a tectonic point of view, three main potentially seismogenic structures join (Figs. 5 and 14A): the eastern closure of the Montello thrust, the Cansiglio thrust and the eastern portion of the Valdobbiadene-Vittorio Veneto-Fadalto thrust. All these tectonic structures show evidence of Quaternary activity. The area was hit by two destructive earthquakes in the last 150 years: the 1873 Mw 6.3 Alpago earthquake and the 1936 Mw 6 Cansiglio earthquake. As a result of the 1936 earthquake, strong site effects affected Ceneda and Serravalle localities.



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# DAY 2

## Stop 2.1 - The sin-tectonic basin of Palù di Livenza

**Coordinates: Lat 46°01'18"N, Long. 12°28'30"E**

The Palù di Livenza basin extends in the NNE-SSW direction at the eastern slopes of the Cansiglio karst massif. In its eastern portion, it is bordered by the left lateral strike-slip fault of Col Longone (Figs. 14A and 15). This setting generated a depressed area hydrologically connected to the Friulian Plain through a narrow passage (b in Fig. 15), that between the Late Pleistocene and the Holocene has been occasionally closed.

The area is characterised by the occurrence of La Santissima and Molinetto springs, that have a fairly important discharge of karst origin and have been waterlogging the basin, favouring the deposition of a 50 m-thick continental sedimentary succession (Bartolomei et al., 1997). According to a new borehole drilled in 2020, palustrine deposits with remains of broad leaves characterise the base of the infill and could be tentatively related to an interglacial phase. This unit is sealed by a thick debris-flow sequence related to the activity of the streams draining the eastern slope of the Cansiglio Massif (Fig. 16). A lake occupied the basin during LGM, as testified by well-laminated deposits and its formation has been probably triggered by the progradation of the alluvial fan of Cellina River (Vivaro unit, Fontana et al., 2019; Fig. 16) that dammed the mouth of the valley of

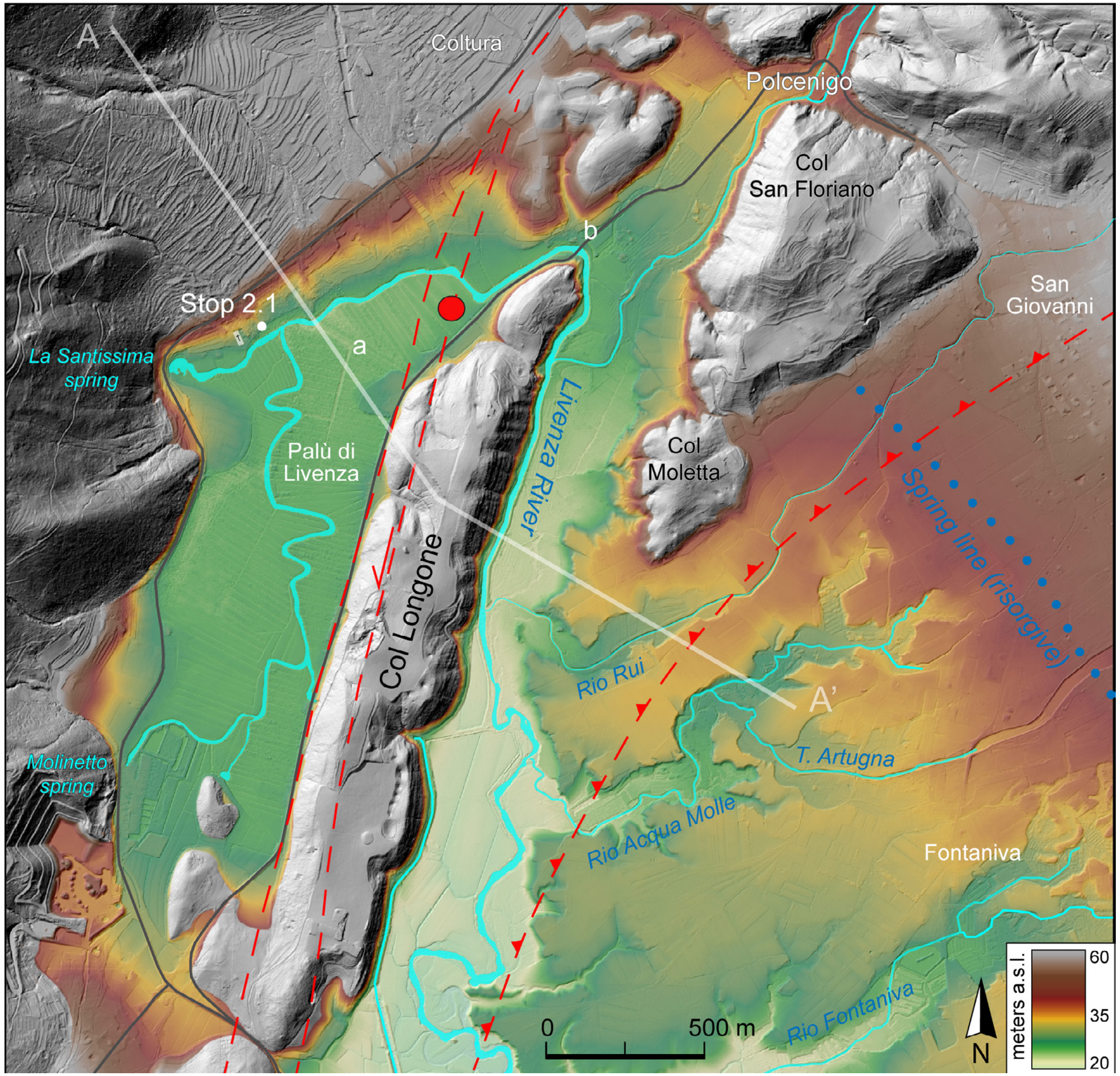


Fig. 15 - Digital elevation model of the area of Palù di Livenza. Line A-A' indicates the trace of the stratigraphic profile in Figure 16. Red dot indicates the location of the trench of Figure 17.

Livenza River with its distal sector. At the end of the LGM or in the Late Glacial, the Livenza River incised the Cellina megafan forming terraces up to 10 m of elevation and leading the area of Palù di Livenza to reconnect to the external plain.

This lower base level induced the formation of a complex drainage network that eroded the LGM lacustrine sediments, scouring them up to 6-7 m of depth. This setting lasted until the Early Holocene, when a lacustrine/palustrine environment was re-established in the area and lasted until modern times (Pini, 2004). The thickness of the Holocene deposits is variable, from 7 m to almost null, and some areas have important archaeological remains (Bassetti and Cavulli, 2002). Palù di Livenza is one of the transnational UNESCO sites for prehistoric pile-dwelling settlements along the Alps. In particular, the archaeological excavations confirmed the exceptional preservation of wooden tools and structures referred to the late Neolithic (4500-3600 BCE, Micheli, 2017; Micheli et al., 2019).

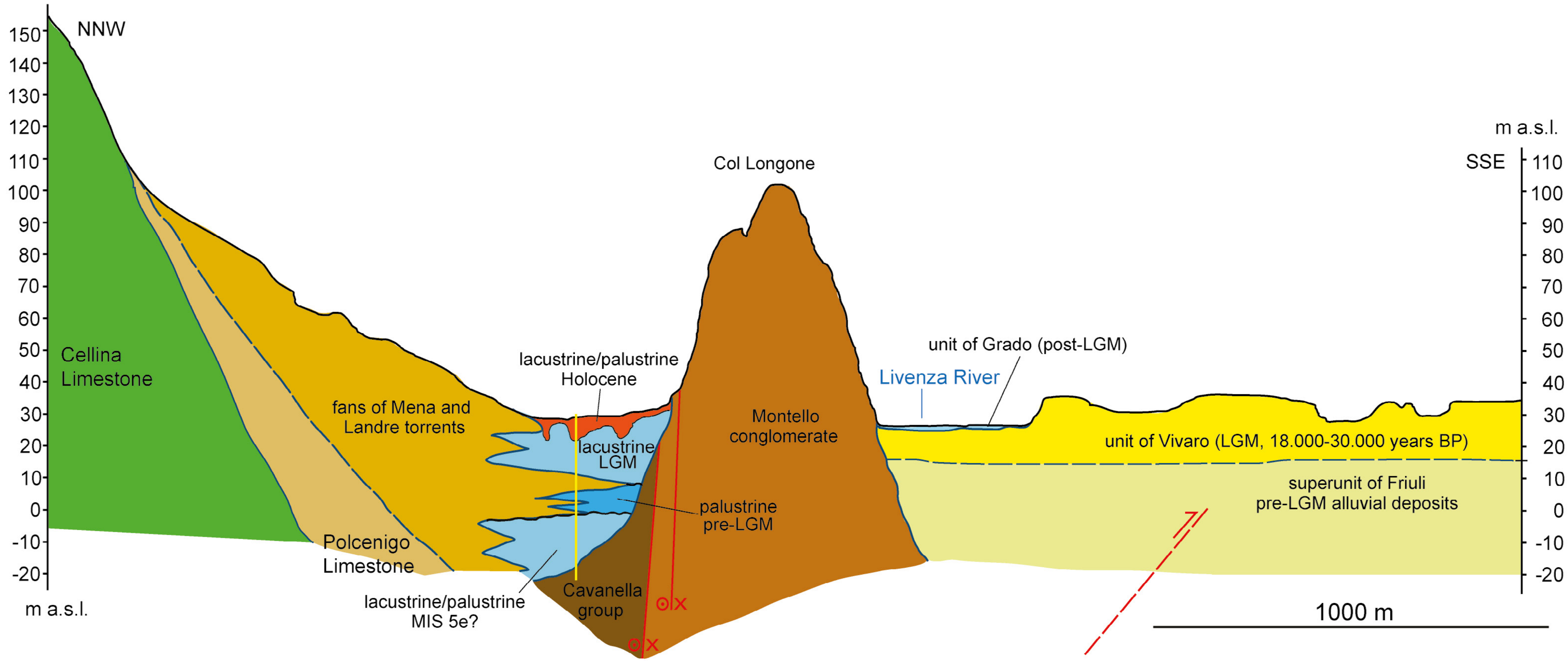


Fig. 16 - Geological section of Palù di Livenza and the distal portion of the LGM alluvial megafan of Cellina River (Vivaro unit). The trace of the section is indicated in Fig. 15.

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The lacustrine succession of the basin is affected by palaeo-liquefaction phenomena (Fig. 17), likely induced by seismic shaking related to the medium-to-strong seismicity of the area, among which the largest and most probable are the 1936 Mw 6, Cansiglio earthquake and/or 1878 Mw 6.3, Alpago earthquake.

