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Late Quaternary landscape evolution of the buried incised valley of Concordia Sagittaria (Tagliamento River, NE Italy): A reconstruction of incision and transgression

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ABSTRACT

While recent landscape changes can be usually easily read through accessible morphological features, relatively ancient processes can be difficult to detect as the associated morphologies and deposits are often buried below younger sediments. With the aim of understanding the evolution of the distal Venetian-Friulian Plain (NE Italy) after the Last Glacial Maximum (LGM), this work presents the analysis performed on a dataset of ca. 2300 mechanical and hand-made cores, which allowed a detailed reconstruction of the formation and evolution of an incised valley, now almost completely filled and with little to absent morphologic expression. Such valley, up to 1.2 km wide, with a depth of 20 m below the LGM alluvial plain and traced for a length of 25 km, is the result of the complex interplay between minor spring-fed rivers and the Tagliamento River. The detailed characterization of the infilling allowed to identify two main phases in the valley evolution. The first one is related to the activity of the paleo Tagliamento River and led to the deposition of a 10 m thick gravelly unit (ca. 19–9.5 ka cal BP). The second phase, which followed a disconnection of the Tagliamento, is linked to the Holocene marine transgression and led to the formation of a lagoon environment within the valley and to the deposition of a ca. 15 m thick unit of lagoon muds (ca. 8 ka cal BP - historic time). This latter unit lays on top of gyttja deposits, indicating for the first time in this area the presence of widespread lacustrine environments in the Early Holocene. This work presents an in-depth analysis on the evolution of a distal plain incised valley, from its formation to its final filling, providing at the same time the means to describe the development of the entire alluvial plain landscape, spanning from the end of the LGM to the middle Holocene. We present new data on the paleoenvironmental and morphologic evolution of the Venetian-Friulian Plain area as a consequence of the interplay between autogenic forces and sea-level rise. Our study allowed to understand the importance of both Alpine rivers and groundwater-fed streams in the formation of large incised valleys in the coastal sector of the whole Venetian-Friulian Plain. Finally, as during the transgressive phase the upstream sediment input in the valley was almost absent, this study provides insights into facies and architecture of a rare example of downstream-controlled filling of an incised valley.

1. Introduction

Incised valleys have been thoroughly investigated through a wealth of studies in the last 30 years (e.g. Thomas and Anderson, 1989, 1994; Zaitlin and Shultz, 1990; Dalrymple et al., 1992; Posamentier and Allen, 1993; Allen and Posamentier, 1993; Blum and Törnqvist, 2000; Boyd et al., 2006; Blum et al., 2013). Quaternary incised-valley fills can provide outstanding paleogeographic and paleoenvironmental archives, as they often preserve the only available records over significant time periods (e.g. Vis and Kasse, 2009; Simms et al., 2010; Bogemans et al., 2016; Clement and Fuller, 2018). These features gain value also in the light of source-to-sink studies, especially linked to the evaluation of sediment budgets (e.g. Mattheus and Rodriguez, 2011; Blum et al., 2013; Bhattacharya et al., 2015).

Excluding the formation of localized fluvial incisions as a consequence of the confluence of different river channels (Best and Ashworth, 1997; Gibling et al., 2011), or due to dramatic fluctuation in the water/sediment ratio, the most accepted and widespread paradigm that explains the downcutting of incised valleys is the lowering of base level. This is normally associated to tectonics, river capture or sea-level drops (Schumm, 1993; Bridge, 2003). Due to the onset and magnitude

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increase of the glacial-interglacial cycles, marine forced regressions have been a rather frequent condition for the worldwide continental shelves and coastal plains during the Quaternary Period. Incised valleys scattered over the world are witnesses of the last sea-level drop and lowstand phase associated to the Last Glacial Maximum (e.g. Lericolais et al., 1998, 2001, 2003; Blum and Törnqvist, 2000; Huuse and Lykke-Andersen, 2000; Lin et al., 2005; Nordfjord et al., 2005, 2006; Mattheus et al., 2007; Chaumillon et al., 2008, 2010; Vis and Kasse, 2009; Amorosi et al., 2009, 2012, 2013, 2016; Ngueutchoua and Giresse, 2010; Labaune et al., 2010; Tanabe et al., 2010, 2013; Estournès et al., 2012; Green et al., 2013; Tropeano et al., 2013; Blum et al., 2013; Longhitano et al., 2015; Breda et al., 2016; Peeters et al., 2016; Gregoire et al., 2017; Gibbard et al., 2017; De Clercq et al., 2018). In post-LGM times, most of these valleys were transgressively infilled in the interplay between continental and marine processes owing to post-glacial sea-level rise. Shoreline transgression, shelf drowning and sedimentary infill obliterated the morphologic expression of many incised valleys (e.g. Maselli and Trincardi, 2013; Maselli et al., 2014; Martínez-Carreño and García-Gil, 2017), while portions of incised valleys located in the vicinity of eventual highstand coastlines remain morphologically recognizable because they host estuaries or rias/limans (e.g. Simms et al., 2010; Traini et al., 2013).

Exceptions and variants to the above typical Late Pleistocene incised valleys also exist, notably in alluvial regions with strong shifts in sediment supply that occurred concurrently with the LGM to Holocene sea-level rise, but followed a climatic response rather than a base-level response (e.g. the outwash plains of LGM-glaciated areas; Dobracki and Krzyszkowski, 1997; Marchetti, 2002; Fontana et al., 2014b; Weckwerth, 2018). Such mechanisms were also in play in the Venetian-Friulian Plain, at the foot of the Dolomites and south-eastern Alps (Fig. 1), where a series of incised valleys connected to river occurring across the Adriatic shelf formed (Fontana et al., 2008, 2014a; Ronchi et al., 2018). The downcutting of such valleys, which functioned in the Lateglacial and Early Holocene, only began after the LGM, owing to a decrease of sediment supply that followed the withdrawal of the mountain glaciers from lower alpine valleys, as documented for the alluvial megafans of Brenta (Mozzi et al., 2013), Piave (Carton et al., 2009), Tagliamento (Fontana, 2006; Fontana et al., 2008, 2012) and Isonzo rivers (Arnaud-Fassetta, 2003). For the Tagliamento River in particular, several post-LGM fluvial incisions into the megafan surface have been recognized (Fig. 1), the most investigated one running from the area of Cordovado to the Caorle Lagoon (Figs. 1 and 2). We here refer to this system as the Concordia Incised Valley (CIV), as this landform played an important role in the story of the Roman city of *Iulia Concordia* (the modern Concordia Sagittaria).

The CIV has been already described in several works, although, until now, the available reconstructions were based on a single stratigraphic section (section A-A' in Figs. 2, 3) and some other scattered subsurface cores (Fontana et al., 2004, 2008, 2012, 2014a; Fontana, 2006). The work presented in this paper reports the analysis performed on a database of about 2300 new cores which allowed to describe with an unprecedent resolution the buried morphology and the characteristics of the infilling of the Concordia incised valley. Being located within few kilometres both from the margin of the SE Alps and from the coastline, the inception and evolution of this incised valley has been strongly influenced by both upstream and downstream controls. Study of its development and filling could thus provide a comprehensive overview on the evolution of the entire northern Adriatic area during the last 20 ka, highlighting the interplay between fluvial and marine processes.

The aim of this paper is to describe in detail the morphology of the CIV and the chrono-stratigraphy and architecture of its infill, providing a reference case for the recognition, interpretation and understanding of the filled incised valleys which characterize the NW Adriatic coast, as well as reference sedimentary archive for sea-level science, vegetation history and archaeology. Such features often represent one of the major unknowns in the subsurface of coastal plains, being difficult to be detected and presenting peculiar geotechnical characteristics, often related to differential subsidence (cf. Floris et al., 2019). Due to the peculiarity of its morphology, which provided isolated terraces and a direct water way to the Adriatic Sea, the CIV represented an interesting environment for the development of ancient human settlements. This study wants also to produce some data for understanding the geomorphological constrains which affected the occupation history of the Venetian-Friulian Plain, thus providing support to the archaeological research.

2. Regional setting

This research considers the distal sector of the alluvial megafan of the Tagliamento River in the Friulian Plain. The Tagliamento is one of the major rivers in the SE Alps (Fig. 1B). Its 2700 km^2 catchment area consists for over 70% of carbonate rocks (limestones and dolostones), its mean annual discharge is about 90 m^3/s with a peak discharge for a flood with recurrence time of 100 years of about 4500 m^3/s (Surian and Fontana, 2017).

From a tectonic point of view, the Friulian Plain is characterized by the interaction between the Alpine south-verging thrust and fold belt and the NW-SE thrust belt of the Dinaric Alps (Ghielmi et al., 2010). The main active tectonic thrusts run along the mountain front and can generate important earthquakes (e.g. 1976 event, Mw 6.5; Burrato et al., 2008). In the proximal portion of the alluvial plain, only minor active faults are documented, some of which deformed the late-Quaternary deposits ("tectonic terraces"; Galadini et al., 2005; Monegato and Poli, 2015). The alluvial plain occupies the Alpine foredeep basin and experiences long-term subsidence. An average vertical velocity of −0.4 mm/a has been assessed since the last interglacial between the terminal tracts of the Tagliamento and Piave rivers based on geological data (Antonioli et al., 2009), while present subsidence rates can be locally up to −10 mm/a according to satellite and ground measurements (Serpelloni et al., 2013; Floris et al., 2019).

In the area, some 20 to 35 m of fluvial and fluvioglacial deposits aggraded mainly during the Last Glacial Maximum (LGM, 29–19 ka cal BP; Clark et al., 2009), forming a megafan distributary fluvial system (Fig. 1; Fontana et al., 2008). At that time, the ongoing sea-level fall started before the LGM had led the Adriatic continental shelf to be exposed for over 300 km south of the present coastline (Pellegrini et al., 2017), while a major glacier system occupied the Tagliamento River catchment, with its terminus at the mountain front (the modern valley mouth, Castiglioni, 2004), supplying the megafan system. The huge sedimentary load was redistributed by outwash streams, fostering the formation of the Tagliamento megafan, which is the main element of the modern landscape of the alluvial plain.

During a final LGM glacial expansion ("Canodusso" phase, ca. 24–22.5 ka cal BP; Zanferrari et al., 2008a; Monegato et al., 2017) a pulse of coarse material, traceable for some 15–25 km downstream the glacial front, was transported along the megafan river channels, while beyond that distance only sand and fine sediments were delivered, feeding a network of further bifurcating channel systems, separated by relatively small flood basins that characterized the distal sector of the megafan. This contrast in dominant grain size (subsurface lithology) and resultant fluvial style (subsurface architecture) is marked by a spring belt (Fig. 2, see also below). Between 22.0 and 19.5 ka cal BP the glacier started its retreat, abandoning the terminal moraines and forming several recessional moraines (Fig. 1; Monegato et al., 2007; Fontana et al., 2014b). During this period ("Remanzacco" phase), the Tagliamento River incised the apex of its megafan for about 15 m (relative to the top of the deposits of the Canodusso phase; Zanferrari et al., 2008a, 2008b). The coeval development in the distal sector was a depositional phase producing several narrow alluvial ridges characterized by gravelly sandy channel deposits flanked by sandy loamy natural levee deposits (Fontana et al., 2008, 2014b). After 19.0 ka cal BP, the major phase of entrenching, responsible for the incised valley systems that are the topic of this study, started affecting both the proximal and the distal

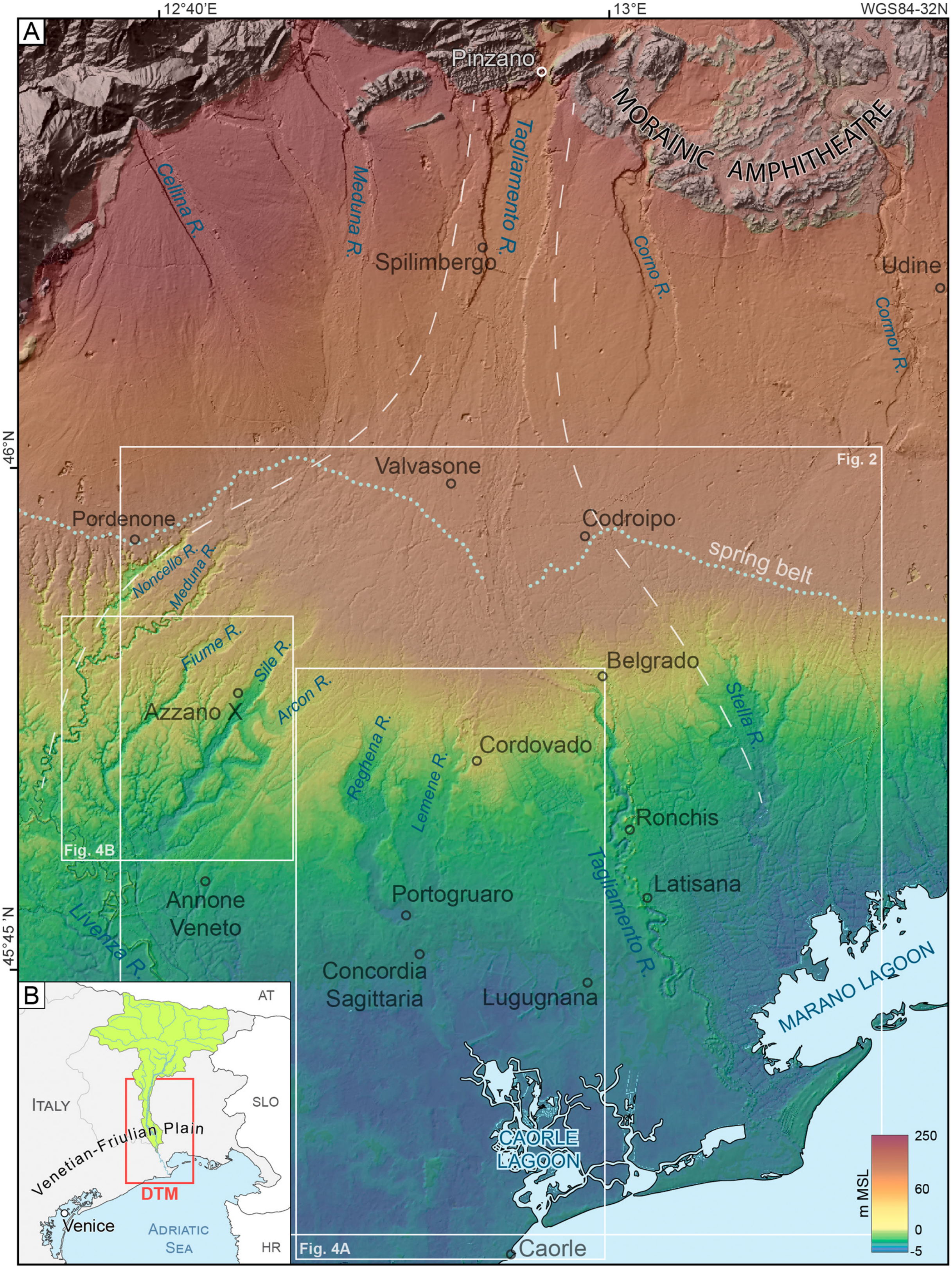


Fig. 1. A) DTM of the Tagliamento Megafan and position of the principal localities in the study area (modified from Surian and Fontana, 2017). B) the green area represents the hydrographic catchment of the river.

