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Late Quaternary palaeoenvironmental evolution of the south-eastern Alpine foreland basin from multi-proxy analysis

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Abstract:	The multidisciplinary analysis of two long sedimentary successions of continental and shallow marine deposits from the Venetian plain (NE Italy), provides new data on the stratigraphic architecture and the landscape evolution of the south-eastern Alpine foreland basin during the last 210-220 ka, with further evidences of a warm temperate phase older than MIS 8. We present and discuss a detailed multi-proxy data set from these successions (GER1 and CB cores). The results of stratigraphic, palynological and micropaleontological analyses are cross-interpreted, showing the potentiality of building a composite section of two close continental successions within the same alluvial system, the Brenta megafan, with 15 km distance between cores along a downstream direction. The chronology of the upper part of the cores is supported by radiocarbon dating, showing the presence of Last Glacial Maximum (LGM) and post-LGM fluvial deposits. Lower down, the estimated chronology relies on the tight integration between palynostratigraphy and lithostratigraphy, as well as on the correlation with other regional biostratigraphic records and the Northern Hemisphere/global isotopic record. The only marine transgression present in the studied successions is attributed to the MIS 7c and constitutes the basal tiepoint for the correlation between the two cores. Below the MIS 7c transgressive marine surface is a fluvial succession with weakly-developed paleosoils and scant pollen content suggesting cold climate (possibly MIS 8), that lies on top of a thick peat showing palynological evidence of a warm temperate climate. The occurrence of well-preserved Pterocarya pollen in the basal peat level (GER1 core) provides new insights for the chronological framing of the problematic last occurrence of Pterocarya in the southern alpine area. Whilst mixed temperate forest persisted throughout MIS 7c-7a, conifers spread during MIS 6. By this time, a glaciofluvial aggradation phase is recorded, highlighting the strong relationship between glacial maxima and alluvial aggradation in the Venetian plain. None of the drilling sites were reached by the Last Interglacial sea transgression. However, the Eemian forest signature is well recorded in CB core, and the following Early to Middle Würm stadial-interstadial sequence is clearly outlined thanks to the joint analysis of the two successions. Broad-leaved thermophilous forests disappeared at the end of the Early Würm and only Pinus and Betula persisted throughout the LGM, during which a chronologically well-constrained glaciofluvial aggradation occurred. The last depositional event corresponds to the post-LGM cut-and-fill of fluvial incised valleys in GER1 core, and to soil evolution and very thin burial by Brenta River fluvial deposits in CB core.

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To Editorial Office
Quaternary Science Reviews

Dear Editors,

I submit to Quaternary Science Reviews a manuscript about the climatic and stratigraphic evolution of the Venetian Plain (NE Italy) during the late Quaternary:

Late Quaternary palaeoenvironmental evolution of the south-eastern Alpine foreland basin from multi-proxy analysis

A. Marcolla*, A. Miola, P. Mozzi, G. Monegato, A. Asioli, R. Pini, C. Stefani

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The research gives an important contribution to the knowledge about the stratigraphic, climatic and environmental evolution of the Venetian plain (NE Italy) since the Middle Pleistocene and enriches the proxy dataset available in the south-eastern Alpine foreland basin.

With the present letter I am stating that:

- All authors contributed substantially to the research. Arianna Marcolla: Investigation, Data analysis, Writing – Original draft preparation; Antonella Miola: Investigation, Methodology, Data analysis; Paolo Mozzi: Conceptualization, Investigation, Writing – Review & Editing; Giovanni Monegato: Conceptualization, Validation, Writing – Review & Editing; Alessandra Asioli: Investigation, Data analysis; Roberta Pini: Validation, Writing – Review & Editing; Cristina Stefani: Conceptualization, Supervision;
- The final version of the manuscript is approved by all the authors;
- The manuscript is original and it has not been submitted for publication until now, or until your revision has been finished;
- The included figures are original;
- The authors 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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July 03, 2020

..Arianna...Marcolla.......

Highlights

- The last two glacial cycles are well recorded in Central Venetian plain (NE Italy).
- Thick alluvial aggradation phases correlate to glacial culminations in the Alps.
- MIS 7.3 transgression is recorded as proximal marine facies in C. Venetian plain.
- Continental conditions persisted in C. Venetian plain during MIS 5.5 sea highstand.
- *Pterocarya* is only present in sediments older than 220 ka.