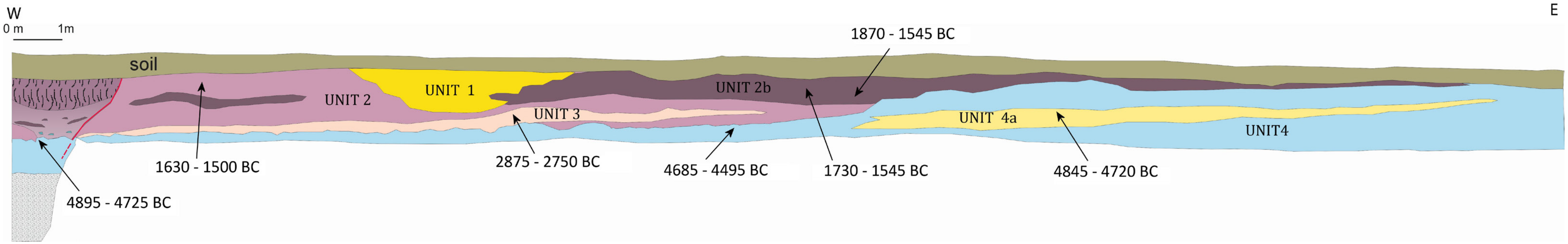


Fig. 17 - Geognostic trench in the NE portion of Palù di Livenza basin (Stop 2.1, see Fig 15 for location). Unit 1: anthropogenic filling; Unit 2 and 2b: clayey-silty peaty sediments with sand lenses (Unit 3); Unit 4: lacustrine deposits, with bioturbations (4a) to the left, the paleo-liquefactions. Northern wall of the trench (Modified after Poli, 2017).

## Stop 2.2 - Overlook of the western Friulian piedmont plain from the Piancavallo

**Coordinates: Lat. 46°05’13”N, Long. 12°31’42”E**

The western Friulian piedmont plain is encircled by the Monte Cavallo massif and the Carnic Prealps. It is characterised by the development of the Cellina and Meduna alluvial fans and their tributaries (Figs. 4 and 18). These two alluvial systems show a remarkable topographic gradient and an evolution that has been conditioned by the tectonic activity of the thrust of the eastern Southern Alps (Galadini et al., 2005; Poli et al., 2016; 2021). The Cellina alluvial fan has its apex at Montereale and was characterised by strong aggradation during the LGM (Avigliano et al., 2002a) with an overall thickness of ca. 30 m. This aggradation lasted during the Late Glacial until about 13.4-13.9 ka cal BP (Avigliano et al., 2002a), when the river started to entrench the fan with a clockwise shift. This created a flight of terraces on the eastern bank and telescope fans at the outlet of the trench (Avigliano et al., 2002a; Zanferrari et al., 2008a). On the western flank, the Cellina fan merged with the local fans at the foot of the Monte Cavallo. The tectonic activity preserved some strips of Middle Pleistocene deposits of the Cellina River, well distinguishable due to their cementation and weathering (Avigliano et al., 2002b). The LGM Cellina alluvial fan merged to the east with the Meduna alluvial fan, which was characterised by a complex evolution due to recent fault activity and the presence of the Sequals Hills (see Stop 2.5 for details). The Meduna alluvial fan can be split in two morphological and sedimentary units: the Arba lobe to the west, and the Travesio lobe to the east

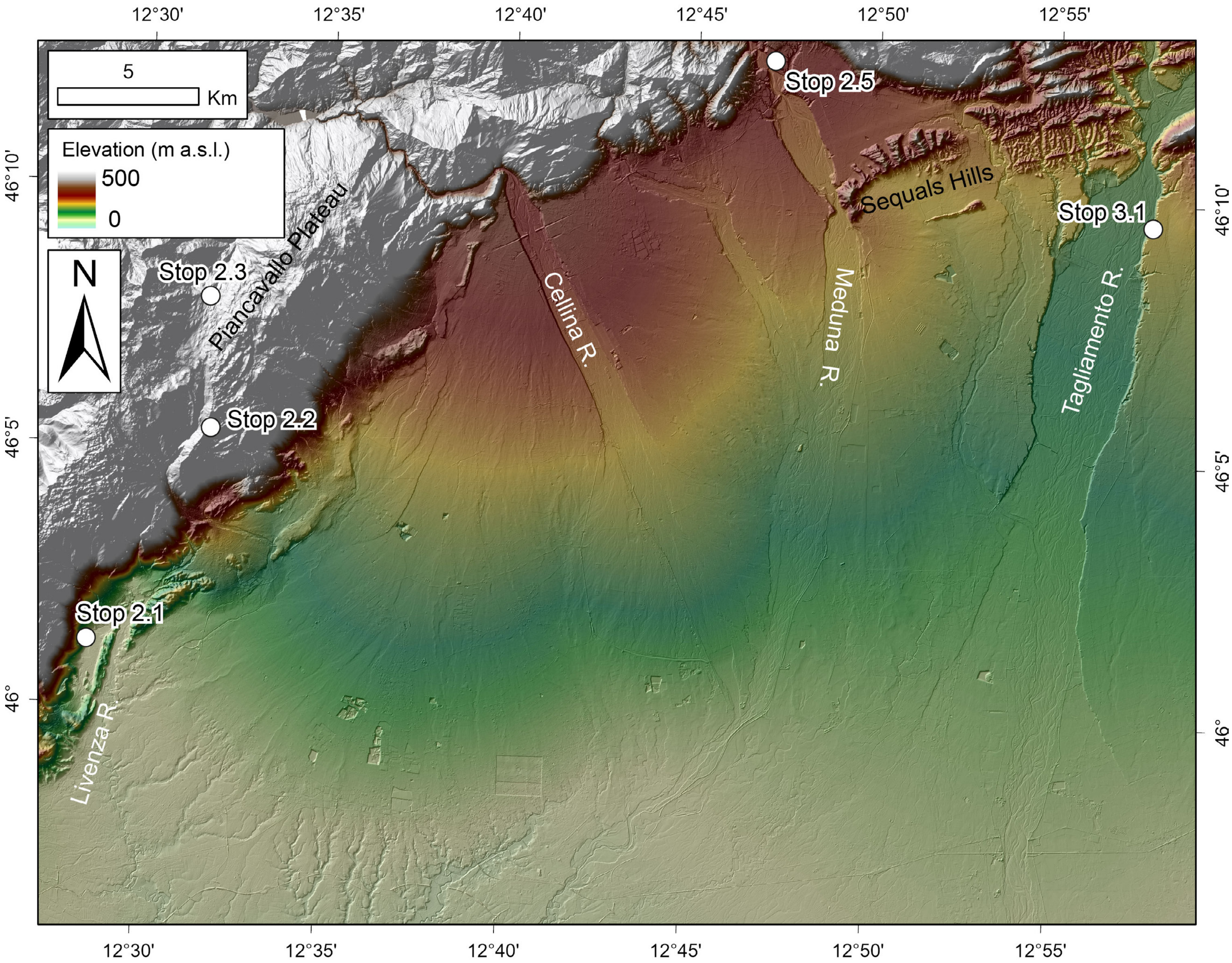


Fig. 18 - Digital elevation model of the western Friulian piedmont plain.

(Avigliano et al., 2002a). The Travesio lobe developed during the LGM and was abandoned at about 18.5 ka cal BP, when the river entrenched the apex of the fan and switched to the west continuing the aggradation of the fan until the Pleistocene-Holocene boundary (Avigliano et al., 2002a). The Late Glacial - Holocene trenches of the Cellina, Meduna and Tagliamento rivers, along with their tributaries, are the major geomorphological feature of the western Friulian plain. This entrenchment reached the basal boundary of the LGM aggradation, exposing it in many sites along the trenches (Avigliano et al., 2002a; Paiero and Monegato, 2003; Monegato and Poli, 2015).

## Stop 2.3 - The moraines at Pian delle More: reconstructing glaciers on the Monte Cavallo during the Last Glacial Maximum

**Coordinates: Lat. 46°7’49’’N, Long. 12°31’45’’E**

After having ascended the road from the Friulian plain towards Piancavallo, we turn towards the mountains and karst plains of the Monte Cavallo, which represents the easternmost extent of the Venetian Prealps. This area is rich in sediments and landforms of glacial origin, most of which can be stratigraphically attributed to the LGM. At their largest extent, glaciers in the Monte Cavallo covered an area of around 50 km$^2$, with ice advancing over the Piancavallo and into the valleys east and west of the main divide (Rettig et al., 2023). Crucially, however, these local glaciers never fully merged with larger glacial systems, such as the Piave glacier to the West (Fig. 3). It is, therefore, possible to accurately reconstruct their past extent and ELA and gain important insights into the local palaeoclimate.

From the previous stop (2.2) we can already observe some of the glacial landforms - the large Monte Cavallo cirque and a right lateral moraine ridge that was formed by the advancing LGM glacier in the Stua valley. Crossing the Piancavallo towards the North, we descend into the catchment of the Caltea stream that drains the eastern slopes of the Monte Cavallo towards the Cellina River. We take a stop at Pian delle More to discuss some additional erosional and depositional landforms of the glacial system (Fig. 19A). Clearly visible are the large cirques of the Val Grande and Val Piccola that represented accumulation areas during the LGM. There is also a series of moraine ridges, ca. 5-10 m high, that delimitates the northern margin of the Pian delle More. Interestingly, these moraines are transverse to the direction of the Caltea Valley and can therefore be interpreted as right lateral moraines of a glacier coming from the aforementioned cirques.
The moraines at Pian delle More are likely related to a post-LGM glacier advance. During the LGM, a glacier coming from the Piancavallo merged with a glacier-fed from the Val Piccola and Val Grande cirques (Fig. 19B). The moraines at Pian delle More must have therefore been formed at a time when ice had already receded from the plateau (Fig. 19C). This plateau-ice close to the glacier ELA was more strongly affected by the early stages of climatic warming after the LGM, while the Caltea valley continued to receive mass-support from the higher situated cirques. Indeed, a two-stage evolution can be seen in many valleys of the Monte Cavallo, where large frontal and lateral moraines indicate the maximum ice extent and smaller moraines, ca. 100 m up-valley, the post-LGM advance.