sectors. At the very apex of the megafan (Fig. 1, downstream of Pinzano), this incision reaches 70 m depth, measured between the top of deposits of Canodusso phase and the bar tops of the modern channel. Previous studies recognized several incised valleys formed by the Tagliamento River in its distal reach. In particular, besides the CIV, other large incised valleys have been documented below the Roman period Tagliamento reach ("*Tiliaventum Maius*" #7 in Fig. 2; Fontana, 2006) and below the present course of the Tagliamento downstream

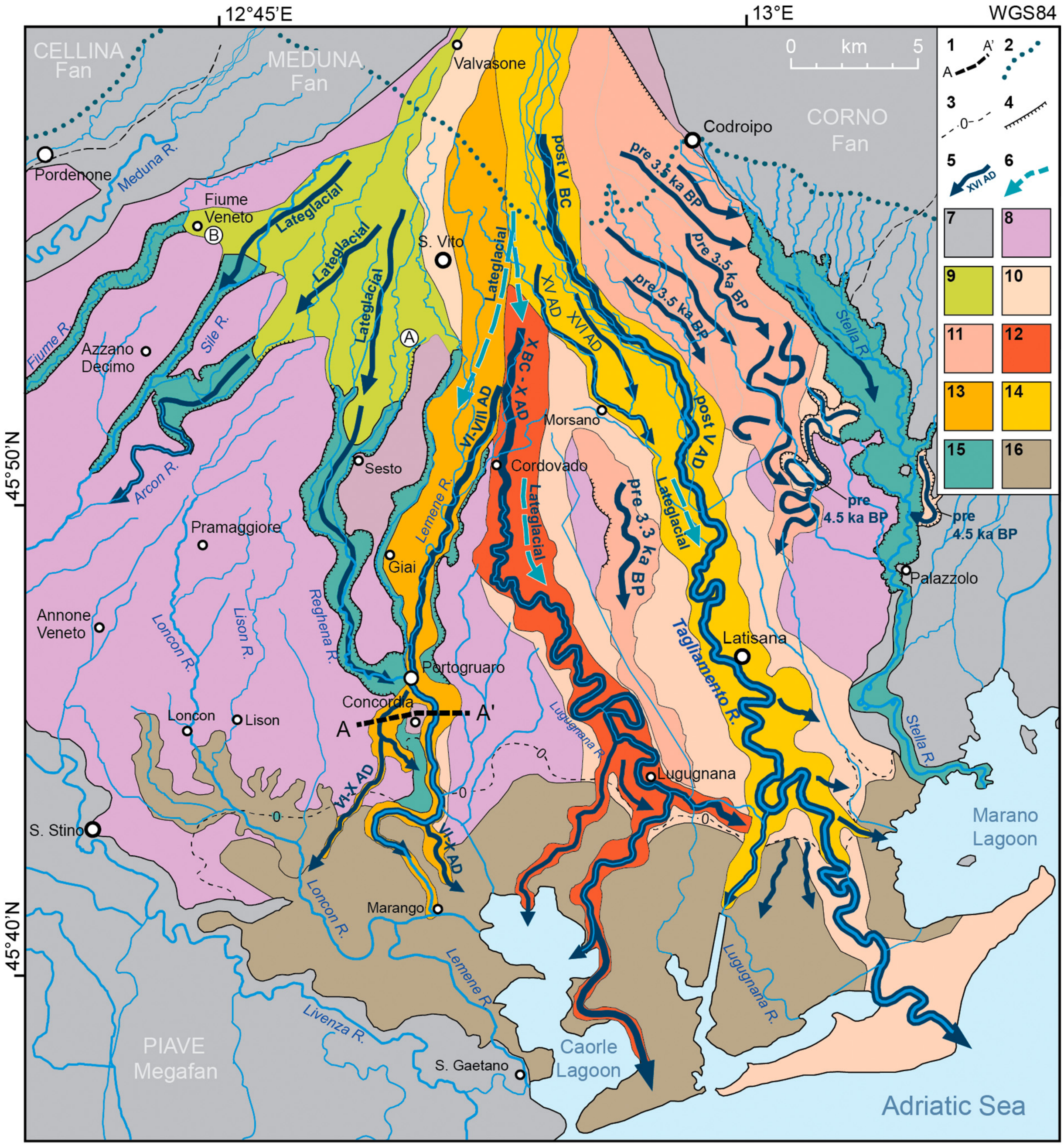


Fig. 2. Simplified scheme of the Tagliamento River evolution during post-LGM (last 17 ka), modified after Fontana (2006). Legend: 1) Trace of stratigraphic section in Fig. 3; 2) Upper limit of the spring belt; 3) Contour line 0 m MSL; 4) Fluvial scarp; 5) Channel belt, with indication of the period of activity; 6) Buried Lateglacial Tagliamento River courses; 7) Deposits of other fluvial systems; 8) LGM alluvial plain deposits; 9) Lateglacial deposits; 10) Undifferentiated post-LGM deposits; 11) Undifferentiated deposits: 3.0–3.5 ka cal BP; 12) Deposits of the Tagliamento River: 1st millennium BCE − < 8th century CE (*Tiliaventum Maius* branch); 13) Deposits of the Tagliamento River: < 6th − 8th century CE (*Concordia* branch); 15) Depressed areas hosting groundwater fed streams; 16) Lagoon deposits: last 5.0 ka.

of Morsano (#5 in Fig. 2). All these entrenched landforms are now almost completely filled by younger sediments. In boreholes, the incised systems at their base are characterized by gravelly deposits, which helped their recognition even with few subsurface data (Fontana, 2006; Zanferrari et al., 2008c; Fontana et al., 2012, 2014a).

The LGM strongly imprinted also the successive hydrographic setting, as the boundary between coarse (more permeable) and fine sediments (less permeable), which formed during the LGM sediment supply acme, corresponds to the upper limit of the spring belt (Fig. 2). Along this belt part of the groundwater is forced to the surface and feeds a dense network of minor streams. These groundwater-fed rivers are characterized by a rather steady water discharge during the year, while their sedimentary load is almost null (Feruglio, 1925; Comel, 1950; Minelli, 2001). The surface of the distal sector of the megafan is therefore dissected by a slightly entrenched fluvial network, arranged into a diverging pattern (#14 and 15 in Fig. 2; inset B in Fig. 4). These scarps generally confine the major groundwater-fed streams of the area (Stella, Lemene, Reghena, Sile, Arcon and Fiume rivers; cf. Comel, 1950, 1958; Fontana, 2006; Fontana et al., 2014a). In the time following the LGM, while in the apical portion of the megafan the Tagliamento River became confined, in the distal portion aggradational and avulsive activity continued longer (Fig. 2; Fontana, 2006).

The relative sea level arrived in the present coastal areas around 7.5 ka cal BP (Amorosi et al., 2008; Vacchi et al., 2016) leading to the submersion

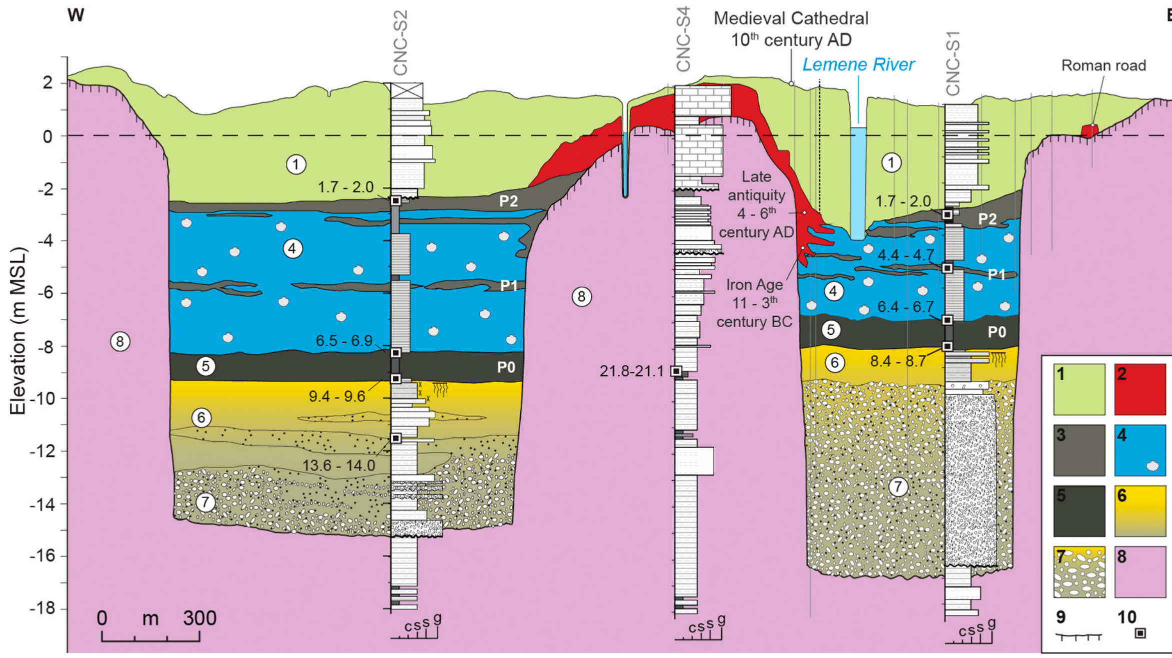


Fig. 3. Reference cross section of the stratigraphic setting near Concordia Sagittaria (modified after Fontana, 2006, 2015; A-A' in in Fig. 2). Legend: 1) Medieval sandy deposits of Tagliamento River; 2) Archaeological remains; 3) Peat layers; 4) Middle-late Holocene lagoon deposits; 5) Fresh-water peat and gyttja; 6) Sandy and silty deposits of Early Holocene; 7) Gravels of Lateglacial and Early Holocene; 8) LGM alluvial deposits; 9) Well-developed soil; 10) Radiocarbon dating (ka cal BP).

of the distal portion of the megafan. The oceanographic reconstruction shows a rather constant wave-climate and the onset of a micro tidal regime in the area through the Mid to Late Holocene (Storms et al., 2008).

Human presence in the area is documented between the end of Neolithic and ancient Bronze Age (ca. 6.0–4.0 ka cal BP) by some small sites located along the incised valley south of Concordia (Fontana, 2006; Rossignoli et al., 2014; Fontana et al., 2018). An important phase of settlement started during the recent Bronze Age, with two major sites existing in the area of Concordia and near S. Gaetano (Fig. 2; Balista and Bianchin Citton, 1994; Bianchin Citton, 1996; Fontana et al., 2017). During the Iron Age Concordia flourished as an important city within the cultural group of the Veneti and since 42 BCE it became a Roman Municipium. The collapse of the Roman Empire and the Medieval floods of Tagliamento caused a partial, although never complete, abandonment of the city (Croce Da Villa and Di Filippo, 2001; Fontana et al., 2019a and references therein). The last major landscape modification in the study area took place between the 6th and 8th centuries CE, through the avulsion that brought the Tagliamento to temporarily abandon the *Tiliaventum Maius* branch and reactivate the *Concordia Sagittaria* one, definitively sealing the CIV (#6 in Fig. 2). The avulsion can be seen as a natural process (potentially triggered by a hydrological extreme event, a “diluvium”; Fontana et al., 2019a), but it was helped by the human changed circumstances in the hinterland and foreland following the collapse of the Roman Empire (Late Classic / Dark Ages / Migration Period times). Large sectors of the Caorle Lagoon had been reclaimed since the beginning of the 20th century and currently about 140 km^2 are artificially drained between Tagliamento and Livenza rivers (Fig. 2).

3. Material and methods

3.1. Lidar DTM

The surface morphology of the study area was investigated analysing a Digital Terrain Model (DTM, MATTM, 2008) obtained by airborne Laser altimetry (LiDAR: Fig. 4). For the territory pertaining to the Veneto Region these data have a cell size of 1 m^2 and a vertical accuracy of ±0.10 m. In the Friuli Venezia Giulia Region, the LiDAR data have a cell size of 1 m^2 and a vertical accuracy of ±0.15 m. They were collected in 2006 by the regional department of Civil Protection (www.irdat.fvg.it). The DTM presented in this work was obtained considering the last returns of the signal, which is representative of the ground (Fig. 4).

3.2. Stratigraphic data and chronology

Two datasets of stratigraphic cores were used (Fig. 5). A first database of ca. 500 cores and ca. 70 cone penetration tests was provided by the environmental office of the Città Metropolitana di Venezia containing log descriptions of cores and penetration tests collected in the last 40 years (cf. Bondesan et al., 2008). These data were acquired mostly for geotechnical purposes (construction of buildings, roads, bridges, wells), and from a geological point of view were placed randomly over the area. These cores cover an investigation depth generally ranging from 6 to 30 m, with a small number reaching down to 70 m. While some of the logs are detailed, most of them are too generic to allow geological interpretation. As a whole, this dataset proved useful in discriminating major sedimentary units such as the “LGM” megafan deposits, main Lateglacial and Holocene fluvial channel deposits and the Holocene coastal plain deposits (e.g. Formations in Bondesan et al., 2008).