Late Quaternary palaeoenvironmental evolution of the south-eastern Alpine foreland basin from multi-proxy analysis

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Abstract

The multidisciplinary analysis of two long sedimentary successions of continental and shallow marine deposits from the Venetian plain (NE Italy), provides new data on the stratigraphic architecture and the landscape evolution of the south-eastern Alpine foreland basin during the last 210-220 ka, with further evidences of a warm temperate phase older than MIS 8.

We present and discuss a detailed multi-proxy data set from these successions (GER1 and CB cores). The results of stratigraphic, palynological and micropaleontological analyses are cross-interpreted, showing the potentiality of building a composite section of two close continental successions within the same alluvial system, the Brenta megafan, with 15 km distance between cores along a downstream direction. The chronology of the upper part of the cores is supported by radiocarbon dating, showing the presence of Last Glacial Maximum (LGM) and post-LGM fluvial deposits. Lower down, the estimated chronology relies on the tight integration between palynostratigraphy and lithostratigraphy, as well as on the correlation with other regional biostratigraphic records and the Northern Hemisphere/global isotopic record.

The only marine transgression present in the studied successions is attributed to the MIS 7c and constitutes the basal tiepoint for the correlation between the two cores. Below the MIS 7c transgressive marine surface is a fluvial succession with weakly-developed paleosoils and scant pollen content suggesting cold climate (possibly MIS 8), that lies on top of a thick peat showing palynological evidence of a warm temperate climate. The occurrence of well-preserved *Pterocarya* pollen in the basal peat level (GER1 core) provides new insights for the chronological framing of the problematic last occurrence of *Pterocarya* in the southern alpine area.

Whilst mixed temperate forest persisted throughout MIS 7c-7a, conifers spread during MIS 6. By this time, a glaciofluvial aggradation phase is recorded, highlighting the strong relationship between glacial maxima and alluvial aggradation in the Venetian plain. None of the drilling sites were reached by the Last Interglacial sea transgression. However, the Eemian forest signature is well recorded in CB core, and the following Early to Middle Würm stadial-interstadial sequence is clearly outlined thanks to the joint analysis of the two successions. Broad-leaved thermophilous forests disappeared at the end of the Early Würm and only *Pinus* and *Betula* persisted throughout the LGM, during which a chronologically well-constrained glaciofluvial aggradation occurred. The last depositional event corresponds to the post-LGM cut-and-fill of fluvial incised valleys in GER1 core, and to soil evolution and very thin burial by Brenta River fluvial deposits in CB core.

Keywords: Middle and Upper Pleistocene glaciations; Venetian plain; Chrono- biostratigraphy; Vegetation dynamics; Sedimentary evolution; Alluvial successions

1. Introduction

The European Alps and their forelands are key areas for detecting Quaternary climate and environmental variations, as they provide different valuable proxies for regional reconstructions of vegetation (e.g., Grüger, 1989; Drescher-Schneider, 2000; Müller et al., 2003; Pini et al., 2009, 2010;

Monegato et al., 2010, 2015; Duprat-Oualid et al., 2017), climate (e.g., Spötl et al., 2007; Heiri et al., 2014; Luetscher et al., 2015) and sedimentary systems (e.g., Garzanti et al., 2011; Fontana et al., 2014). Improving of these datasets in terms of accuracy, time resolution and time scales is crucial for the development of robust paleoclimate reconstructions that can allow better understanding of global circulation during climatic extremes (Martinson et al., 1987; Siddall et al., 2006; Braconnot et al., 2007; Löfverström et al., 2014; Löfverström, 2020).

The south-eastern Alpine foreland basin lies between the Mediterranean region and the southern side of the Alps (Fig. 1). It shows considerable subsidence rates (0.5 - 1.3 mm/yr; Bortolami et al., 1984; Carbognin et al., 2002, Kent et al., 2002) that causes the Venetian-Friulian plain to act as a sedimentary basin, preserving stratigraphic evidence of local climatic fluctuations, as well as of the Middle-Late Pleistocene global glacioeustatic cycles (Kent et al., 2002; Massari et al., 2004; Pini et al., 2009; Monegato et al., 2011). Its sedimentary evolution since the onset of the Pleistocene glaciations (Muttoni et al., 2003) has been strongly influenced by glacial-interglacial cycles. These caused the development of glacier piedmont lobes during cold periods (Monegato et al., 2007; 2017), even in relatively small alpine catchments, while the proximity of the Adriatic Sea led to marine transgressions during interglacial periods.