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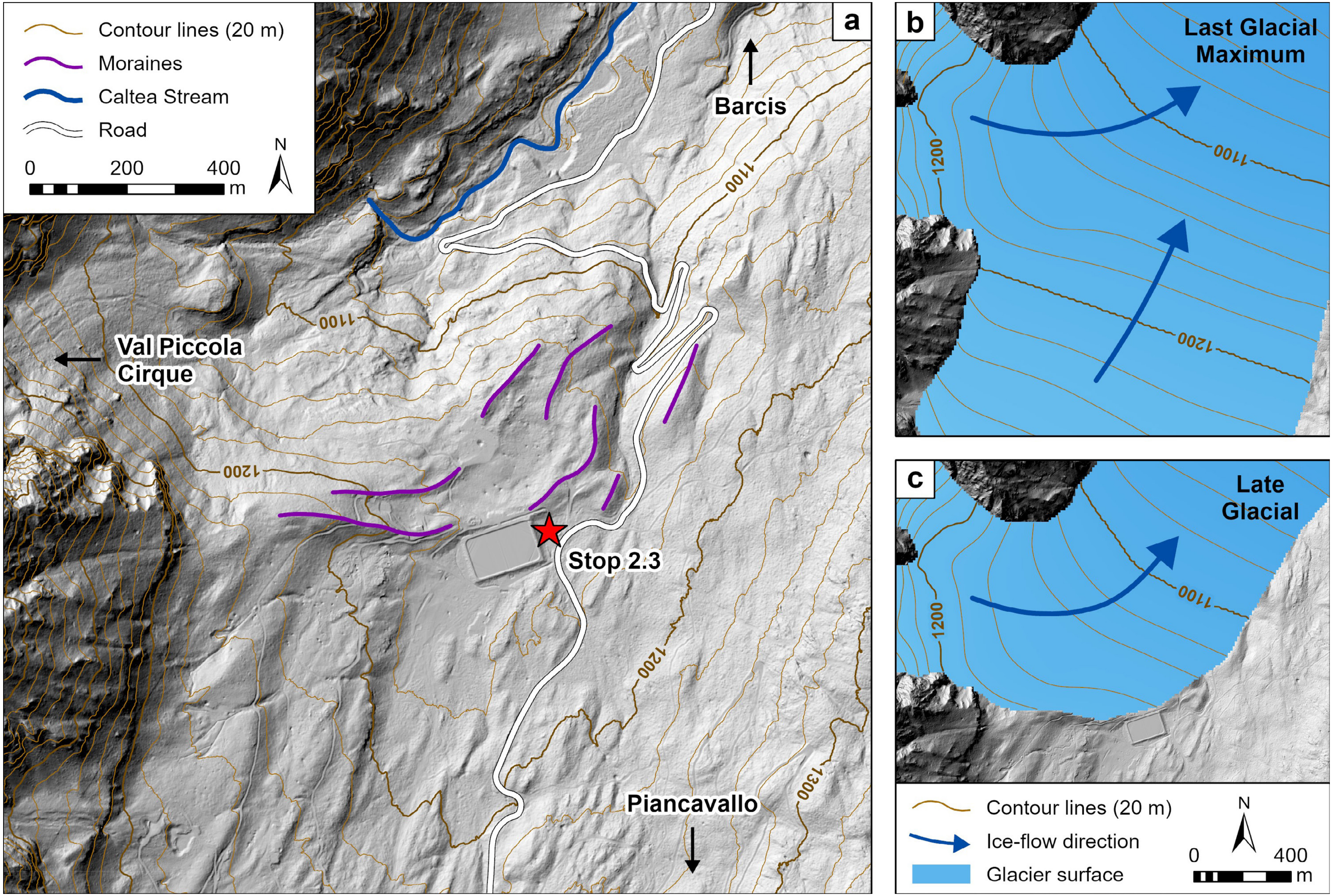


Fig. 19 - The moraines at Pian delle More. A) Location of the moraines. B) Reconstruction of ice extent during the LGM. C) Reconstruction of ice extent during the Late Glacial, at a time at which ice had already receded from Piancavallo. Underlying elevation data: FVG-DEM (eaglefvg.regione.fvg.it).

## Stop 2.4 - The lacustrine sediments from the Caltea Valley: insights into palaeo-vegetation and -climate of a pre-LGM interstadial

**Coordinates: Lat. 46°8’54’’N, Long. 12°32’26’’E**

Leaving the Pian delle More, we follow the road through the Caltea Valley towards Barcis. Numerous large limestone boulders are scattered alongside the road, providing further evidence for glacial transport through the valley. At an elevation of ca. 900 m a.s.l. (see Fig. 20A), around 80 m above the present level of the Caltea stream, we arrive at a small forest road, where a section of pre-LGM lacustrine sediments has been discovered and first described by Fuchs (1969).

The sediment log of the section is shown in Figure 20B. Most notable is the presence of laminated silts that locally attain a thickness of 1-2 m. Further down the valley, in a small ravine, the thickness of this unit increases to over 8 m. The lamination of the silt is represented by slight changes in colour and grain size, alternating from darker, finer laminae to lighter ones with higher sand content. Partially, also larger lenses of sand can be found. Both the grain size and the distinct lamination point to a deposition of the silt in a lacustrine environment with limited fluvial input. Underneath and above the silt, layers of sandy gravel appear, indicating that fluvial deposition prevailed in the valley before and after the formation of the lake. Ultimately, the section is capped by a firm, matrix-supported diamicton that can be interpreted as a till from the ultimate ice advance during the LGM.

Remarkable is that the lacustrine deposits contain a large number of plant macrofossils including cones, needles, twigs, and pieces of bark (Fig. 20C, 20D, 20E). These macrofossils were identified as spruce (*Picea abies*) and larch (*larix*) remains (Fuchs, 1969), evidencing the establishment of a boreal forest at this site. This must have occurred during a relatively warm interstadial climate, as the valley was glaciated during stadial conditions. The chronology of the lake sediments has, until recently, remained poorly constrained with only a single radiocarbon date (29350 ± 460 $^{14}$C a BP) being reported by Fuchs (1969). Rettig et al. (2023) have collected a total of 9 new macrofossils from this section. However, all of these new radiocarbon measurements resulted in non-finite $^{14}$C ages, meaning that the formation of the lake predates the limit of the radiocarbon method (~45 ka BP). The preservation of such an extensive lake record of a pre-LGM interstadial in a narrow pre-Alpine valley is an exceptional case. Further studies may both allow us to better resolve the chronology of these deposits and reveal interesting insights into the climate and vegetation of this interstadial period in the southeastern Alps.

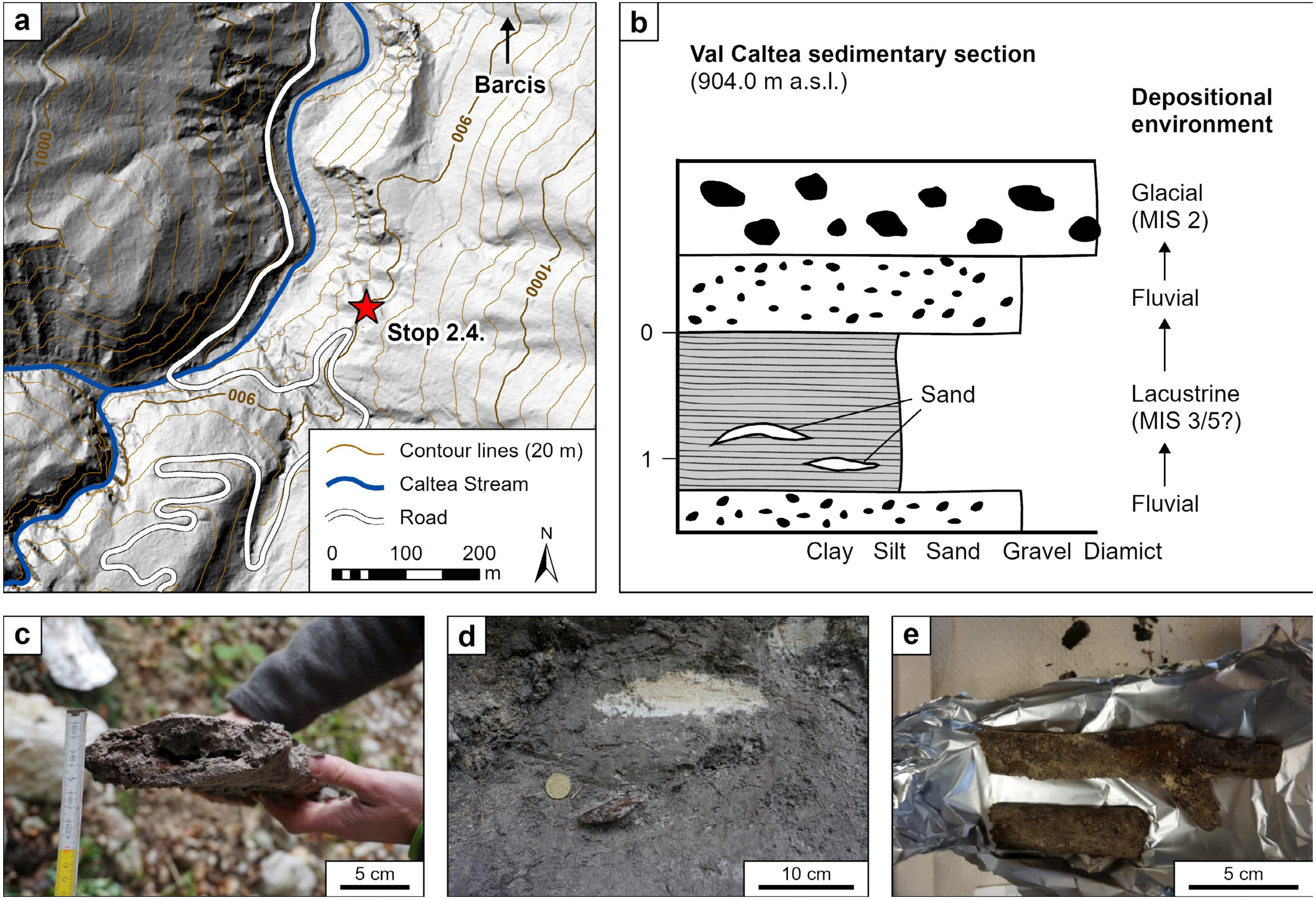


Fig. 20 - The lake sediments of the Caltea Valley. A) Location of the section. Underlying elevation data: FVG-DEM (eaglefvg.regione.fvg.it). B) Log drawing of sedimentary units within the section. C) A large tree trunk that was found within the lacustrine deposits. D) Close-up photograph of the lacustrine deposits. Note both the tree macrofossil and a larger sand lens. E) Two branches that were found within the deposits and that were used for radiocarbon dating by Rettig et al. (2023).