A second database of ca. 1800 cores, all hand cored, was established by the authors and their students (Dept. of Physical Geography, Utrecht University, in collaboration with Geosciences Dept., University of Padova), between 2012 and 2019, during didactic fieldworks held in the study area (Fig. 5). The coring equipment consisted of Edelman and gouge hand augers, respectively for sampling above and below groundwater. Van der Staaij suction corers were used for sampling waterlogged sand deposits (Van de Meene et al., 1979; Wallinga and Van der Staay, 1999). This combined equipment allowed to reach a mean investigation depth of ca. 5 m, with a maximum reached depth of 19 m (hand gouged). These cores were logged at fixed ten centimetres resolution, for texture of sediments (of clastics and of organics), colour, carbonate content (field-tested via reaction to 1 M HCl), visible macrofossils such as brackish and fresh water molluscs (for common species with indication of the genus) and plant debris (e.g. reed, wood). The texture of

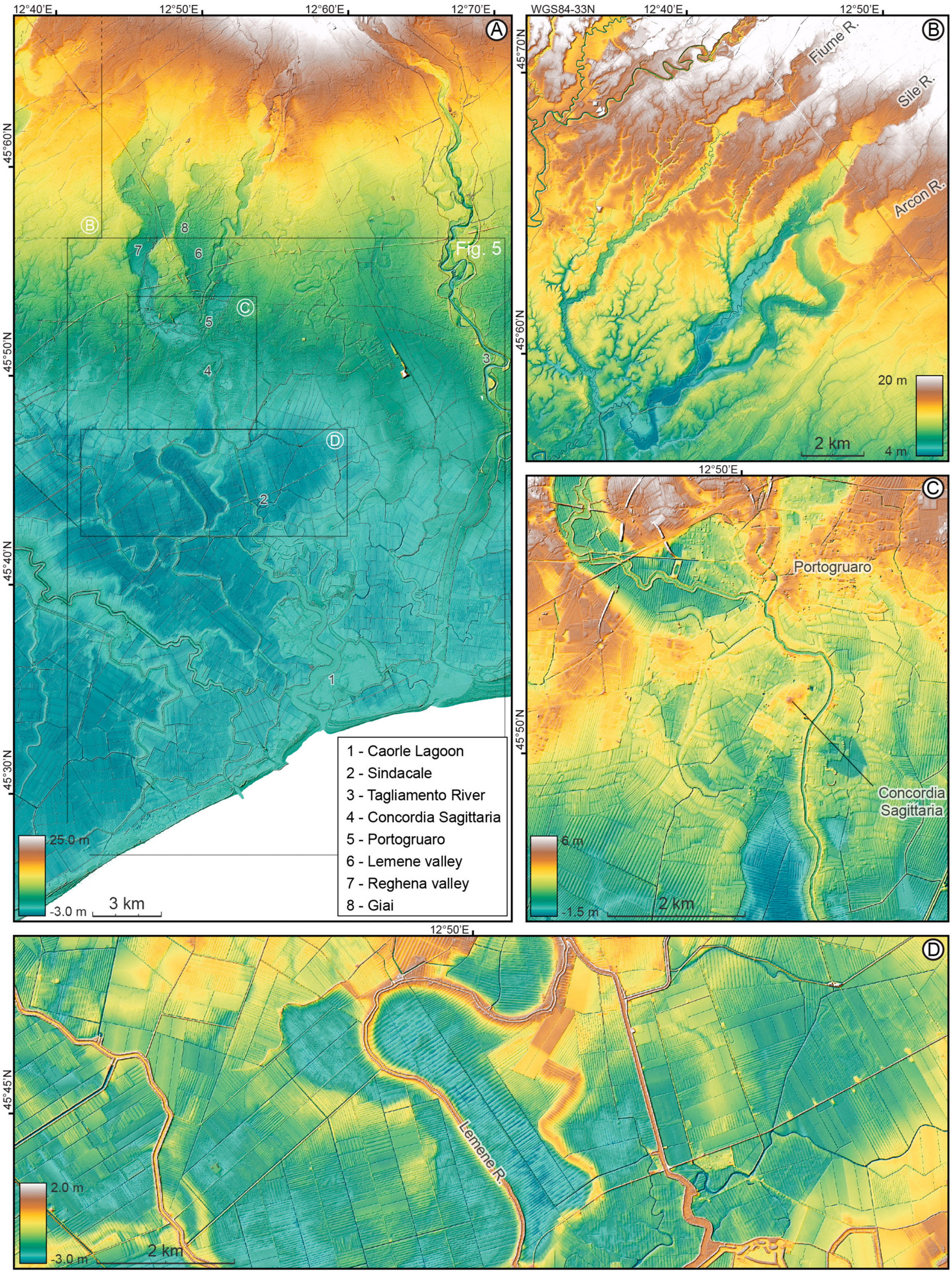


Fig. 4. Lidar-derived DTM of the study area.

clastic sediments was logged according to USDA classification (cf. Thien, 1979; FAO-ISRIC, 2006). Sand grain size class (>63 μm) was estimated by comparing to a field reference ("sand ruler"). The hand cores were placed along strategically planned cross-section lines, with a typical spacing of ca. 100 m (densified over certain features). The details on paleoenvironments in the different stages of the buried incised valley evolution in this work are based on this latter dataset.

A series of 21 radiocarbon dates, calibrated with IntCal13 (Reimer et al., 2013), where obtained on samples from cores of the two databases and are used for constraining the evolution of the

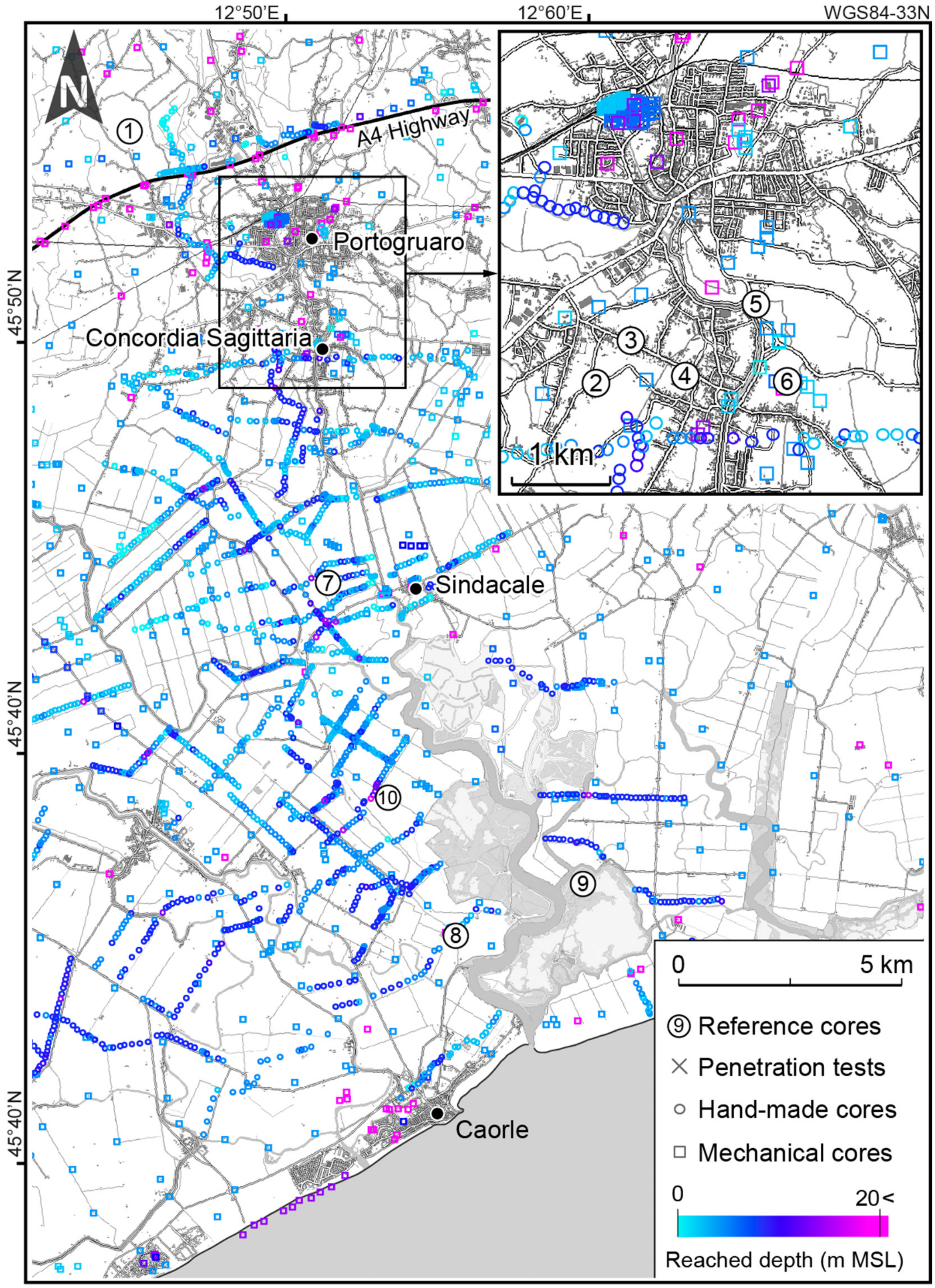


Fig. 5. Location of the cores considered in this work. Location of notable cores with dated samples: (1) SUM1; (2) CNC-S2; (3) CNC-Alte; (4) CNC-S4; (5) CNC6493400; (6) CNC-S1; (7) UU-170624; (8) CNC-S3; (9) Rocca2; (10) FRA1. All the dates are reported in Table 1. The location of the area is shown in Fig. 1.

reconstructed features (Table 1). Further information on the age of the depositional units has been also provided by the comparison with the chronology of the widespread archaeological sites found in the area, especially for the Roman period (cf. Fontana, 2006; Fontana et al., 2017, 2019a). All the available data were stored and analysed in a GIS environment through the software ArcMap (ESRI). For all the collected coring data, surface elevation was resampled using the LiDAR DTM of the area, in order to calculate the absolute height of contacts (m MSL).

3.3. Subsurface reconstruction

The reconstruction was performed by producing a series of cross-sections (transects, cf. Section 4) based on sedimentological (facies, architectural elements) and stratigraphical (cross-cutting relationships, geochronological constraints) correlations among the different deposits described in the borehole logs. Using the information obtained from interpreting the cross-sections, a detailed 3D reconstruction of the main discontinuity recognizable in the subsurface, i.e. the unconformity

Table 1
Radiocarbon dates available in the area. The location of the samples is provided in Fig. 5. Source: a – Fontana (2006); b – this work; c – Donegana et al. (2005); d – Zanferrari et al. (2008c).

#	Lab code	Core	Lat N	Lon E	Height (m)	Sample depth (m)	Meaning	^{14}C age (a BP)	Calibrated 2σ age (a BP)	Median (a BP)	Source
1	Beta-184395	CNC6493400	45.763	12.85	1	4.00	P2	1910 ± 80	1690–2041	1851	a
2	Beta-184249	CNC-S2	45.756	12.83	1.6	5.54	P2	1920 ± 60	1717–1992	1864	a
3	LTL4967A	CNC-Alte	45.759	12.83	1.7	4.30	P1	3998 ± 45	4382–4581	4477	a
4	Beta-184247	CNC-S1	45.757	12.85	1.1	6.18	P1	4080 ± 70	4424–4729	4601	a
5	Beta-184248	CNC-S1	45.757	12.85	1.1	8.10	Top P0/Base Lagoon	5700 ± 70	6390–6656	6494	a
6	Ua-24876	Rocca2	45.647	12.93	0.3	5.45	Top P0/Base Lagoon	5730 ± 45	6432–6638	6527	a
7	Beta-184250	CNC-S2	45.756	12.83	1.6	10.38	Top P0/Base Lagoon	5910 ± 70	6553–6913	6736	a
8	Beta-184251	CNC-S3	45.652	12.89	−1.4	7.19	Top P0/Base Lagoon	6080 ± 80	6747–7164	6952	a
9	ETH-87035	UU-170624	45.706	12.85	−0.2	14.80	Top P0/Base Lagoon	7006 ± 30	7784–7934	7850	b
10	Ua-24872	CNC-S1	45.757	12.85	1.1	9.26	Bottom P0/Top U1	7785 ± 65	8415–8727	8563	a
11	ETH-107110	FRA1_1346	45.664	12.87	−2.0	13.46	Bottom P0/Top U1	7809 ± 27	8521–8642	8580	b
12	ETH-87036	UU-170624	45.706	12.85	−0.2	15.50	Bottom P0/Top U1	8064 ± 28	8972–9032	9003	b
13	Ua-24055	CNC-S2	45.756	12.83	1.6	11.13	Bottom P0/Top U1	8515 ± 65	9405–9604	9507	a
14	Ua-24054	CNC-S2	45.756	12.83	1.6	13.54	Fine/coarse limit U1	11,960 ± 95	13,567–14,049	13,810	a
15	Rome-1623	Bannia 2	45.919	12.74	19.3	2.10	Fluvial activity in adjoining incise valley	12,050 ± 110	13,690–14,172	13,909	c
16	ETH-107113	FRA1_2350	45.664	12.87	−2.0	23.50	Coarse unit U1	12,220 ± 33	14,045–14,307	14,119	b
17	Rome-1622	Bannia 1	45.919	12.74	19.3	1.80	Fluvial activity in adjoining incise valley	12,375 ± 115	14,059–15,010	14,472	c
18	Rome-1696	Boscat-Cimitero	45.908	12.81	22.3	1.00	Fluvial activity in adjoining incise valley	12,420 ± 90	14,140–14,997	14,536	d
19	Ua-24056	SUM1	45.794	12.8	5.2	1.85	LGM aggradation (U0)	15,565 ± 175	18,445–19,234	18,825	a
20	Ua-24053	CNC-S4	45.756	12.45	2.2	11.07	LGM aggradation (U0)	18,055 ± 175	21,420–22,343	21,878	a
21	Ua-24052	CNC-S4	45.756	12.45	2.2	29.31	base LGM (U0)	24,275 ± 375	27,663–29,046	28,321	a

marking the top of the LGM alluvial deposits and the base of the valley incision, was created in a GIS environment. This process followed several rounds of iteration between cross-section interpretation and GIS interpolation, revisiting the stratigraphic interpretation of geotechnical logs, and planning of additional hand coring lines (campaigns 2016, 2017, 2018, 2019). A less detailed earlier reconstruction of the unconformity (Primon and Fontana, 2008; Fontana et al., 2012) has served as the starting point of the GIS interpolations and strategic section planning. Cores with uncertain interpretation due to an imprecise or ambiguous logging were avoided in the reconstruction. The lengths of the cores that did not reach the top of the LGM deposits have been used as limiting points to assess the minimum depth of the base of the CIV. A series of contour lines were manually drawn interpolating all the true depths and limiting points, thus allowing to constrain the interpolating algorithm in the light of the geomorphologic and stratigraphic evidence. The interpolation has been performed with the *Topo to Raster* tool provided by ArcGIS software which embeds interpolation contour line and point data combining algorithms of Hutchinson (1989). We ran these without the sink removal and forced drainage options.

A thorough revision of all the available stratigraphic logs and geotechnical tests improved the mapping of the depth of the top of the LGM deposits below the coastal plain south of Concordia Sagittaria. For the LGM-dissecting and burying sedimentary units, the spatial distribution, paleoenvironmental (e.g. gradients from freshwater to brackish water), architectural relationships (e.g. transgressive contacts) and chronological constraints (numeric ages obtained on organic beds at various depths) were evaluated to cross-validate our interpretation and to secure that the reconstruction is internally consistent.

4. Results

4.1. Facies and geometries of the filling

We here describe the sedimentary units making up the stratigraphy of the area in chronological order, and following a nomenclature conform to recent geological literature and reports for the study area (Bondesan et al., 2008; Fontana et al., 2008, 2012, 2014a, 2019b). From here on, cross-sections labelled *Section A* to *K* refer to panels in Figs. 7, 8 and 9. The descriptions of the sedimentary units (U#) are followed by the interpretation of the depositional environments.

4.1.1. LGM alluvial plain deposits (U0)

4.1.1.1. Description. The top of this unit is marked by a rather well-developed and overconsolidated soil, with brownish colours spanning 2.5Y-10YR. A key characteristic is the occurrence of calcic horizons (Bk/Ck) with centimetric carbonate concretions and widespread mottling. Below the pedogenized horizons the sediment is characterized by typical greyish/blueish colours resulting from gley conditions. This unit is constituted by decimetre-thick layers of silt and clayey silt, sometimes alternated with lenses of fine sands and silty sands that can be characterized by planar or cross lamination. Organic and peat horizons up to 30 cm thick and with a large lateral continuity can be occasionally found intercalated in the upper meters of the unit. The pollen analysis performed on these peat horizons documented a cold steppe-like environment characterized by the formation of large peat fens due to the occurrence of waterlogged soils (cf. Miola et al., 2006; Fontana et al., 2008, 2012). The paleontological content of this unit is scarce and constituted solely by continental gastropods, such as the genera *Planorbis* and *Cingolum* (Fontana et al., 2012). The assessed age of this unit spans approximately from 28 ka to 19 ka cal BP (#19 to 21 in Table 1). U0 is cropping out in the northern part of the study area (Fig. 2), while it is buried in the costalal sector.

4.1.1.2. Depositional environment. The incised valley of Concordia was carved in U0, which is constituted by LGM alluvial plain deposits. The overconsolidated soil found at the top of U0 is locally named “caranto” (cf. Mozzi et al., 2003; Fontana et al., 2014b and reference therein). Most of the LGM unit aggraded during the Canodusso phase, while in some sectors last narrow gravelly to sandy fluvial ridges formed during the Remanzacco phase (Fontana et al., 2008). The facies associations and planform fluvial style have been interpreted to represent a sandy braided river (Canodusso phase), shifting to wandering typology for the final paleochannels (Remanzacco phase). Note that this is the style for the part of the LGM megafan distributary system over some 10–20 km downstream of the spring belt (Fig. 2): in the more proximal sectors (fan apex, see above) and in more distal sectors (e.g. beyond the modern coastline; Ronchi et al., 2018), the coeval style may have been different.

4.1.2. Lateglacial fluvial deposits (U1)

4.1.2.1. Description. The unit at the bottom of the CIV filling (U1) is mainly composed of sandy-gravels and gravelly-sands (Fig. 6-H) capped by a thick and stiff silty layer characterized by the presence of rare centimetric scattered carbonate concretions (arrows in Fig. 6-G). Because of its depth (up to 15 m below ground level), the unit is rarely reached by hand cores and can only be penetrated and sampled with mechanical coring equipment. The description is thus based on only a few deep mechanical cores. The gravels are well-rounded and characterized by a fining downstream trend, with a maximum diameter that spans from 7 cm in the northern reach (*Section B*) to 3 cm in the central and southern ones (*Sections C*, *K*). U1 appears to have a variable thickness, from ca. 10 m north of Portogruaro (*Section A*) to ca. 14 m in the most downstream sector (*Section K*). This downstream increase is echoed in the thickness of the gradually fining upper part of U1, that is 1.5 m thick in *Section B* and 7 m in *Section K*. This unit is separated from U0 by an erosive unconformity which defines the base and the flanks of the valley. U1 is barren of macrofossils, except for some very rare wood fragments. Pollen analysis carried out in core CNC-S2 (Fig. 3) registered a strong dominance of *Pinus* and the secondary occurrence of *Betula*, *Juniperus*, *Salix* and *Artemisia*, documenting the presence in the surrounding plain of a coniferous forest (Favaretto and Sostizzo, 2006). A date obtained from an organic sample recovered from the contact between the gravel deposits and the overlying fine-grained subunit gave an age of ca. 13.8 ka cal BP (#14 in Table 1), while a wood fragment recovered within the coarse portion was dated at ca. 14.1 ka cal BP (#16 in Table 1). U1, which crops out slightly north of *Sections A* and *B*, gradually deepens downstream along the valley from −3 m MSL to −18 m MSL. The gradient of the top of U1 varies between 4 and 0.6‰.

4.1.2.2. Depositional environment. U1 is constituted by channel bed deposits of the Tagliamento River. According to the characteristic elements of the gravelly-dominated rivers, in *Section A* the facies matches typologies C and D as described by Miall (1996), in *Section K* it matches D and E typologies. In a natural, unconfined alluvial setting, this would indicate a gravelly wandering to meandering river with relative deep main channels. A modern analogue can be identified in the reach of the Tagliamento River near the town of Morsano (Figs. 2, 4a). This also happens to be the location where the modern river changes from gravel to sand bed river.

4.1.3. Basal peat (P0)

4.1.3.1. Description. The organic-rich layer that blankets U1 is mainly constituted by stiff, black peat deposits, often characterized by millimetric clayey laminae (arrows in Fig. 6-F)and by the presence of macro remains of plants, such as pieces of wood and roots. This layer is characterized by a variable thickness and can reach a maximum value of ca. 1.5 m (#5 in Fig. 3). Downstream of *Section G*, P0 is partly constituted by a laminated calcareous gyttja (sensu Bos et al., 2012), characterized by a pinkish colour, alternating with detritus gyttja of pale brownish colour (Fig. 6-E). The pollen content of P0 was analysed in detail in core CNC-S2 (cf. Figs. 5 and 7), documenting the progressive increase of *Quercus*, *Corylus*, *Tilia*, *Ulmus*, *Vitis*, *Rosaceae*, *Alnus*, *Salix* and *Fraxinus excelsior*, with the related decrease of *Pinus* and *Juniperus* (Favaretto and Sostizzo, 2006). The geochronology of this unit is constrained by nine radiocarbon dates

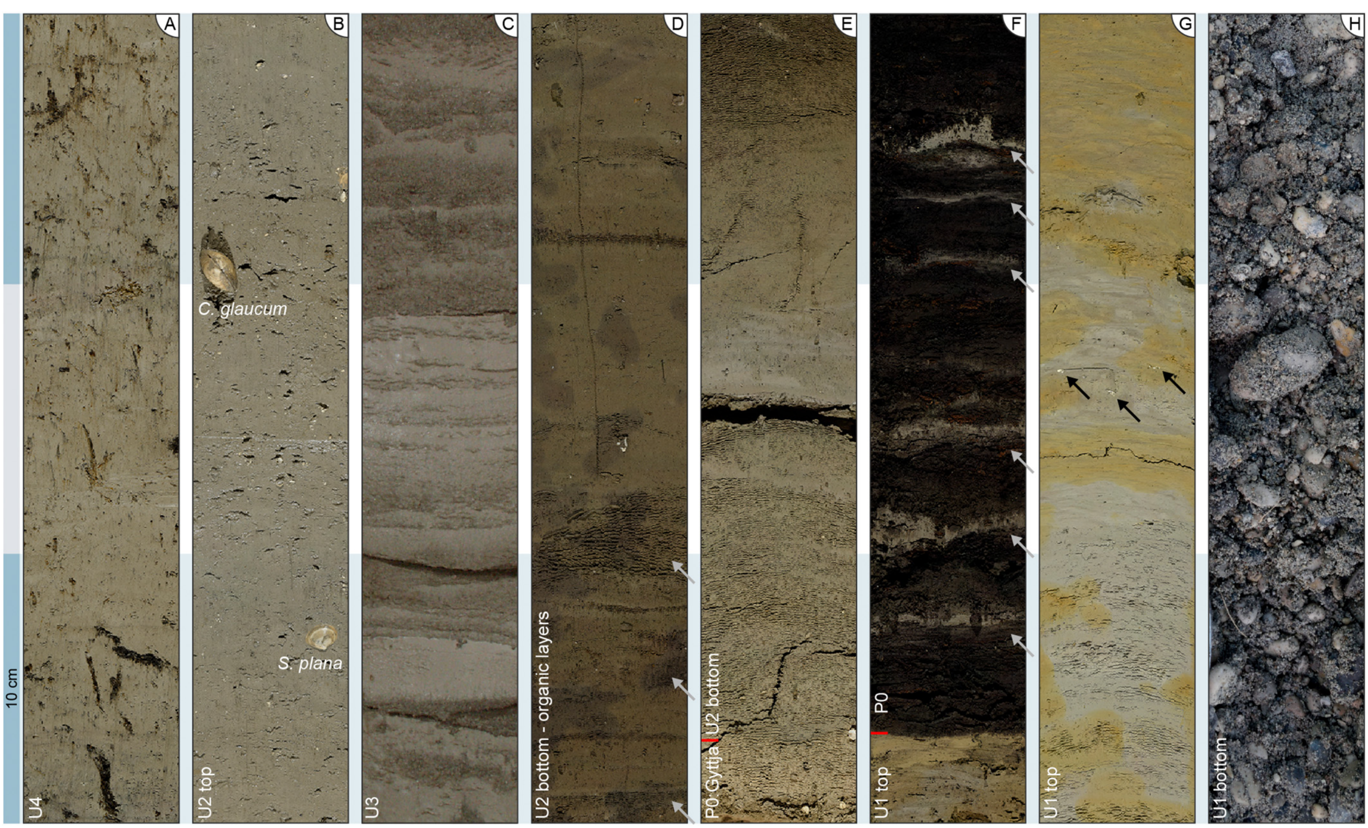
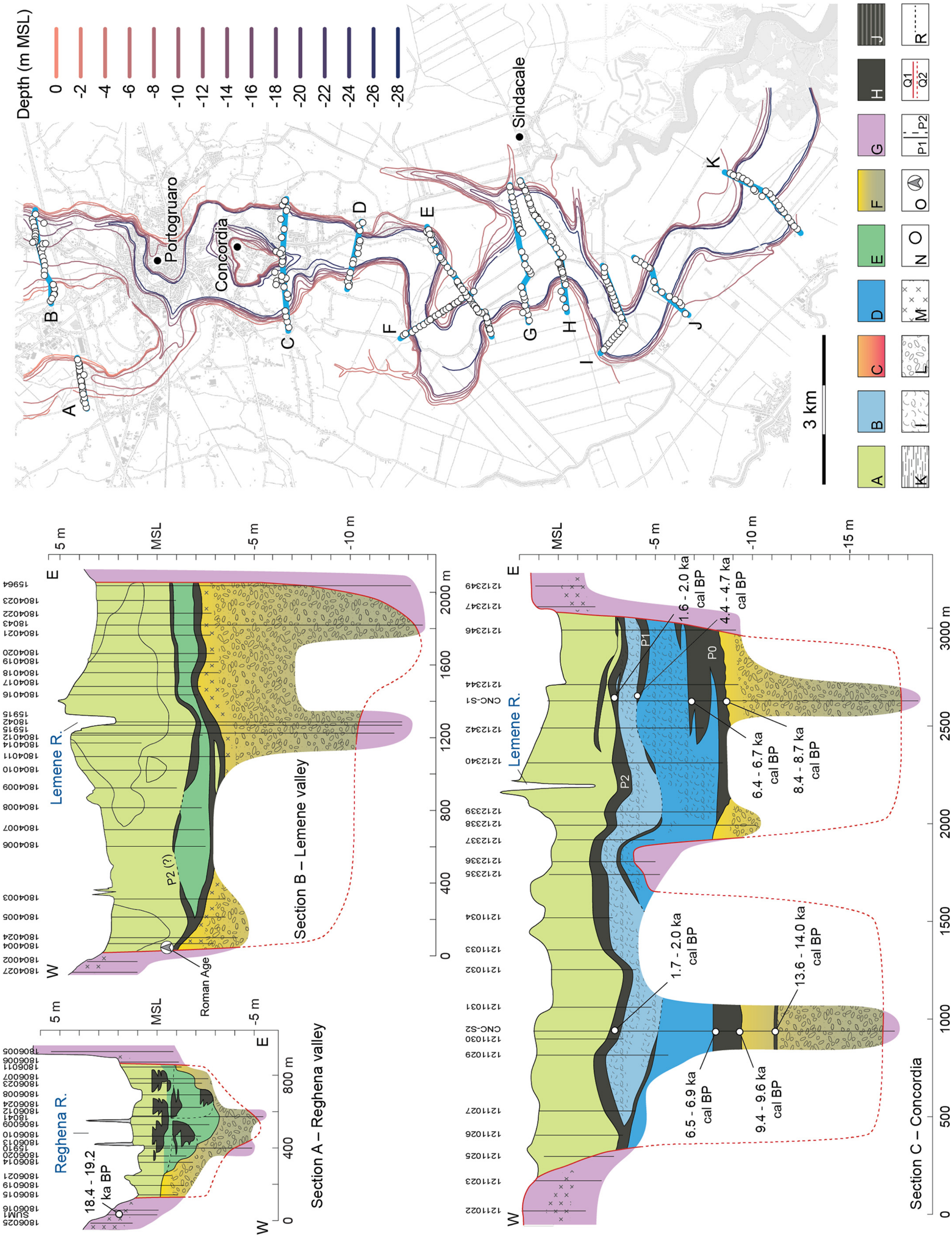


Fig. 6. Samples from core FRA1 (location in Fig. 5) expect for C, which was sampled from the western sector of *Section I*. A: 125–155 cm, greyish-yellowish (2.5Y 4/2) silty and sandy fluvial unit (U4); B: 325–355 cm, shallow lagoon deposits (U2), mainly silts and clays, with *C. glaucum* and *S. plana*; C: Sandy laminated tidal channel unit (U3); D: 865–895 cm, deep lagoon deposits (U2), mainly silts and clays, with high organic content and organic-rich layers (arrows); E: 1170–1200 cm, contact between the lagoon deposits of U2 and the underlying laminated calcareous gyttja of P0; F: 1321–1351 cm, contact between the basal peat (P0) and the underlying U1 fluvial deposits. Arrows indicate clayey laminae; G: 1430–1460 cm, top portion of Lateglacial fluvial deposits Unit (U1), stiff silty layer with rare carbonate concretions (arrows); H: 2130–2160 cm, bottom portion of Lateglacial fluvial deposits Unit (U1), sandy-gravels and gravelly-sands.


Section A – Reghena valley
Reghena R.
18.4 - 19.2 ka BP
Section B – Lemene valley
Lemene R.
Roman Age
P2 (?)
Section C – Concordia
Lemene R.
P0
P1
P2
1.6 - 2.0 ka cal BP
4.4 - 4.7 ka cal BP
6.4 - 6.7 ka cal BP
8.4 - 8.7 ka cal BP
1.7 - 2.0 ka cal BP
6.5 - 6.9 ka cal BP
9.4 - 9.6 ka cal BP
13.6 - 14.0 ka cal BP
Depth (m MSL)
Portogruaro
Concordia
Sindacale
3 km

spanning from ca. 9.5 to ca. 8.5 ka cal BP at the base (#10 to 13 in Table 1; −15.7 to −8.2 m MSL) and between ca. 7.9 and 6.5 ka cal BP at the top of the basal peat (#5 to 9 in Table 1; −15.0 to −5.2 m MSL). P0 has been documented along the whole extent of the buried incised valley. The top of this unit has been intercepted at different depths, from ca. −9 m MSL, near Concordia, to −16 m MSL in the southernmost sector (cf. Figs. 6, 7 and 8).