## Stop 2.5 - The tectonic terraces of Meduno

**Coordinates: Lat. 46°12’42”N, Long. 12°46’56”E**

The Meduna River valley is characterised by a terrace flight in its lower reach (Fig. 21). The left slope is made of a complex succession of fluvial conglomerates, interbedded with glacial and glaciolacustrine deposits (Monegato and Poli, 2015). This record has been strongly affected by tectonic activity along the front of the eastern Southern Alps (Galadini et al., 2005; Poli et al., 2009).
The upper sector of the Meduna fan is also characterised by the interference with the Sequals Hills, that have deflected the path of the river through the time. During the LGM the Meduna River took two different directions (Avigliano et al., 2002a). At the beginning, it flowed towards the southeast across the Travesio narrow forming the Travesio lobe. After 18.5 ka cal BP (Avigliano et al., 2002a; Monegato and Poli, 2015) the river switched towards the south, forming the Arba lobe. At the apex in Meduno, the Rivalunga terrace represents a remnant of the LGM fan before the switch. Considering the ongoing deformation and the entrenching of the Meduna River at 18.5 ka cal BP, this surface was unaffected by fluvial deposition since that time (Monegato and Poli, 2015).
The NE-SW striking, SSE verging Meduno thrust runs at the base of the hills between Maniago and Meduno. The outlet of Meduna Valley was strongly influenced by the most recent tectonic climax along the Maniago thrust,

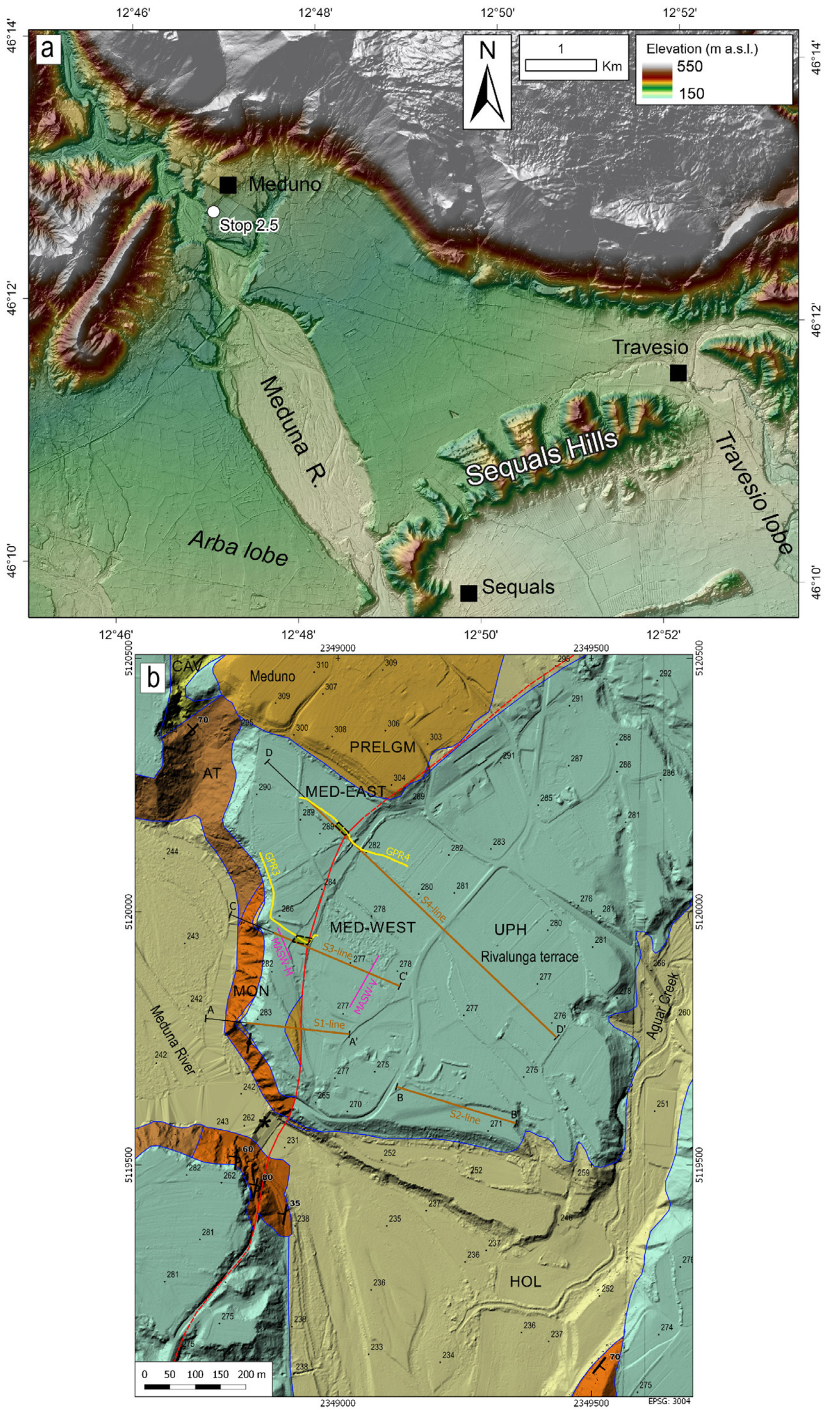


Fig. 21 - A) Digital elevation model of the Meduno area; B) Geological and geomorphological map of the Rivalunga terrace. Shaded relief from DTM supplied by Friuli Venezia Giulia Region (grid: 1x1m). Red line: trace of the Meduno Thrust as observed in the palaeoseismological trenches and around Ponte Maraldi. Brown lines: traces of seismic reflection, seismic tomography and geoelectrical profiles. Yellow lines: GPR profiles. Light green areas: palaeoseismological trenches MED_EAST and MED_WEST (Fig. 23). White point marks Ponte Maraldi location (Fig. 22). CAV: Aquitanian–lower Serravallian Cavanella group; AT: lower Serravallian–Tortonian (Tarzo marl and Vittorio Veneto sandstone fms.); MON: upper Tortonian–lower Messinian Montello conglomerate; PRELGM: Pliocene-Quaternary continental succession (Friuli Supersynthem); UPH: Upper Pleistocene (LGM) – Holocene *p.p.* alluvial and fluvioglacial deposits of the Meduna catchment; HOL: Present alluvial deposits (from Poli et al., 2021a).

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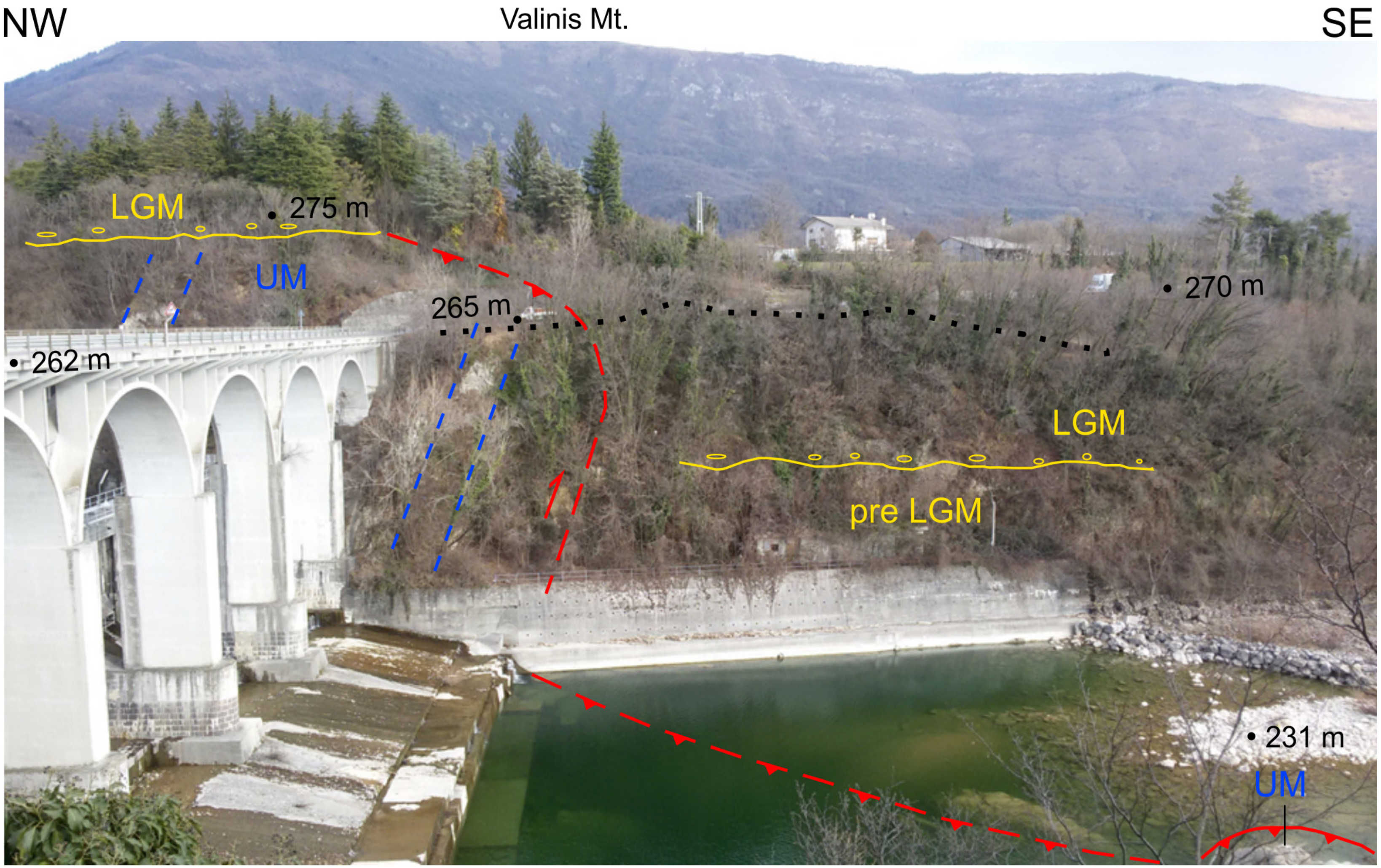


Fig. 22 - Left side of River Meduna near Ponte Maraldi (Meduno) (Modified after Poli et al., 2021a). The overturned Upper Miocene Montello conglomerate (UM: blue dotted line) and the sub-horizontal LGM gravels of the Meduna River (LGM bottom: yellow line) join along the high-angle, NNE-SSW striking, WNW-dipping oblique ramp of the Meduno Thrust (Stop 2.5).

inducing a sedimentary thickness variation of the LGM deposits of about 20 m. This indicates a slip rate of about 0.6 mm/yr for the last 30 ka (Monegato and Poli, 2015; Fig. 22). In correspondence of the N280° striking oblique ramp of the Meduno thrust, the Late Pleistocene Rivalunga terrace shows a set of scarps perpendicular to the Meduno Valley. Palaeoseismological trenches (Poli et al., 2021a) carried out across the scarps of the Rivalunga terrace exhibited both reverse shear planes and extrados fracturing, which deformed alluvial and colluvial units. $^{14}C$ datings of the colluvial units showed that the most recent fault movements occurred after 1360 AD and 1670 AD (Fig. 23). The age of the deformed stratigraphic units compared with the earthquakes listed in current catalogues (Rovida et al., 2022), suggests that the 1776 earthquake (Mw 5.8, Io=8-9 MCS) could represent the last seismic event linked to the Meduno thrust activity, in good agreement with the classification of the fault displacement hazard proposed by Blumetti et al. (2015) and Guerrieri et al. (2015).



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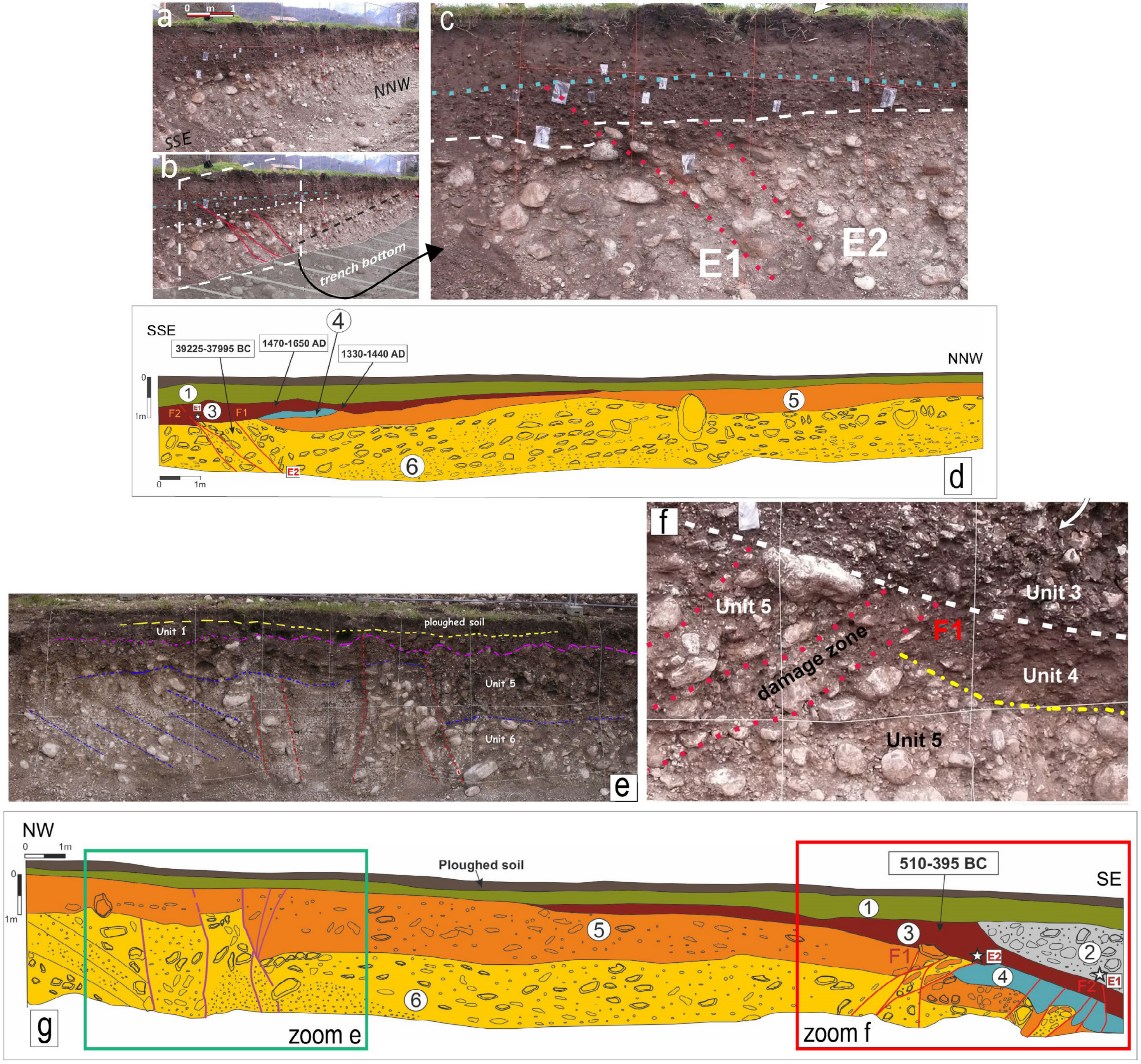


Fig. 23 - A) Palaeoseismological trench MEDUNO_EAST; B) the shear zone affected the southern edge of the trench; C) particular of the shear zone affected the historical unit 3; D) interpretation of MEDUNO-EAST trench wall. Red lines: reverse faults. E) extrados fractures at the northern portion of the trench MEDUNO-WEST (green rectangle); F) damage zone localised near the tectonic scarp of trench MEDUNO-WEST (red rectangle); G) interpretation of MEDUNO-WEST trench wall. One metre for the mesh grid. Numbers refer to stratigraphic units; E1 and E2: identified seismic events; F1 and F2: fault planes (mod. after Poli et al., 2021a).

## DAY 3

### Stop 3.1 - The stratigraphy of the Friulian piedmont plain in the Tagliamento fluvial scarp of Aonedis

**Coordinates: Lat. 46°09'33"N, Long. 12°57'25"E**

Downstream the valley outlet at the Pinzano narrow, the Tagliamento River deeply entrenches the Friulian plain with a river scarp up to 60 m high and a 2 km wide riverbed (Figs. 18 and 24). Just upstream of the Pinzano narrow the Tagliamento River joined the tributary Arzino River; the related deposits can be easily distinguished by petrographic analysis, the Arzino is characterised by sandstones and grey carbonates (dolostones and limestones), whereas the Tagliamento contains also volcanic, low-grade metamorphic rocks and red siltstone and sandstone (Monegato and Stefani, 2011).

The incision of the Tagliamento in the plain cut the sedimentary succession, revealing its stratigraphic architecture (Fig. 25, Paiero and Monegato, 2003; Zanferrari et al., 2008a; Fontana et al., 2019). This section was interpreted in the past as the overlapping of the Tagliamento LGM glaciofluvial deposits on an older Arzino alluvial fan (Venturini et al., 2004).

At the Pinzano narrow the Lower Pleistocene conglomerates, ascribed to the Tagliamento catchment (SPX in Fig. 25A, Paiero and Monegato, 2003; Martinetto et al., 2012), unconformably lie on the Messinian conglomerates. Another unconformity separates these conglomerates from the Pinzano and Via di Molin subsynthems (Lower-Middle Pleistocene) formed by cemented-to-loose gravels and sands related to the Arzino catchment ($BGM_1$ and $BGM_2$ in Fig. 25). A well-developed palaeosoil marks the boundary with the Aonedis Synthem; this is easily recognisable from the abundance of yellowish sandy layers (AON in Fig. 25B). This unit is again related to the Arzino alluvial fan. The upper boundary is an erosional surface carved by the outwash streams of the Tagliamento glacier during MIS 6 (Middle Pleistocene) and ascribed to the Plaino Synthem (Zanferrari et al., 2008a; Fontana et al., 2019). Along the Ponte Creek this boundary is marked by a well-developed palaeosoil (Zanferrari et al., 2008a). The Villuzza Synthem, laying above, is a younger sedimentary deposit related to the Arzino alluvial fan in the Piedmont plain (VLZ in Fig. 25). It was recognised in both scarps of the Tagliamento incision and dated to the Late Pleistocene (Monegato et al., 2010). The succession is sealed by the 20 m-thick glaciofluvial gravels of the Tagliamento ascribed to the LGM (Fig. 25). This complex stratigraphic architecture (Fig. 25) has been influenced by the activity of the Arba-Ragogna thrust front (Galadini et al., 2005; Poli et al., 2009). The boundaries of these units are displaced by the thrust in the correspondence of the Ponte Creek cut (Rio Mordaro and Rio Ponte in Fig. 25A). Along the Ponte and Mordaro creeks the glaciofluvial units interfinger with the related glacial deposits (Paiero and Monegato, 2003).

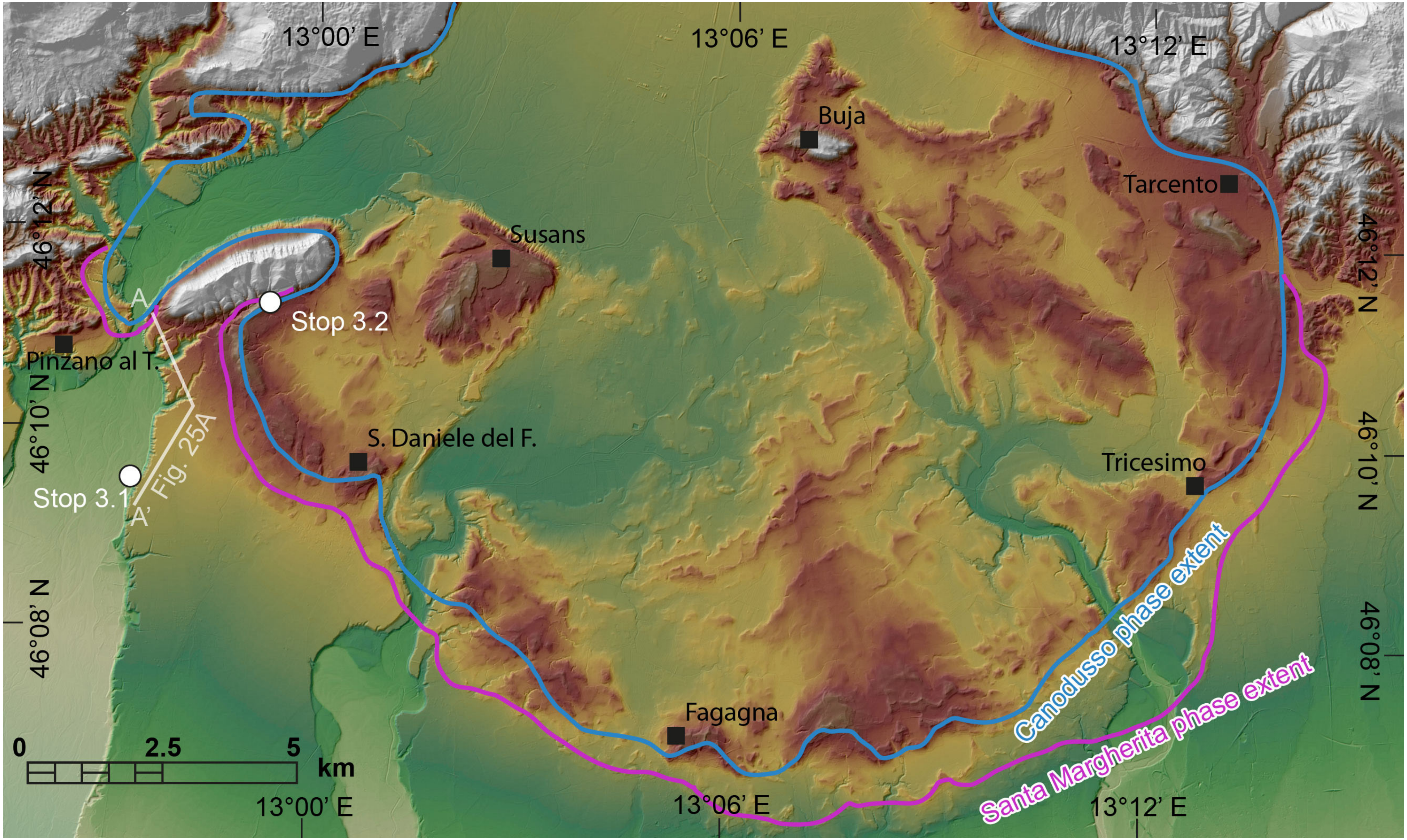


Fig. 24 - Digital elevation model of the Tagliamento end moraine system with highlighted the extent of the Santa Margherita (28.0-24.5 ka cal BP) and Canodusso (23.2-22.8 ka cal BP) phases (mod. after Ivy-Ochs et al., 2022).