4.1.3.2. Depositional environment. A thorough analysis of the depositional environment of P0 is provided in Section 5.3.

4.1.4. Lagoon deposits (U2)

4.1.4.1. Description. A soft silty and clayey deposit (U2), usually characterized by a rather homogeneous light grey to greenish colour (2.5Y 6/1–4/2; Fig. 6-B, -D, -E), overlies P0. No sediment structure is usually recognizable within this unit, which only occasionally shows some sandy laminations. As a sedimentary body, U2 is wedge-shaped in longitudinal direction: its thickness reduces from almost 17 m in the southern sector (*Section K* in Fig. 9) to zero in the northmost part of the study area (absent in *Sections A* and *B*; Fig. 9). Commonly present macrofossils are fragments and preserved shells of *Cerastoderma glaucum*, *Loripes lacteus*, *Bittium scabrum*, *Gibbula* sp., *Abra* sp., *Hydrobia* sp. and, more rarely, *Rissoa* sp., *Scrobricularia plana*, *Cerithium* sp., *Nassarius* sp., *Theodoxus fluviatilis* and *Theodoxus danubialis* (the latter two encountered in U2 in the inland fringe only). The qualitative analyses performed on foraminifera from core CNC-S1 (Figs. 3 and 5) documented common presence of *Ammonia beccari tepida* throughout the unit, while also *Ammonia perlucida*, *Elphidium gunteri*, *Haynesina germanica* are occasionally encountered (Bondesan et al., 2005). Spiral fragments of agglutinans forams with organic cement also occur, diffused throughout the core. Land-derived plant remains, mainly fragments of reeds (*Phragmites* sp.) can be rather common in U2, sometimes buried in vertical position and sometimes accumulated in organic horizons with decimetre thickness. Pollen spectra from core CNC-S2 (Fig. 3) register a dominance of aquatic plants. By excluding this local component, the predominance of *Quercus*, *Corylus*, *Tilia*, *Ulmus*, *Vitis*, *Rosaceae*, *Alnus*, *Fraxinus* and *Salix* can be observed, along with the first appearance of *Acer* and *Fagus* (Favaretto and Sostizzo, 2006). The presence of some organic-rich layers (including units P1 and P2 described below) within this unit allowed to obtain ages spanning from ca. 8.0 to 2.0 ka cal BP (#9 to 1 in Table 1; −8.8 to −3.0 m MSL retrieval depth). The top of this unit can be usually identified between 0 and − 3 m MSL. It constitutes the modern surface in the seaward part of the study area (shallow lagoon floor reclaimed in the first half of 20th century, presently in agriculture).

4.1.4.2. Depositional environment. The presence of rhythmic sandy laminations, the very unconsolidated nature of the deposits and the mollusc assemblage (cf. Pérès and Picard, 1964; Vacchi et al., 2016), are typical of subtidal lagoonal depositional environments. The micropaleontologic evidence suggests the presence of a hyposaline environment (Bondesan et al., 2005), at least in the open parts of the lagoon.

4.1.5. Tidal channel deposits (U3)

4.1.5.1. Description. Relatively coarse-grained sediments, characterized by widespread mud flasers, form channel-shaped bodies encased within U2 (Fig. 6-C). These are mainly constituted by grey sands, but the percentage of mud, creating rhythmic interbedding of silty and fine sand lenses, increases northward. A fining upward trend (in some cases from ca. 400 to ca. 150 μm) and an overall fining trend moving landward (from ca. 300 to ca. 50 μm) are recognizable. Besides pervasive millimetric flaser lamination, thin layers of organic material also occur at regular intervals. The layering of the unit is marked also by the occasional occurrence of clay chips, sometimes clustered in centimetric horizons (locally reworked and reincorporated mud flaser). A variable depth, ranging from −1 to −5 m MSL, has been observed for the top of these deposits, whereas the lowest sample was recovered from ca. −11 m MSL. Macrofossils are rare and only sparse shell fragments of brackish water species can be recovered (e.g. *Abra* sp., *C. glaucum*, *L. lacteus*), while no plant remains are usually visible. U3 can be tracked in all the stratigraphic transects south of Concordia (cf. Figs. 7, 8 and 9), thus suggesting a longitudinal continuity within the incised valley. The unit can be tracked over a minimum length of ca. 8 km.

4.1.5.2. Depositional environment. The presence of flaser beddings, which are highly diagnostic for tidal channel deposits (De Raaf and Boersma, 1971; Martinius and Van den Berg, 2011), the stratigraphic position within U2 and the presence of brackish shells, point toward a tidal channel origin of U3.

4.1.6. Intercalated peat layers (P1 and P2)

4.1.6.1. Description. Several peat layers were identified within and on top of the lagoonal deposits (U2). While the majority of these peat layers appear as patches of limited areal size with no apparent longitudinal continuity, two of them can be tracked almost along the entire length of the buried incised valley. These peat layers, identified as P1 and P2, have a variable thickness – in places exceeding 1 m, in other places just a few centimetres. The older one, P1, is intercalated within U2, has a thickness between 0.1 and 0.7 m and its encountered at depths ranging between −3 to −5 m MSL (Fig. 12). Two radiocarbon dates give an age of ca. 4.5 ka cal BP (#3, 4 in Table 1). The younger one (P2), is a widespread upper organic level that overlies the lagoon deposits in the northern part of the valley of Concordia, down to *Section E*. The top of this peat bed has been dated to ca. 1.9 ka cal BP (#1, 2 in Table 1; Fig. 6-B). Some archaeological constraints are also available for the upper organic layer: traces of ancient human activity dating to late Bronze Age (1400–1100 BCE) were detected below P2 (cf. Bianchin Citton, 1996). A Roman necropolis found along the via Annia (location in Fig. 5), used between 2nd century BCE and 5th century CE, is partly intercalated with P2 (Fontana, 2015).

4.1.6.2. Depositional environment. A thorough analysis of the depositional environment of P1 and P2 is provided in Section 5.3.

4.1.7. Medieval fluvial deposits (U4)

4.1.7.1. Description. The younger organic horizon (P2), in the study area is covered by a greyish-yellowish (2.5Y 4/2) silty and sandy unit (Fig. 6-A), often characterized by an evident cross to planar bedding. The soil formed on top of this unit is weakly developed (entisol, cf. Soil Survey Staff, 1999) and the diagnostic feature is the presence of common carbonate concretions with a diameter of 1 to 5 mm (Fontana, 2006). The thickness of U4 is variable, up to 5 m near Concordia where it tops the CIV fill, reducing to less than 1 m where it wings out laterally away from the CIV fill, onlapping and aggraded over the LGM alluvial plain. Macrofossil remains are generally absent, but occasionally paludal assemblages of *Viviparus viviparus*, *Planorbis* sp. and *Helix pomatia* are encountered. A series of archaeological layers, dating up to the second half of the 5th century CE (Valle and Vercesi, 1996; Fontana et al., 2004;

Fig. 7. Compilation of cross sections available for the Concordia incised valley. Legend: A) Medieval fluvial deposits (U4); B) Lagoon deposits < ~4.5 ka cal BP (U2); C) Tidal channel deposits (U3); D) Fine-grained lagoon deposits > ~4.5 ka cal BP (U2); E) Early and Mid-Holocene fluvial deposits; F) Lateglacial fluvial deposits (U1); G) LGM alluvial plain deposits (U0); H) Organic deposits; J) Gyttja deposits; K) Lamination; I) Abundant shell remains; L) Gravels; M) Carbonate concretions; N) Dated sample (ka cal BP); O) Archeologic remains; P1) Core; P2) Projected core; Q1) Unconformity; Q2) Reconstructed unconformity; R) Reconstructed surface.

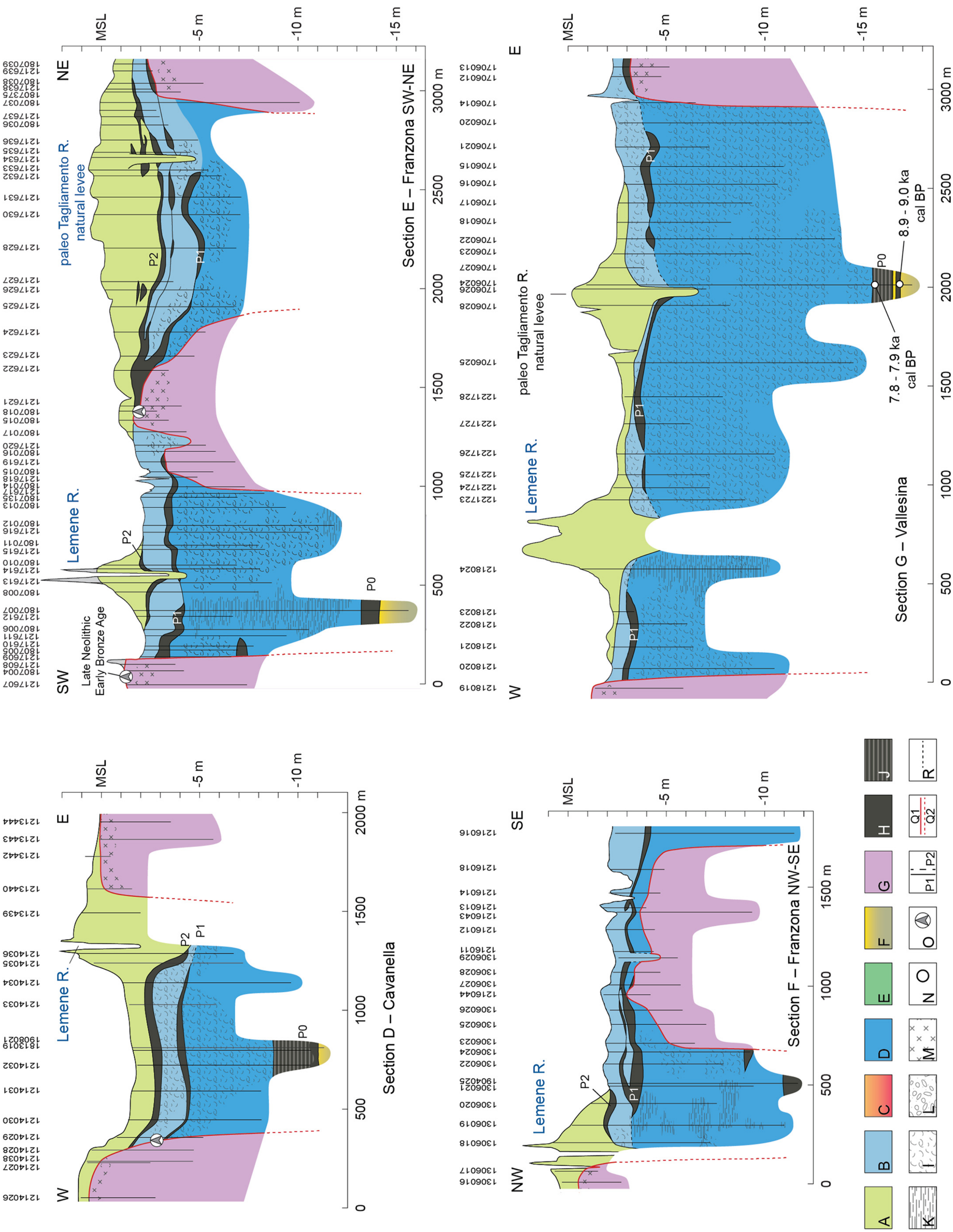


Fig. 8. Compilation of cross sections available for the Concordia incised valley. Location in Fig. 7; Legend in caption of Fig. 7.

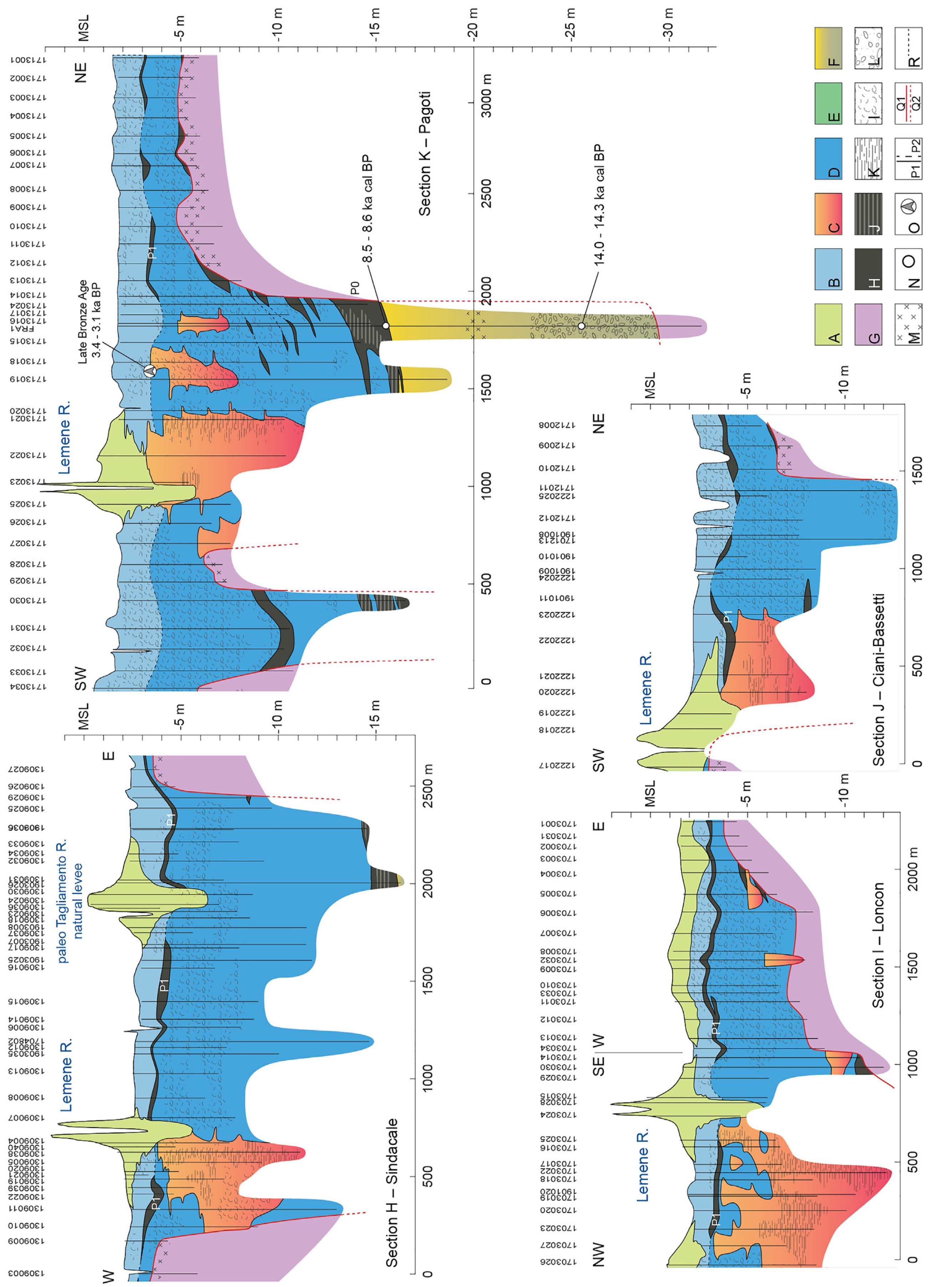


Fig. 9. Compilation of cross sections available for the Concordia incised valley. Location in Fig. 7. Legend in caption of Fig. 7.

Fontana, 2006), are intercalated within this unit. In the northern part of the valley, these deposits generally form the present topographic surface (Figs. 2 and 4). In the most upstream part of the fill of the CIV, where unit P2 can no longer be traced as a peat, U4 is underlain by minor amounts of local fluvial deposits with buried soil features, representing the local terrestrial equivalents of units P2, P1 and the brackish lagoon rim facies in unit U2.