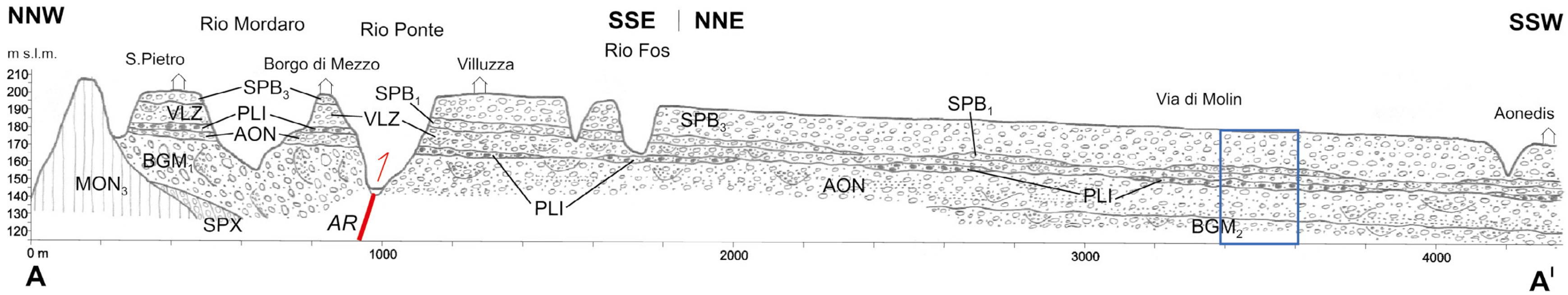



Fig. 25 - A) Schematic cross-section of the Tagliamento eastern scarp (San Pietro – Aonedis section of Zanferrari et al., 2008a), note different throws caused by Arba–Ragogna Thrust (AR). $MON_3$: Montello conglomerate; SPX: San Pietro di Ragogna conglomerate; $BGM_1$: Pinzano subsynthem; $BGM_2$: Via di Molin subsynthem; AON: Aonedis Synthem; PLI: Plaino Synthem; VLZ: Villuzza Synthem; $SPB_1$: Santa Margherita subsynthem; $SPB_3$: Canodusso subsynthem. X5 vertical magnification, the blue frame shows the location and extent of the slope of Fig. 25B. B) Detail picture of the Tagliamento scarp (Stop 3.1) with underlined the bounding surfaces.

## Stop 3.2 - The Tagliamento end moraine system, an overlook from the lateral moraine of Canodusso

**Coordinates: Lat. 46°11'28"N, Long. 12°59'37"E**

The Tagliamento end moraine system is the largest (~220 km$^2$) morainic amphitheatre (Fig. 24) of the southeastern side of the Alps and was formed by the piedmont lobe of the Tagliamento glacier (Monegato et al., 2007). The glacier accumulation area encompasses the Carnic and western Julian Alps and Prealps with contribution by the Piave and Gail glaciers, respectively from the west and the north (Ivy-Ochs et al., 2022). The landforms that form the hilly landscape of the morainic aphitheatre are dated to the LGM, except for a smooth hill in the eastern sector ascribed to the Middle Pleistocene (i.e., the Plaino hill, Zanferrari et al., 2008b). The MIS 6 glacial deposits are buried, and crop out in the deep cuts of the Mordaro and Ponte creeks. Remnants of older glaciations are missing in the piedmont area, whilst they can be detected in the lower reach of the valley (Monegato and Stefani, 2011; Servizio Geologico d'Italia, 2013; Zanferrari et al., 2013).
The LGM piedmont lobe was shaped in four branches because of the presence of the bedrock hills of Ragogna, Susans and Buja that forced the glacier to split. The different stabilisation phases of the glacier front determined the shaping of the end moraine system and the frontal outwash plain, characterised by four distinct fans and megafans (Fig. 4, Fontana et al., 2010; 2014b). During phases of ice build-up, the glacier settled terminal moraines. Those related to the first spread (Santa Margherita phase, 26.5-25 ka cal BP) are the outermost ones and were reshaped by outwash rivers related to the second major advance at 23 ka cal BP (Canodusso phase); these latter are the most continuous and highest moraines of the system (Figs. 26 and 27). During the withdrawal phase, from 22 to 19 ka cal BP, the

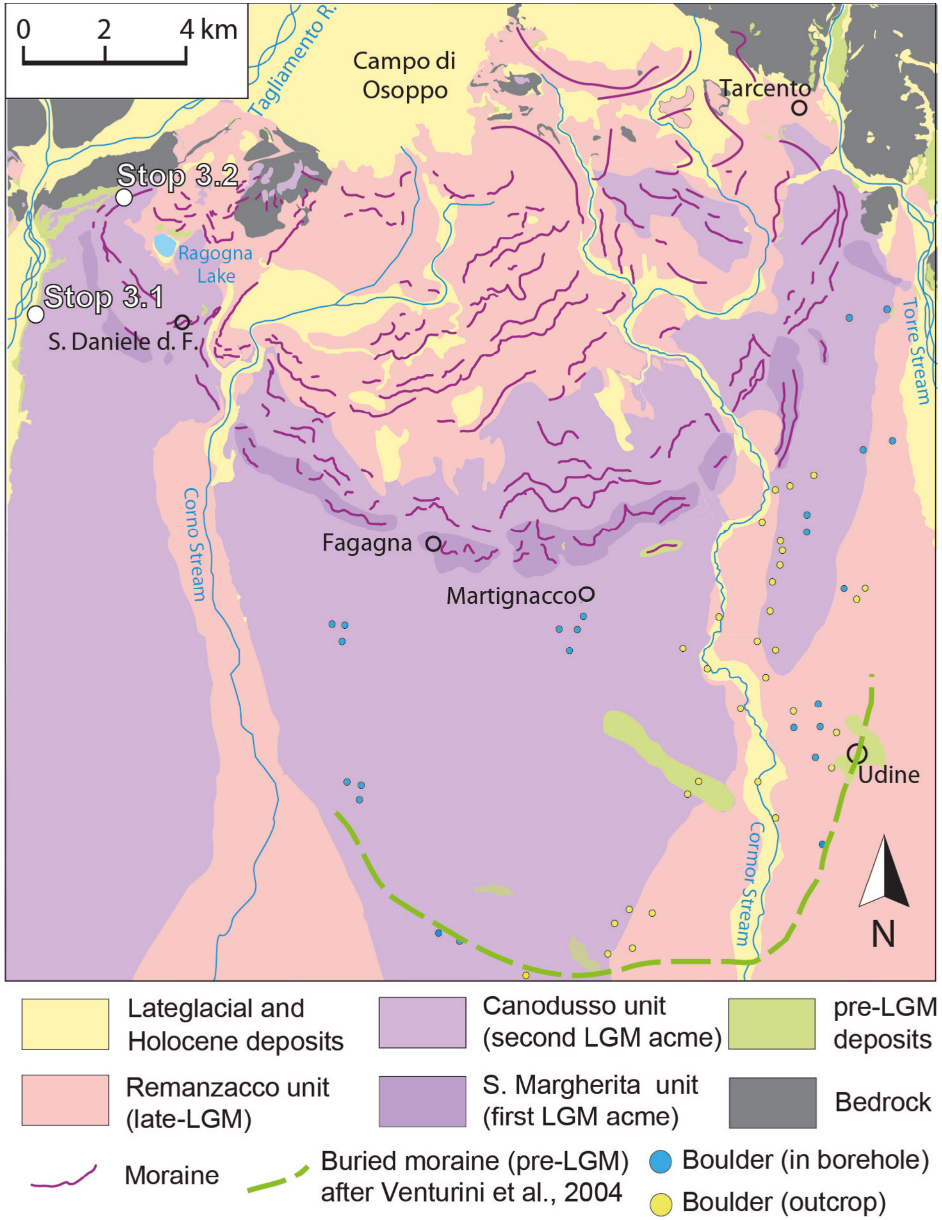


Fig. 26 - Geological map of the Tagliamento end moraine system and the related outwash plain (Modified after Monegato et al., 2020).

glacier front was definitively split in four branches, as can be detected by the shape of the frontal moraines, which form small amphitheatres and are separated by the bedrock hills. Among the ridges, many ephemeral lakes and ponds were created. Some of them survived as palustrine areas with peat formation from the Late Glacial to the Holocene (Marocco and Vaia, 1991; Zanferrari et al., 2008b). The outwash rivers of this phase were concentrated in four major paths: the present Tagliamento trench, the Corno di San Daniele Valley, the Cormor Valley and the Torre megafan (Fig. 24). The Corno and Cormor valleys deeply entrenched the end moraine system; along their cuts the stratigraphic successions can be observed in several large outcrops.

The chronological reconstruction of the Tagliamento glacier system during the LGM indicates that the ice tongues were very dynamic and can be considered warm-humid based glaciers (*sensu* Eyles et al., 1983), whose sliding bottoms were characterised by meltwater. The remnants of glacial lake outburst floods were recognised in the eastern sector of the outwash plain (Fig. 26, Monegato et al., 2020). The abundance of meltwater is also important considering the size and thickness of the outwash plain, where the average thickness of the LGM gravels is about 20 m (Fontana et al., 2010).

The Tagliamento end moraine system is the first glacial amphitheatre where different LGM glacier advances were dated (Monegato et al., 2007), thanks to the abundance of organic remains that were found buried by glacigenic sediments. These remnants, supported by palynological analysis, showed that the landscape surrounding the glacier snout was characterised by pioneering forest and tree groves (Monegato et al., 2007, 2015); moreover, the pollen record evidenced the first important cold oscillation in the Late Glacial at 16.5-15 ka cal BP (Ragogna oscillation). The growth of the vegetation during the LGM was supported by the high precipitation rates (Del Gobbo et al., 2023) that fed glaciers at the lowest ELA of the whole southern side of the Alpine range (Monegato, 2012; Rettig et al., 2021, 2023).

## Stop 3.3 - Pozzuolo del Friuli tectonic terraces

**Coordinates: Lat. 45°59’26”N, Long. 13°11’33”E**

The Pozzuolo terrace represents the surficial effect of the Pozzuolo Thrust System (POTS): a NW-SE oriented imbricate reverse fault system, which extends for about 30 km from San Daniele del Friuli to Trivignano, in the LGM Friuli Plain. POTS is characterised by a polyphase tectonic evolution, representing an inherited Palaeogene Dinaric front, reactivated also during the Miocene neo-Alpine phase. At present, the POTS accommodates deformation through slip-partitioning, with an oblique component on the NW-SE trending Pozzuolo 1 strand (POZ1) and dip-slip kinematics on the S-verging Terenzano Thrust (TZ) (Venturini, 1987; Venturini et al., 2002; Patricelli and Poli, 2020). TZ develops at the hanging-wall of Pozzuolo 1 Thrust and extends with an E-W trending, bordering towards the South the Pozzuolo relief. As shown on the SW-NE oriented geologic section of Figure 27, both POZ1 and TZ propagate upwards through the Pliocene-Quaternary succession, causing the outcropping of the Lower-Middle Miocene Cavanella group and the Pliocene-Quaternary conglomerate, and giving rise to the Pozzuolo high (Fig. 28 and 29).

https://doi.org/10.3301/GFT.2023.07

The isolated terrace extends between Sammardenchia to Pozzuolo over an area of about 5 km$^2$ and it rises for about 2-5 m. Only along the Cormor Torrent the river channel has been eroding a fluvial scarp of 11 m and lead the Miocene to crop out (n. 2 in Fig. 28). This site has been investigated by many scholars since the beginning of modern geology (e.g., Pirona, 1861; De Gasperi, 1909; Feruglio, 1920, 1925; Comel, 1946) and its palaeontological content was recently reviewed (Bizzarini et al., 2020).

The tectonic related landforms continue west of the Cormor Torrent with the terraces of Carpeneto, this setting clearly representing a case of antecedence, with the stream cutting through the hard Miocene and Quaternary bedrock during the uplifting activity. The raised terrace clearly affected the alluvial activity and represented an obstacle that could be overcome only west of Pozzuolo and east of Sammardenchia. Along these ways two gentle alluvial fans (n. 4 and 5 in Fig. 28) formed at the end of the LGM, when the Remanzacco subsynthem was forming (i.e., 22-19.5 ka BP). At that time the Cormor Torrent incised a wide valley upstream of Pozzuolo, while aggraded downstream.

Over the terrace, pre-LGM gravels are the dominant lithology, and they can be locally cemented. Polycyclic soils evolved on this parent material, with profiles up to 3 m thick and characterised by Bt horizons up to 5YR in colour (Figs. 30A and 30B). Significant erosion affected the surface of the terrace that has been largely remodelled by the evolution of the hydrographic network and, in the last millennia, by

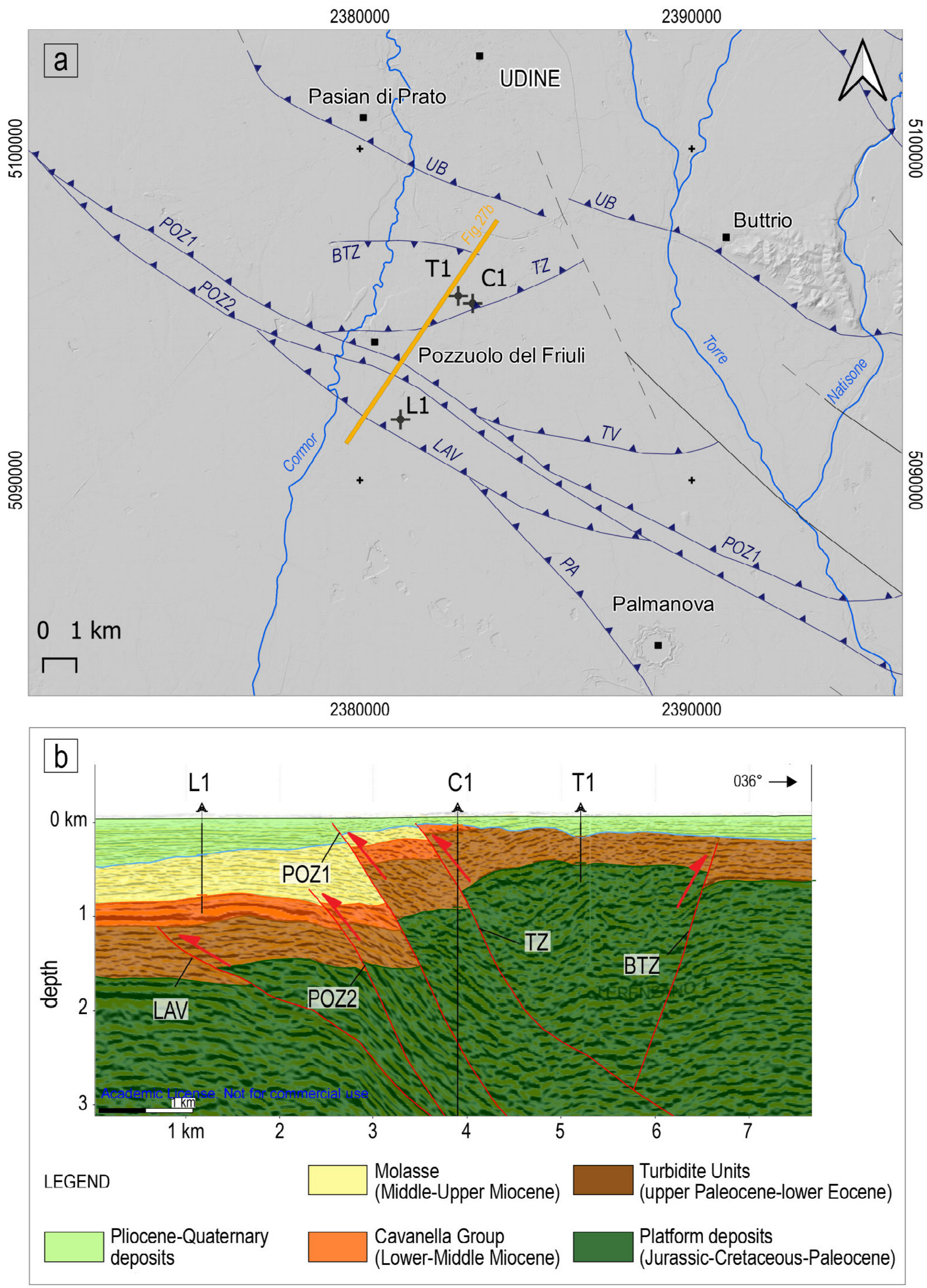


**Fig. 27 - A) shaded relief map of the Pozzuolo del Friuli area (orange line: section trace of Fig. 27B), B) geological cross-section, derived from the conversion of interpreted ENI seismic line, across the Pozzuolo terrace showing the structure of the Pozzuolo Thrust System. Acronyms: BTZ: Terenzano Backthrust; LAV: Lavariano Thrust; PA: Panzano Thrust; POZ1 and 2: Pozzuolo1 and 2 Thrusts; TV: Trivignano Thrust; TZ: Terenzano Thrust; UB: Udine-Buttrio Thrust. C1: Cargnacco; L1: Lavariano; T1: Terenzano exploration wells.**

anthropogenic activity. Over the Pozzuolo terrace sparce traces of early-Neolithic villages are documented, especially in the Cûeis area (n. 1 in Fig. 28), dating back to 5500-4800 BCE (Fontana and Pessina, 2011 and references therein). The extensive archaeological excavations carried out in the area led to the recognition of loess deposits draping the topography, with thicker accumulation in the pre-existent topographic