4.1.7.2. Depositional environment. The stratigraphy, paleoecological content and morphology of the deposit clearly point toward a fluvial unit formed during the early Medieval period.

4.2. Morphology of the Concordia incised valley

The combined use of Lidar-derived topography and stratigraphic data allowed to reconstruct the DEM of the unconformity separating the deposits of the LGM megafan from the post-LGM units (Fig. 11). Considering the buried portion of the valley and the northern tract where it still has some topographic evidence, the fluvial incision of Concordia can be followed for over 25 km. Using the DTM and the geological surveys available in the northern part (Bondesan and Meneghel, 2004; Bondesan et al., 2008; Fontana, 2006; Zanferrari et al., 2008c; Fontana et al., 2012), the valley can be tracked upstream to a point of origin, slightly south of San Vito al Tagliamento (Figs. 1, 4-A). This location lies within the spring belt (Fig. 2) and in this zone the post-LGM paleochannels of Tagliamento were flowing almost at the level of the pre-existing LGM alluvial plain, as the bottom of the Lateglacial channel is generally between 1.5 and 3 m below the top of the LGM surface (Donegana et al., 2005; Fontana, 2006). South of Portogruaro the buried portion of the incised valley can be tracked for a total length of about 12 km and it has a roughly north-south direction, with a marked deviation toward east in its downstream portion. The buried tract of the valley is characterized by the presence of sharp bends with curvature radiuses spanning from 800 to 1500 m, while the overall width of the valley spans between 400 and 1200 m. The available data allow to follow the top of U1 in many locations, as the sediments covering this unit are generally soft and can be passed by hand coring rather easily. The dataset does not allow to assess the full depth of the incision (i.e. to the base of unit U1) along its entire path, but the available cores suggest that the erosive unconformity at the base of the incised valley is characterized by a variable topography, probably marked by localized deeper scours (Fig. 11). The maximum depth reached by the tract of the incised valley now used by Lemene River is assessed to be between −14 and −16 m MSL (Figs. 7 and 8). It is much shallower along the valley now occupied by Reghena River, where the top of the LGM deposits was intercepted by mechanical cores at ca −6 m MSL or less (Figs. 7 and 8). The depth of this latter branch dramatically increases right downstream of the merging point, where a value of about −14 m MSL was detected by mechanical cores. Some minor incised tributary channels join the main trunk of the valley. A most remarkable example of deeply incised tributary gully is represented by a 400 m wide system merging to the main valley from the east (*Sections G* in Fig. 8 and *H* in Fig. 9). The maximum observed depth is recorded in the area of *Section K* (Fig. 9), where a mechanical core reached the basal unconformity of the valley at −29 m MSL (20 m below the LGM surface). At the moment, observational data does not yet allow to map the continuation of the CIV downstream of this sector. High-resolution geophysical surveys, that have been performed along the coast below the bathymetry of −10 m MSL, did not find any evidence of large incised filled valleys between Tagliamento and Piave rivers (cf. Trincardi et al., 2011).

5. Discussion

The detailed reconstruction of the CIV buried morphology and of the architecture of its basal Late-Pleistocene fluvial units and Holocene infill poses some major questions about its geomorphic origin (incision phase) and subsequent evolution (transgressive filling and submergence below the eventual lagoon), also in the light of the other incised fluvial landforms documented over the Tagliamento megafan. Key issues are: i) When did the CIV start its incision and how long did it function? ii) Which processes led to the incised valley formation and what is the relation between the CIV and the other incised valleys of the distal megafan? iii) Which processes explain the sequence of deposits filling the CIV and what is the relation with general Holocene coastal plain development of the region (relative sea-level rise, barrier-lagoon establishment, Tagliamento River avulsions).

5.1. Timing of valley incision

The timing of formation of the CIV can only be estimated considering the age of the top of LGM unit eroded by the fluvial incision and the age of the sediments which filled the bottom of the valley. In the study area the last phase of LGM aggradation is dated between 19 and 18 ka cal BP (Fontana et al., 2012, 2014b; #19 in Table 1), thus providing a *terminus post quem* for the beginning of the erosive phase. During the formation of U1 the river actively reshaped the valley walls through lateral migration driven both by autogenic river dynamics as directly documented in the CIV filling at least until 13.8 ka cal BP (#14, #16 in Table 1). Local significant reworking to the slope morphology could be induced by the formation of the hydrographic network draining the surface runoff from the top of LGM alluvial plain into the valley. Moreover, it is worth noting that the 5 to 15 m high valley-rim scarps, mainly formed by silts and clays (U0), could have triggered the occurrence of local slumps along the slopes of the CIV. Such slumps should be considered to be *syn*-incisional.

The age of the base of P0, resting on the top of U1 and dating to 9.5–8.6 ka cal BP (#10 to 13 in Table 1), constrains the end of the fluvial phase connected with the activity of Tagliamento River within the valley. However, this peat formation was proceeded by a fairly prolonged phase of pedogenesis as suggested by the occurrence of large carbonate concretions in the loamy upper part of U1, pointing toward a possible time lag between the end of U1 deposition and the start of P0 accumulation. That lag period would be represented by valley wide pedogenesis (very local drainage only) and would imply that the Tagliamento River and floodwaters had stopped to make use of its CIV course, somewhat after 13.8 ka and well before 9.5 ka.

It is worth noting that all the chronologic constrains available for other incised valleys of the distal Tagliamento megafan indicate a similar chronology of activity. In particular, in the head portion of the Reghena fluvial incision (#A in Fig. 2), a layer of pine cones (*Pinus sylvestris, Pinus mugo*) dated ca. 14.5 ka cal BP (#17 in Table 1) is found at a depth of 1 m, sealed by sandy silts and resting on top of sandy gravelly sediments (Fontana, 2006; Zanferrari et al., 2008c). This indicates a phase of activity of this incised valley which is contemporaneous to the reactivation documented at the top of U1 (#14 in Table 1). Similarly, in the head sector of the fluvial incision now occupied by Sile River (#B in Fig. 2), two peat layers separated by a gravelly veneer were dated 14.5 and 13.9 ka cal BP (#15, 17 in Table 1). The pollen analyses carried out in these peat layers document the dominance of *P. sylvestris* and *P. mugo*, while thermophilous trees were absent (Donegana et al., 2005), as also indicated by the pollen composition documented for the same period in the area of Concordia (Favaretto and Sostizzo, 2006).

These data suggest that the phase of activity of the Tagliamento River, which carved the CIV and deposited the basal unit U1, was rather rapid: it started just after 19 ka (last megafan channel activity date) and it had arrived at the downcut level where unit U1 is found before 13.8 ka cal BP. Moreover, this process was not unique to the CIV feature only but occurred at multiple locations across the distal portion of the megafan. This short period chronologically matches with the dramatic changes that occurred in the fluvial systems of Tagliamento immediately after the glacier withdrew from the alluvial plain (cf. Monegato et al., 2007, 2017; Fontana et al., 2014b). In a regional and Alpine perspective, the formative phase of the CIV corresponds to the first part of the Lateglacial, likely beginning during Greenland Stadial 2 (GS-2), when the climatic conditions were still cold (Vescovi et al., 2007; Belli et al., 2013). This coincides with the Daun glacial advance recognized in the Alps (Ivy-Ochs et al., 2009). The geochronological and paleobotanical evidence suggests that since the transition to Greenland Interstadial 1 (GS-1) the incision of the CIV and the other megafan incising systems halted, allowing the accumulation of a loamy organic top of Unit U1.

5.2. Incised valley formation

When the Tagliamento glacier retreated from the mountain front, the river system that it fed experienced a sharp drop in amounts of material delivered to the outwash plain. Sediment trapping moved upstream into the deglaciating mountain catchment, essentially starving the fan system downstream (Fontana et al., 2008). It is worth noting that no major post-LGM terraces are present above the modern valley floor in the mountain catchment of the Tagliamento River. It is likely that a major Lateglacial depositional trap was active in the so called area of "campo di Osoppo" (Fig. 1), located between the terminal moraine system and the Alpine front, where a significantly thick fluvial and lacustrine deposits is reported (Zanferrari et al., 2013). In the Piave River catchment, a contemporary analogue mountain river system some 40 km west of the Tagliamento, the damming effect generated by the withdraw moraines and postglacial landslides and subsequent upstream trapping and downstream starvation is well demonstrated. That system remained blocked, and the alluvial plain starved, until about 9 ka cal BP (Pellegrini et al., 2005; Carton et al., 2009).

The erosion phase that led to the formation of the deeply incised gorge in the apex of Tagliamento Megafan (cf. Section 2) can be attributed to this condition of sediment starvation of the system (Fontana et al., 2014a), but the downcutting of the CIV must have had an additional, different triggering mechanism, as the presence of a knickpoint between the apical gorge and the distal incised valley (Fig. 12) clearly indicates. Given the inland distance to the contemporary coastline, which was still in the early phase of the marine transgression (post-LGM, pre-MWP1a), sea-level induced base level change is not considered a trigger. The effects of such rise were probably strongly buffered by the anomalous extension and gentle geometry of the exposed continental shelf, a 300 km long alluvial plain with a mean topographic gradient of ca. 0.02% (Fontana et al., 2014a). A base level change induced by a tectonic trigger can also be excluded, as the presence of Lateglacial fluvial incisions is documented in the distal sector of almost all the alluvial megafans along the southern Alps (Fontana et al., 2008, 2014a; Carton et al., 2009; Mozzi et al., 2013), pointing to a general cause, and not to the possible effect of local deformations.

The CIV downcutting appears intimately connected to the dynamics of the Tagliamento River of the time. In its distal sector, the Tagliamento megafan is characterized by a typical apron shape within which the incisions show a radial pattern of dissections (Fig. 1). In that, the landforms strongly contrast with the single incised valley seen in the proximal portion of the megafan where the post-LGM Tagliamento valley leaves the apical gorge at greatly incised depth, but progressively loses valley wall height downstream, until the flanking relief almost disappearing approaching the upper limit of the spring belt (Figs. 1, 2), beyond which fine-dominated sediments start to be dominant. This spring belt is the same boundary that constitutes the germinal zone of CIV and other radial incised valleys.

It is worth noting that also in other megafans of the Venetian-Friulian plain several incised river valleys exist downstream of the spring line (Fontana et al., 2014a). Moreover, as for Tagliamento, some of them are located in sectors where in the post-LGM no main alpine rivers have been active. This setting is particularly evident in the western portion of the Cellina megafan (Fig. 1), which has been abandoned by its formative river since about 20 ka cal BP (Fontana et al., 2019b), but has been later dissected by a number of spring water-fed streams (incised to 10 m below the top of LGM surface). Such processes actively contributed to the formation of multiple trenches which could have acted as precursors for the formation of a well-developed incised valley through the direct action of a major river.

Two slightly different mechanisms of river piracy explaining the radial incisions can be proposed: 1) retrogressive retreat of the spring-water rivers head could have led these minor streams to intercept and capture (a part of) the Tagliamento River; 2) floodwater downcutting of the Tagliamento could have carved a path which led to a connection with a spring-fed river entrenchment, triggering a (partial) avulsion. The zone where the incised valleys starts corresponds to the area where the topographic gradient has a significant decrease (i.e. from 3 to 1‰). The geomorphological and geological mapping evidence also identifies this location as the major avulsion node of the Tagliamento River during post-LGM, not only in Lateglacial times but throughout the Holocene as well (Fig. 2). Moreover, during the Lateglacial, important hydroclimatic fluctuations and multiple unstable retreating glaciers higher up in the mountain catchment are likely to have released meltwater floods regularly (extreme events), which could have fostered repeated and alternating avulsions at the spring belt node, allowing the Tagliamento to activate different channel belts with a radial pattern. After having fallen prey to Tagliamento capture, the downstream sectors of the valleys underwent a severe widening and deepening, reaching its final dimension by vertical erosion of the bed and lateral erosion of the valley walls. Another case of river piracy in the distal portion of the Tagliamento megafan is documented on its western sector (Fig. 4B), where the incised valleys now occupied by Arcon and Sile streams merged. This process led the Arcon River to be almost abandoned, while the Sile River continued to entrench in the downstream sector up to its junction with the Livenza River (cf. Comel, 1950).

The above paraglacial autogenic mechanisms are significantly different from autogenic alternating aggradation/incision and consequent avulsion processes described for classic alluvial fans (cf. Leopold et al., 1964; Horton and DeCelles, 2001, Ventra and Clarke, 2018). The main difference recognizable in the Tagliamento system, as in most of the megafans of northern Italy, consists in the retrogressive head erosion driven by spring-fed rivers expressed in the fine-dominated sector of the megafan connecting to the proximal sector (potentially using smaller sand bodies within the fines as a preferential path). In part this is due to the difference between megafans (build by distributary fluvial systems, multiple grain sizes, fines dominating the distal portion) and classic alluvial fans (mainly aggraded as coarse-grained facies: gravelly fans). The dominance of fine-grained deposits in the Tagliamento megafan downstream of the spring belt, not only seems to be a key factor in a hydrological sense in forcing groundwater up to appear as springs and feeding local rivers, but also was a key factor in channelling waters for the larger river system of this megafan, resulting in a short-lived set of radial incised valleys, with longer lived morphologic preservation.

Lateral migration of the Tagliamento-fed channels appears to have been a main process in controlling the planform shape of the CIV and other radial incised valleys. This is most clearly documented north of Portogruaro near Giai (#8 in Fig. 4), where the CIV, now occupied by the Lemene River, almost merged with the fluvial incision now occupied by the Reghena River. The two erosive landforms are separated by a remnant isthmus of relict LGM alluvial deposits that is only 200 m wide. These two valleys merged downstream, near Portogruaro and south of Concordia Sagittaria, leading to the formation of the isolated terrace where the ancient city of Concordia was settled since Bronze Age. The Reghena fluvial incision is shallower (*Section A* and *B* in Figs. 7, 11) and it represents a sort of hanging valley, suggesting that the CIV had been used by Tagliamento for a longer period and it probably captured the valley branch now occupied by Reghena through lateral migration.

While the Tagliamento was modelling the CIV, deepening of the valley likely activated undercutting-triggered local collapses of the walls which would produce talus deposits on the CIV valley floor that constrained river flow and promoted further incision of the river bed, while removing the talus by lateral erosion. Malatesta et al. (2017) suggest this process to lead to an overall box-shaped valley, which is consistent with the geometries we observed (Figs. 7 to 10) in our detailed mapping.

The Tagliamento branches extracted coarse material from the apical incised valley upstream and redistributed this downstream using the radial incised valleys. In the CIV system we see this in unit U1, which has a downstream fining trend. During Lateglacial times the coarse material evidently was transported much further downstream than it had been in the LGM and would do after the Early Holocene (i.e. in last 7 ka). This is clear from comparing the coarse/fine material transition which in the CIV is at least 15 km downstream of the LGM limit and about 8 km of the modern one. The gravel portion of U1 is largely constituted of such remobilized proximal-megafan material. Volumetric comparisons indicate that while a considerable amount of sediments eroded in the apex can be regarded stored within the CIV, an equally considerable remaining volume must be stored in the other morphologically expressed valleys (#15 in Fig. 2) and buried counter parts (e.g. below the *Tiliaventum Maius* branch; #12 in Fig. 2). The gravels are also encountered in the youngest U0 channel deposits (#14 in Fig. 2; “Remanzacco” phase, first 15 m of apical valley incision – see above). Only a small further portion of gravels may have been directly delivered from the mountain catchment of Tagliamento at the time that the apical valley was incising.

When the CIV valley was downcutting, it would have gradually received increasing amounts of gravel. The composition of U1 represents the final state when abundance of gravel in the river bed would have shielded the substrate from further erosion – at least in its upstream reaches where the gravel component is most abundant. From the available data it was not possible to locate the exact transition from dominantly coarse grained (gravels and gravelly sands) to dominantly sandy deposits (gravelly at depth only). Considering the present situation along the Tagliamento River, where the channel bed material shifts from gravelly to sandy within 2 km (cf. Fontana, 2006), it is likely that also along the CIV this grain-size transition is sharp.

The upper part of U1 shows a fining upward trend. Upstream (*Section B*) this develops over 1.5 m and ends in a very thin loam clearly related to shallowing of gravelly channels where bars accumulated. Downstream it develops over 7 m and tops into a thicker loamy unit, which may indicate that this far downstream the fluvial style was that of a meandering river (at least in the last stages of Tagliamento River activity within the CIV).

When measured against the surface of the megafan alluvial plain, the longitudinal profile of the CIV shows increasing depth, spanning from ca. 18 m in Concordia (*Section B* and *C*) to ca. 20–25 m (i.e. −25 to −30 m MSL) at *Sections H* to *K* (Fig. 12). Projecting the gradients of the LGM top and CIV base, the CIV is expected to continue downstream of *Section K* for several kilometres. Based on its direction in the southmost part of our mapping (Fig. 11), we speculate it merges with the buried radial incised valley to its east (same direction as the younger *Tiliaventum Maius*; #12 in Fig. 2) below the area of Caorle Lagoon. The geophysical surveys carried out in the Adriatic shelf have shown no evidence of filled incised valleys in the area between the present mouths of Tagliamento and Piave rivers (Trincardi et al., 2011; Ronchi et al., 2018) below −10 m MSL. This would suggest that the CIV and related incised landforms either pinch out progressively up to disappear above the bathymetry of −10 m MSL, or at the coastline they hold a fill that is geophysically indiscernible from surrounding distal megafan deposits.

5.3. Freshwater marsh and lacustrine environments becoming a lagoon liman

The occurrence of a fairly thick layer of peat and waterlain organics and marls (P0) resting on top of U1 clearly points toward establishment of a river-sediment starved freshwater marsh environment in the CIV. This implies a shift of the Tagliamento River away from the CIV. The waterlogged environment in the CIV was sustained by the spring-fed local rivers and aquifers intercepted from the flanks of the valley (evident from geographic setting and supported by the dominantly carbonaceous gyttjaic facies), besides rainfall generated runoff on the surrounding megafan plain (testified by the gully-incisions from local tributary branches, Fig. 11). The remains of paludal and continental plants

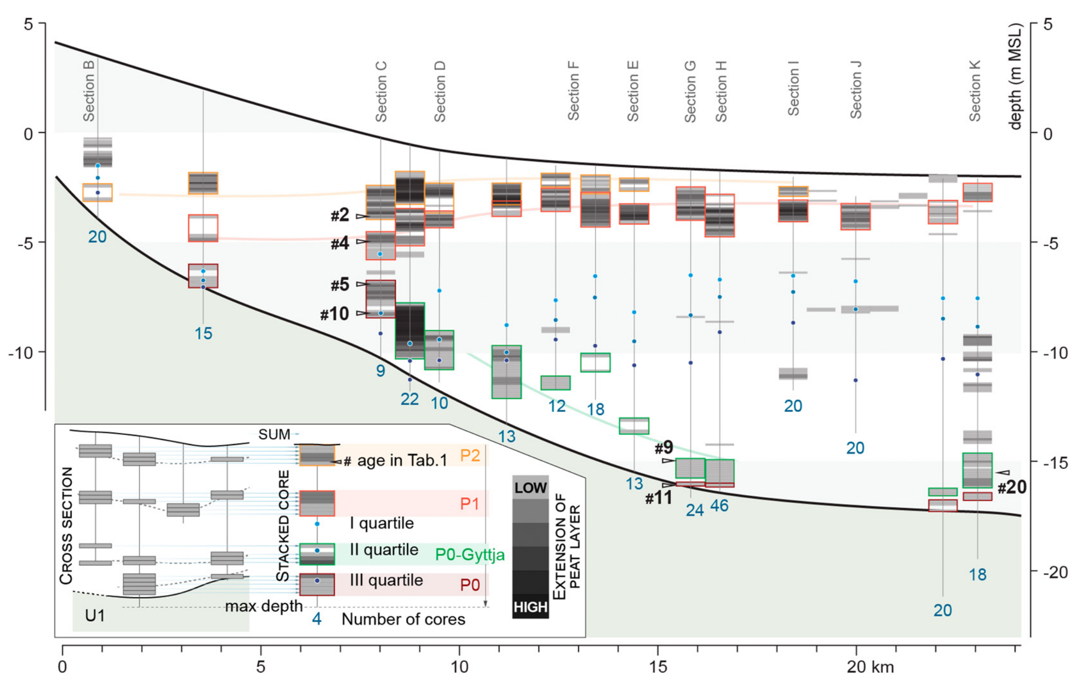


Fig. 10. Longitudinal distribution of the peat layers in the infill of the CIV. This section is built by stacking the peat layers of every available cross section into a single ideal core. The shades of grey give a qualitative estimation on the quantity of peat layers recognized at the same depth. The number of stacked cores and the quartiles, indicating the percentage of cores which reached the reported depth, provide an estimation of the reliability of the represented peat layers.

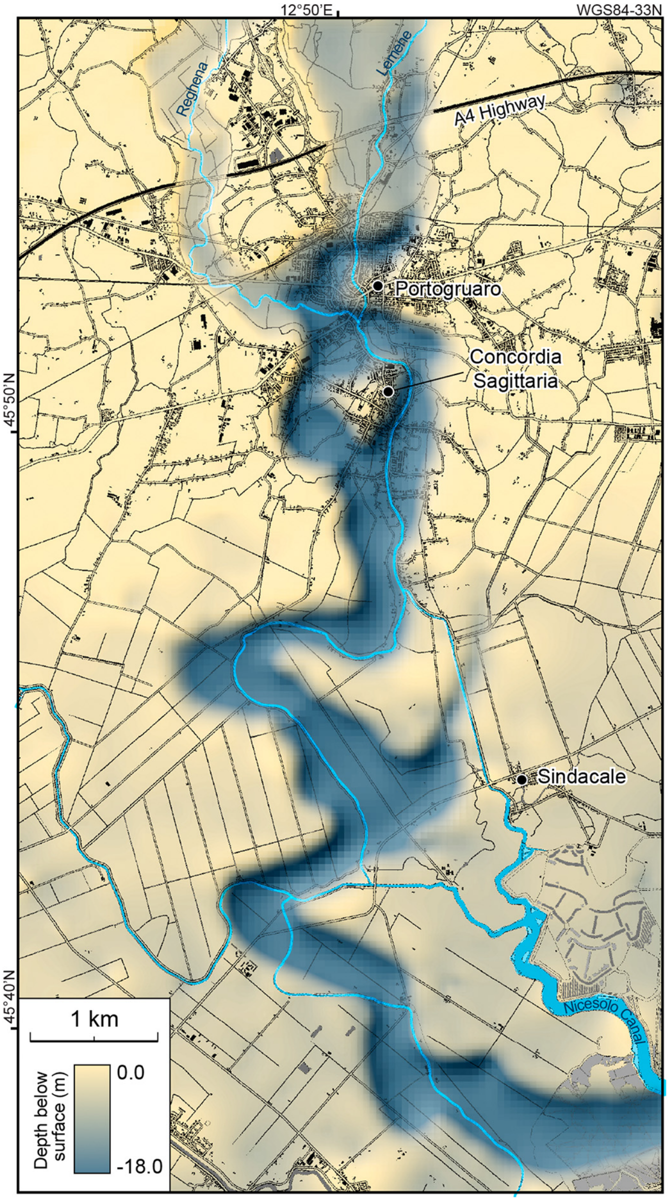


Fig. 11. Reconstructed DTM of the erosive unconformity at the base of the Concordia incised valley. The location of area is shown in Fig. 5.

constituting P0 accumulated during a time span covering about 1 ka. The pollen analysis of this layer documents the nearby common occurrence of broadleaf trees in a freshwater/lacustrine marsh along with hygrophilous species as *Salix*, *Fraxinus* and *Alnus* (Favaretto and Sostizzo, 2006).

The base of the organic-rich layer is dated between 9.5 and 8.6 ka cal BP (#10, to 13 in Table 1), when the Adriatic Sea reached a relative level between −25 and − 20 m MSL (Vacchi et al., 2016). Groundwater tables in the CIV at the onset of P0 accumulation were around −15 m (dated basal peat in *Section G*) in the downstream sector and around −9 m in the upstream sector (dated in *Section C*) and probably spring-discharge and surrounding aquifer recharge. While P0 accumulated, the sea-level rise is reckoned to have imposed a base-level control to the water tables, firstly in the southern sector. This induced a rise of the water table, slowly at first when the open sea was still at distance, and accelerating and picking up the same pace as sea-level rise when it had transgressed more nearby, at that point also affecting groundwater tables in the upstream tract. Such explain progressive increase of accommodation space within the valley prior to the effective marine incursion and drowning. As a consequence of the negligible sediment input at this time, the consequent accumulation of plant debris was favoured and generated an overall effect of backstepping paludification (Fig. 13).

In the southern tract of the CIV, from *Section D* to *K* (Figs. 8 and 9), several boreholes sampled gyttjaic deposits, which testify the development of eutrophic lacustrine environments of modest water depth (Fig. 13; Bos et al., 2012). The available data do not allow precise reconstruction of the extent of this environment and to discriminate if a few single lakes with length of some kilometres existed or if there were multiple smaller basins. The depths at which the gyttjaic deposits are encountered (e.g. in *Sections G* and *K*) suggest the lacustrine environments in the south to be a separate cluster from those in the north (Fig. 13). The occurrence of separate lacustrine deposits implies the presence of closed depressions along the valley, which can be related to the morphology of the valley floor and/or to the formation of natural dams (e.g. valley wall slides) which could have obstructed spring-fed discharge in the CIV. This is the first time that a lacustrine environment of Early Holocene age is documented in the lowlands of northern Italy and its infill potentially represents a unique archive for investigating the paleoecology of that period.

Continuing post-glacial relative sea-level rise in the Adriatic Sea, induced a progressive salinization in landward direction in the CIV, promoting a shift from the freshwater environment at the bottom of the incised valley of Concordia into a brackish marsh/lagoon environment (Fig. 13). Downstream, this is recorded in deposits from −16 m MSL upwards (*Section K*), more inland it is recorded from −8 m upward (*Section C*; Figs. 7-9, 12). The transgressive process was diachronous. Lagoonal depositional onlap appears to have followed an upstream path controlled by the steepness of the valley floor and the rate of sea-level rise (Figs. 10, 14). This phase can be dated between ca. 7.9 (in *Section G*; #9 in Table 1) and 6.5 ka cal BP (in *Section C*; #5 and 7 in Table 1). Two more such transgressive contact dates (#6 and 8 in Table 1) were obtained from cores outside the CIV and directly overlying the megafan surface, indicating that the RSL level was at about −10 m MSL around 7.0 ka cal BP (Fontana et al., 2017; Fig. 14).

The thickness of tidal channel deposits (U3) in the seaward portion of the lagoon fill indicates a relatively steady position for a longer part of the time since the transgression. The landward fining trend that characterizes unit U3 suggests a tidal-current energy decrease toward the inner portion of the incised valley, in good accordance with the expected trend for tidal channels intruding drowned incised valleys (cf. Dalrymple et al., 1992). It is worth noting that the classic tripartite subdivision for a tide-dominated estuarine environment (marine-dominated, mixed-energy, river-dominated; sensu Dalrymple and Choi, 2007) does not entirely apply to the case of the CIV as the riverine input, provided only by spring-fed rivers, suffered a strong sedimentary starvation and, thus, it is almost absent in the sedimentary record. The fining-upward trend of U3, recognized in some cores, may be the result of an overall progressive abandonment of the lagoon as a consequence of a relative sea-level stability (Fig. 14).

Once the lagoon was established in the CIV and well across the valley shoulders in its southern parts (Fig. 13, D-F), the environment become comparable to that along the landward lagoon rim in the wider surroundings. The relative inland position of the lagoon incursion into the CIV makes it a lagoon liman. The setting remained favourable for recording Late Holocene evolution, to begin with the (re)expansion of peat beds. The presence of such organic horizons beyond the very rim of the lagoon suggests the occurrence of freshening phases into the otherwise brackish environment (*Sections C* to *K*; Fig. 10). The liman-like setting with spring water fed rivers at the upstream end would explain the CIV sedimentary record to have been responsive to such discharge shifts. P1 and P2 as the most widespread peat horizons could well be the result of a more

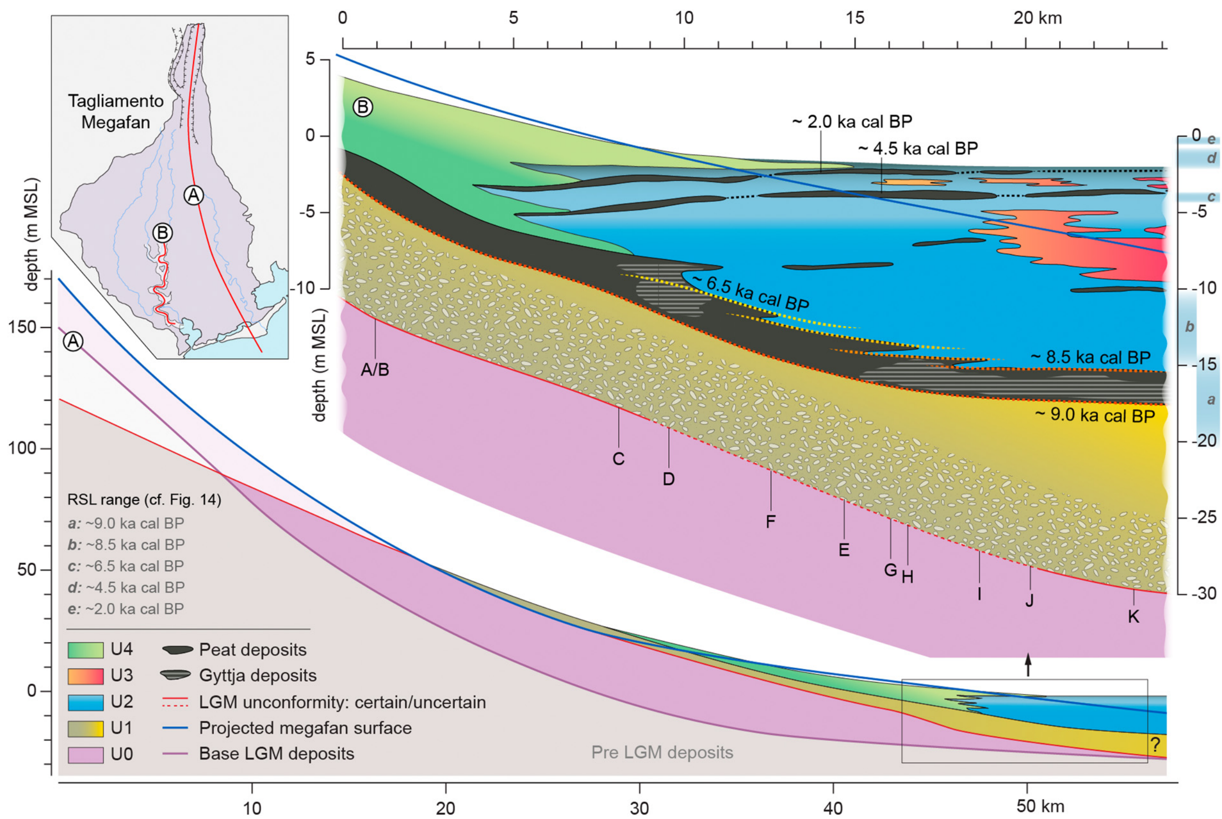


Fig. 12. A – Idealized longitudinal profile of the Tagliamento megafan showing the relation between the apical gorge and the distal fluvial incisions. B – Longitudinal profile of the CIV; the dashed lines provide an indication of the different time relations among the sedimentary units.

pervasive hydroclimatic forcing (and vice-versa the lagoonal incursion separating them). The fall-back explanation is to see the P1 and P2 developments as response to the gradual silting up of the lagoon as the consequence of relative slowdown of the sea-level rise (also explaining the termination of U3, discussed above).