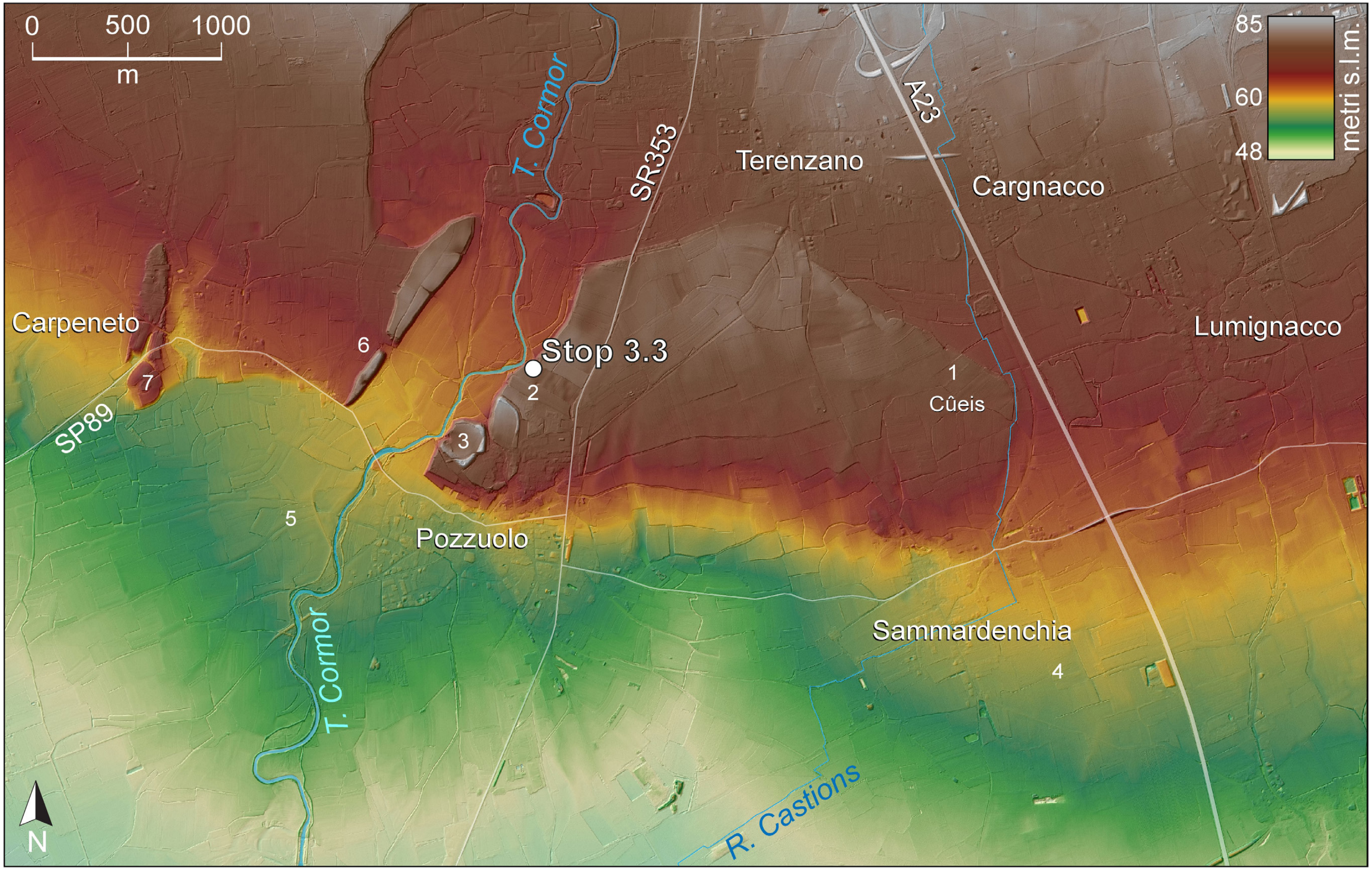


Fig. 28 - Digital elevation model from LiDAR data (mod. after Fontana and Ferrari, 2020). 1) Area of archaeological excavations of Cûeis 1985-2005; 2) Miocene outcrop; 3) Castelliere; 4) and 5) alluvial fan; 6) Eastern hill of Carpeneto, War Memorial; 7) Western hill of Carpeneto S. Michele.

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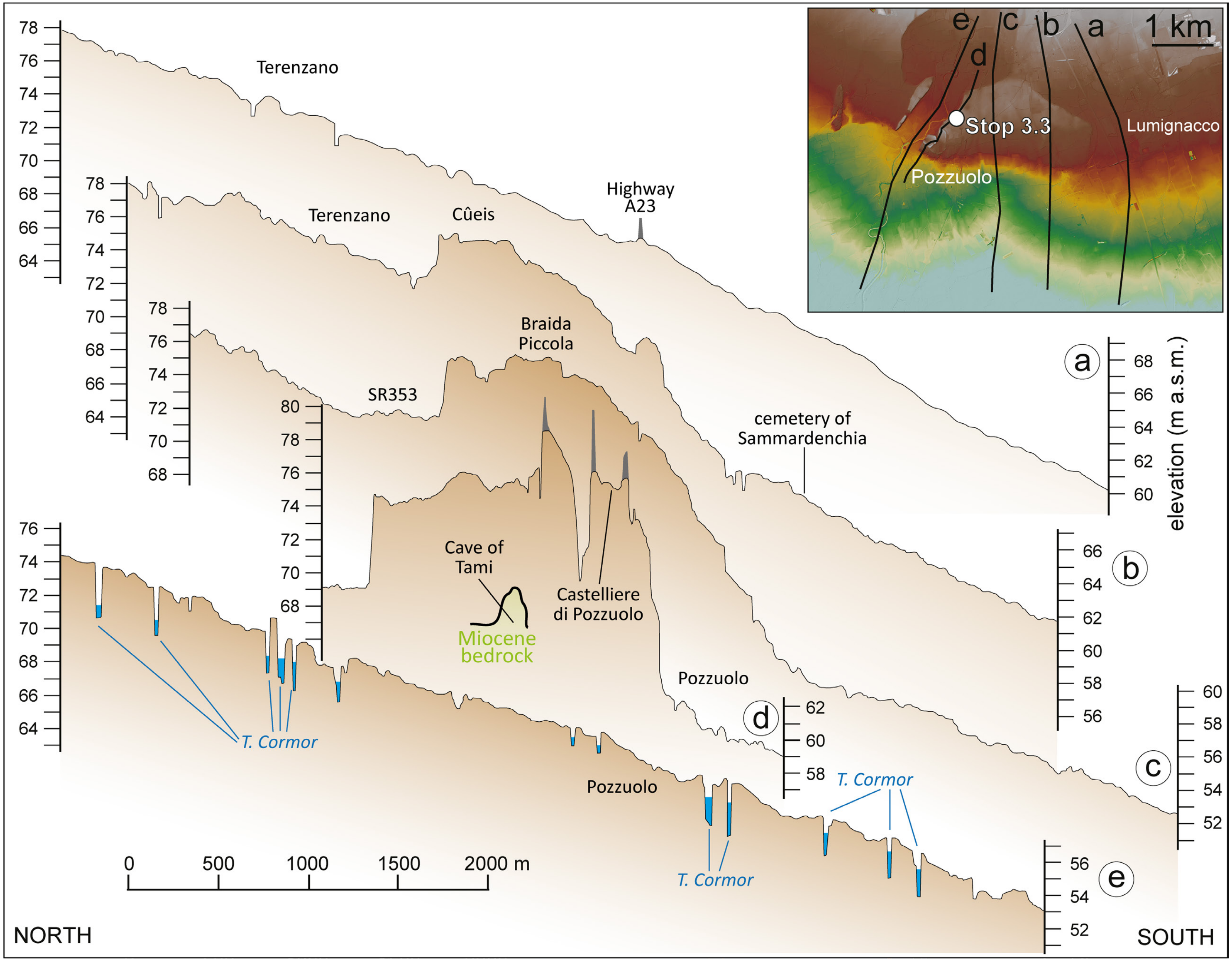


Fig. 29 - Topographic profiles perpendicular to the slope of the plain (Modified after Fontana and Ferrari, 2020). For the location, see the black traces indicated in the inset map at the top right.

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depressions (Fontana and Ferrari, 2020). The loess-like deposits are characterised by a yellowish colour and typical prismatic structures (Fig. 30B). These sediments deposited during the LGM and probably, in some parts, also during previous glacial phases, allowing to infer a minimum age of the terrace of 130 ka.

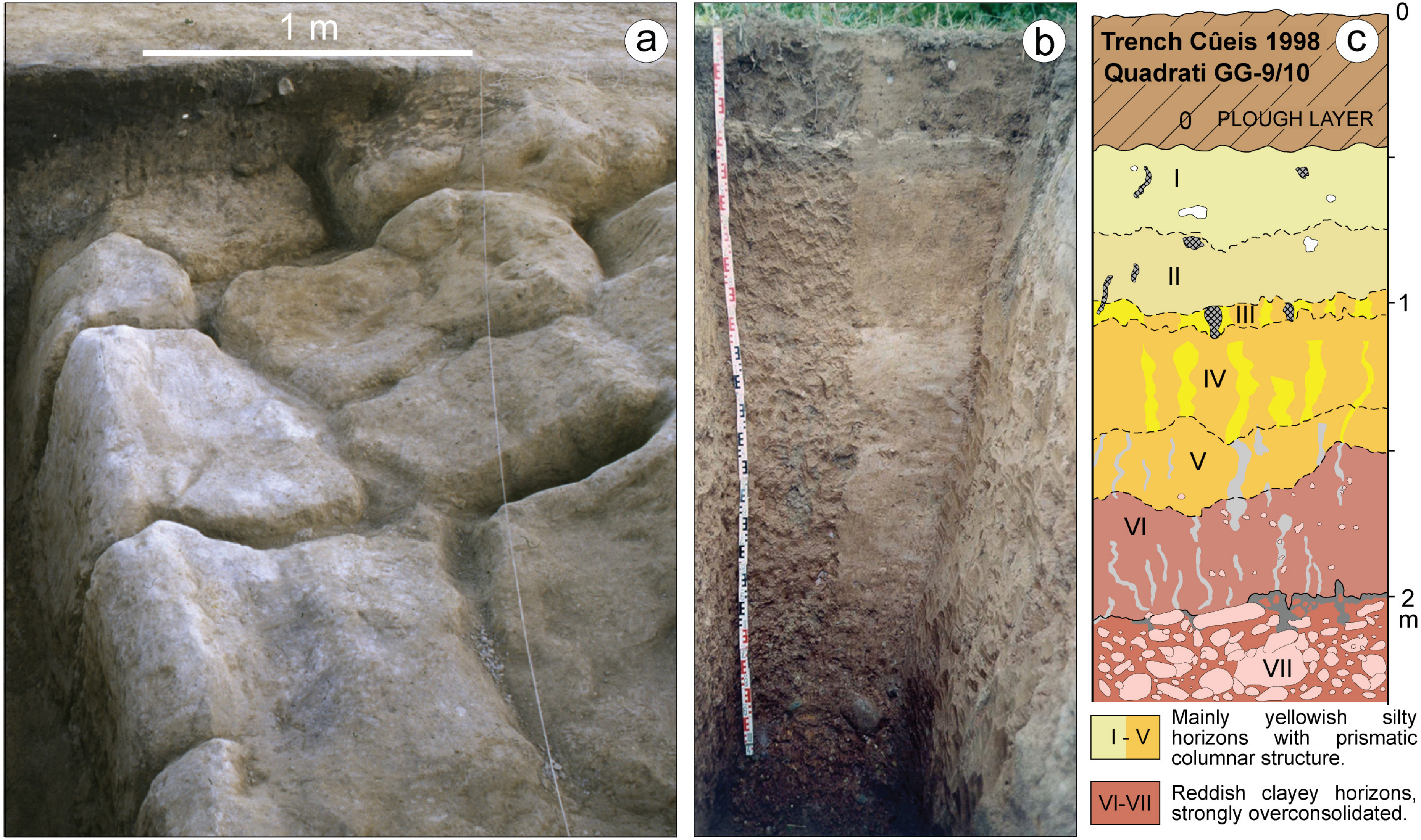


Fig. 30 - Pedo-stratigraphic profile and plan view of the deposits cropping out in Cûeis (see Fig. 28 for location), near Sammardenchia, at the easternmost sector of the Pozzuolo terrace. A) Plan view of the prismatic structure of the loess exposed during the archaeological excavation at Cûeis (2001); B) Photo of pedo-stratigraphic profile (1998); C) Detailed log of profile B).

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*Manuscript received 17 February 2023; accepted 05 July 2023; published online 21 September 2023;*
*editorial responsibility and handling by M. Massironi.*