In the first case, the freshening of the lagoon rim waters and salt marshes is controlled by upstream factors, which can be identified in the temporary flowing of a stream into the valley, in the effect of distal Tagliamento floods or in climatic-driven forcing related to the precipitations in the area. The new sedimentary input can promote a temporary shift from a lagoon to a brackish/freshwater swamp environment with a temporary rise of the valley floor above mean sea level, while also providing a higher freshwater discharge. The P1 peat layer, dated at ca. 4.5 ka cal BP, falls exactly in a period of enhanced flooding activity recorded in Europe and, more specifically, in the study area (Benito et al., 2008; Macklin et al., 2010; Rossato et al., 2015; Andrič et al., 2020), thus endorsing the hypothesis of an upstream control. Moreover, around 4.5 ka cal BP the Tagliamento experienced an important avulsion phase (Fontana, 2006) which led the river to temporarily follow also the direction of Lemene River (Fig. 2; Fontana, 2006).

The second case implies a regional signal given by a decrease in the rate of the sea-level rise, which would had left space to the groundwater and the runoff/spring water discharge. As this process would be entirely climatic-controlled, other pieces of evidence should be expected, such as a clear signal on the marine record and the presence of indicators in the filling successions of the other incised features of the northern Adriatic Sea. Variation in the rate of sea-level rise can be replaced by a different lagoon sedimentation modulated by local morphological factors, such as the temporary presence of sandy spits or barriers that change the connection of lagoon and the open sea. It must be noticed that the presence of several bottlenecks (Fig. 13) along the incised valley may have facilitated the formation of such barriers. It is not unlikely that the extent and the southern boundary of horizon P2 could also have been influenced by an ancient human intervention for the reclamation of the area. It is worth noting that the Romans reclaimed large sectors of the alluvial plain, altering the surface hydrography and probably affecting also the water circulation in the valley bottom, especially near Concordia (cf. Marcello and Comel, 1963; Fontana, 2006, 2015).

5.4. Differential sediment compaction

Given the near-coastal setting it is possible to assume that the peat layers discussed in Section 5.3 originally formed almost at the same elevation, or just slightly above, the paleo sea-level. Dates from peats sampled at locations that have suffered least from compaction since deposition would be Sea Level Index Points and those from sites with post-depositional compaction "terrestrial limiting" data points (e.g. Van de Plassche, 1986; Horton and Shennan, 2009; Vis et al., 2015; Hijma and Cohen, 2019). The majority of datapoints obtained from the fill of the CIV are of the latter type. While the accumulation of organic material in waterlogged environments can be assumed to take place in almost-horizontal conditions, the cross-sections show the peat and organic layers to exhibit marked undulation (Figs. 7 to 9). This shows them to have been differentially compacted, especially where they are overlain by medieval Tagliamento silts (Unit U4) and underlain by many meters of soft fine-grained lagoonal deposits (lower half of Unit U2). Height differences up to 2 m are observed in places (e.g. Fig. 8-F). The thickness of the peat beds has been affected as well. Direct comparison with available RSL curves (Peltier, 2004; Lambeck et al., 2011) provide a first, although rough, external evaluation of the subsidence induced by sediment compaction (Fig. 14). For layers P1 and P2, it has earlier been inferred that they originally formed within 1.5 m above MSL (Vacchi et al., 2016). This was a general limit for such lagoon rim peats in the wider NE Italian coastal plain, in the liman setting of the CIV it could well have been less.

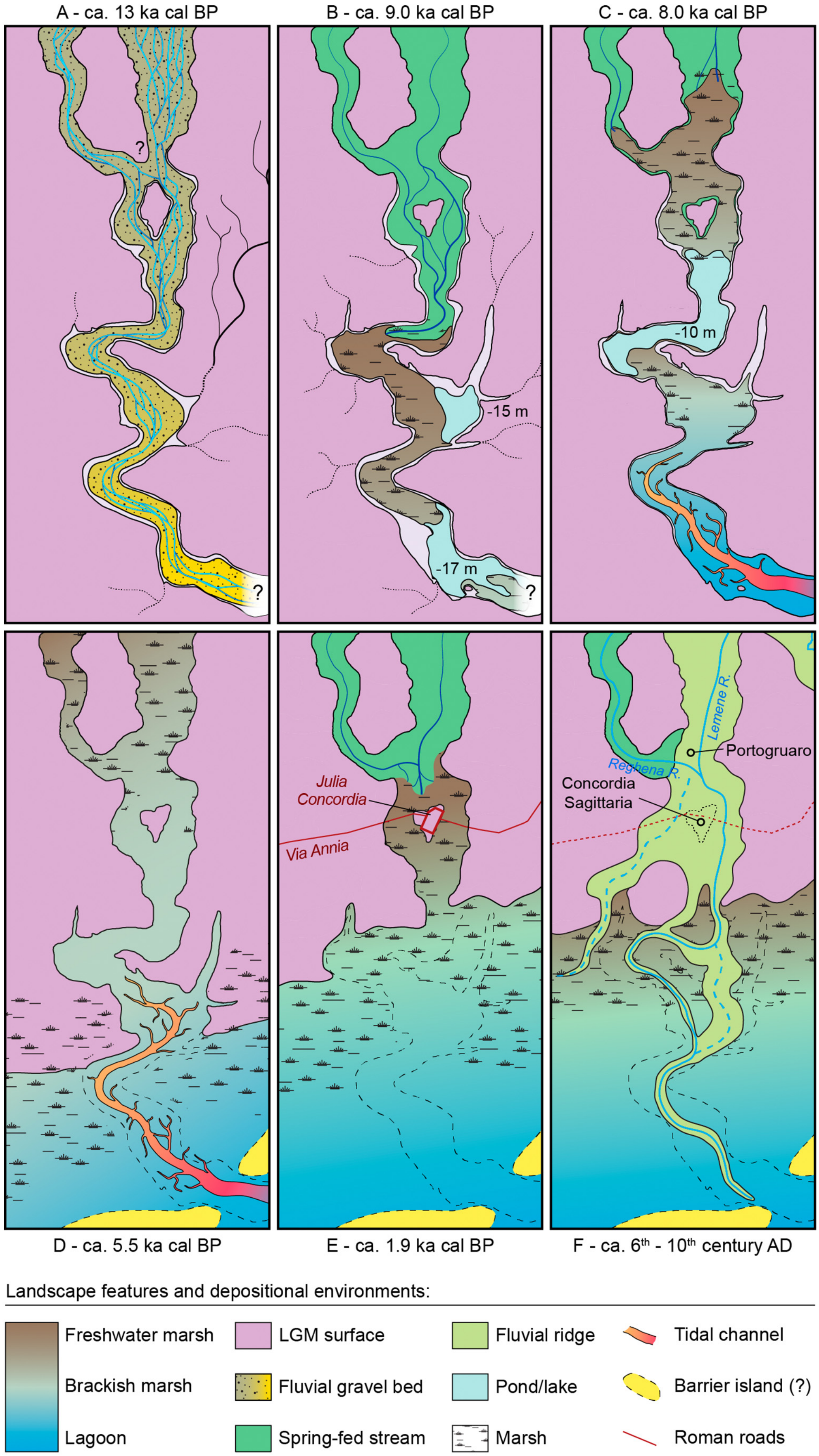


Fig. 13. Graphic overview of the evolution of the CIV.

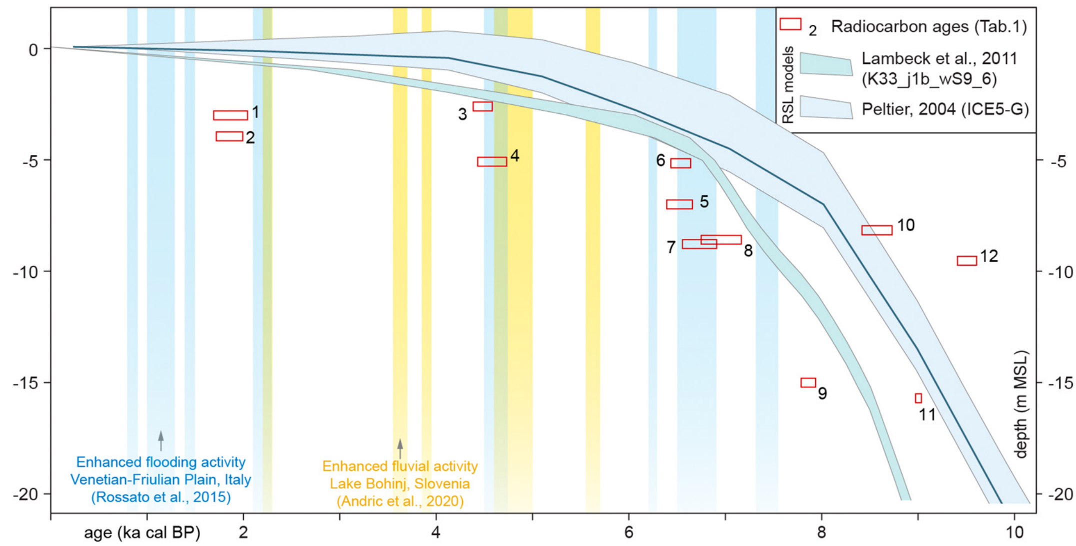


Fig. 14. Available RSL models for the northern Adriatic.

The current encounter depth thus suggests maxima of 4 to 7 m of downward movement owing to compaction (samples #2 and #4; Fig. 14).

5.5. Medieval burial of CIV and modern evolution

The present landscape of the study area has been strongly imprinted by the Medieval floods of Tagliamento and the related alluvial deposits (Fontana et al., 2019a), which almost sealed most of the CIV (#13 in Fig. 2). In particular, the flood phase occurred between the end of 6th and 7th centuries, with a major event around 589 CE. This phase resulted in an almost continuous sedimentation along the valley until 2 km south of Concordia (*Section D*) while, downstream, it fringed along several fluvial ridges. With its convex morphology, the large fluvial ridge formed along the top of the valley of Lemene River partly blocked the outflow of the valley now used by Reghena River. This difficult drainage situation led the valley of Reghena to experience stagnating conditions, favouring the accumulation of plant remains, as documented in *Section A*, where the thickness of peat deposits is much significant than in the other valley. The Medieval deposition sealed the former surface at the base of the valley, where formerly was accumulating the peat horizon P2.

The sedimentation of U4 was very fast in the general perspective of the evolution of the CIV, as it took place in a period spanning from few years to some decades, and it led to the deposition of 1 to 4 m of sediments. This depositional phase dramatically changed the topography and completely sealed some important portions of the CIV, probably triggering the compaction of the previous unconsolidated lagoon and organic deposits (Fig. 10). It is worth noting that reclamation had been already carried out in some areas since the Roman period, but in the coastal sector it was strongly enhanced since the beginning of the 20th century, when pumping stations and canals started to maintain the groundwater table at least 1 m lower than the ground. It is likely that this is the major cause for the deformed geometries displayed by the sedimentary markers of the upper part of the valley infill.

6. Conclusion

This work allowed to map the geometry and infill of an incised valley carved by the Tagliamento River in the distal Friulian Plain over a length of 25 km with unprecedented detail. Chronometric, sedimentological and paleoenvironmental information allowed to reconstruct the phases of incision (post-LGM) and burial of this system (Holocene transgression), and relate the dynamics to the Last Glacial (LGM megafan development, geomorphological system understanding) and Holocene (Early Holocene environment, NE Adriatic Sea transgression, coastal plain evolution) of NE Italy at large. In particular:

- The entrenching of the river started after 19.5 ka cal BP and lasted to at least until 14 ka cal BP. The circumstances that lead to the formation of the river carving the CIV can be related to the interplay of spring-fed river head-cutting and Tagliamento River flood water routing. In the case of the CIV, this culminated into a Tagliamento avulsion, exacerbating the laterally and vertically eroding tendency. Its deposits are the basal unit of the CIV (U1). Elsewhere on the megafan surface, downstream of the spring belt, a series of further head-cutting incised valleys are seen as originated with essentially similar mechanics, only differing in duration and degree that they were used as conduits by the Tagliamento River branches.
- The Tagliamento stopped using the CIV at the end of the Lateglacial or in the earliest Holocene, which gave way for a sediment-starved, spring-water fed valley floor environment. This is recorded by modest soil formation in the top of Unit U1, and its burial by a peat layer (P0) resting on top, and dated between 9.6 and 8.4 ka cal BP. The subregional occurrence of gyttjaic deposits reveals rare lacustrine environments to have been present within the valley. Their first discovery in the NE Italian lowlands holds great potential for the paleoenvironmental reconstruction of the area in the Early Holocene.
- The marine transgression that affected the study area from the Middle Holocene onwards (ca. 8.0 ka cal BP) led to the submersion of the CIV and its southern shoulders. A lagoon environment occupied the CIV for considerable distance inland, making it a liman (by around 6.5 ka cal BP). The lagoon lasted for several millennia within the valley. Gradual silting up and events of relative freshening, notably at 4.5 ka cal BP, and between the 1st millennium BCE and the 6th century CE, caused freshwater peat layers to intercalate with lagoonal deposits. We provide arguments supporting an hydroclimatic cause for such processes (the spring-fed aspect of the CIV continued in the lagoon liman stage) combined with seaward morphodynamics (variable connection of lagoon to open sea).

Declaration of competing interest

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

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