The thick glaciofuvial succession related to the aggradation phase of the Last Glacial Maximum (LGM, 26.5-19 ka, Clark et al., 2009) provided valuable evidence for detailed reconstructions of the climatic and environmental changes occurred since the LGM (Mozzi, 2005; Miola et al., 2006; Mozzi et al., 2010; Monegato et al., 2011; Fontana et al., 2008, 2010a, 2014; Rossato et al., 2018). Conversely, information on the pre-LGM evolution are scarce because of the significant depth, generally more than 30 meters, at which the relative sediments are found (Fontana et al., 2010a), while the cropping out of the succession is scattered and limited (Venzo, 1977; Monegato et al., 2010; Rossato et al., 2013).

The available continuous stratigraphic records, whose investigation provided information on the last climatic cycles older that the LGM in the Venetian-Friulian plain, are Venezia1 core (Müllenders et al., 1996; Massari et al., 2004), the AzzanoX core (Zanferrari et al., 2008; Pini et al., 2009), and Lake Fimon cores (Pini et al., 2010; Monegato et al., 2011, Fig. 1). These last two provided continuous and detailed biostratigraphic records for the last glacial-interglacial cycles and are, therefore, reference cores for the correlation of pre-LGM successions in the Venetian-Friulian plain.

In the present work, we reconstruct the palaeoenvironmental and vegetation history in the central Venetian plain since the Middle Pleistocene, basing on the palynology, micropaleontology, physical stratigraphy and radiocarbon dating of two long cores: the new Geriatrico 1 core (GER1), 130 m deep, and the Ca' Borille core (CB), 103 m deep, only partly studied by Cucato et al. (2012). We furthermore discuss regional stratigraphic correlations with other master cores in the Venetian-Friulian plain and surrounding areas. The main aim of this research is to reconstruct the sedimentary and environmental evolution of this foreland basin in relation to global climatic and eustatic changes. The studied boreholes lie close to both the mouth of major Alpine valleys (i.e. Brenta, Astico and Piave valleys) and the Venice Lagoon and Adriatic coastal plain. Their centrality between the Alps and the Adriatic Sea makes them key sites for analyzing the relative forcing of mountain glaciations and glacio-eustatic fluctuations on the alluvial and coastal systems.

2. Geological setting

The Venetian-Friulian plain is part of the foreland basin of the Southern Alps (e.g., Massari et al., 1986; Stefani et al., 2007; Mancin et al., 2009) and, though geographically-speaking it is the eastern extension of the so-called Po Plain, it has been formed by rivers that are not presently tributaries of the Po River (Castiglioni, 1999).

Since the Mesozoic, its structural setting was affected by the combined dynamics of the Southern Alps, the Northern Apennines and the External Dinarides, which led to a complex and fragmented architecture, influencing the deposition of the sediments during the Quaternary (e.g., Massari et al., 1986; Pola et al., 2014; Toscani et al., 2016). This configuration has led to a persistent subsidence, affecting the area during the Middle-Late Pleistocene and still ongoing (Carbognin et al., 2002; Kent et al., 2002), which determined the sensitivity of the plain to the major eustatic fluctuations, with the consequent alternate deposition of continental, transitional and marine sedimentary units. The study area is located close to the SW boundary of the Venetian-Friulian foredeep, that is marked by the NW-SE trending, active Schio-Vicenza strike-slip fault system (Pola et al., 2014 and references therein).

Large sectors of the present surface of the Venetian-Friulian plain consist of glaciofluvial sediments deposited during the considerable LGM aggradation phase, which in the Alps corresponds to the late Würm climate-stratigraphic unit (Chaline and Jerz, 1984) with the basal boundary at 35 ka cal BP (Spötl et al., 2013). These deposits formed fan-shaped alluvial features, properly called fluvial megafans (Fontana et al., 2008; 2014, Fig. 1).

Some high–quality deep boreholes drilled in the framework of different geological and geomorphological studies (Fontana et al., 2010a), allowed to investigate pre-LGM deposits and, specifically, to reach the sediments related to the penultimate glacial culmination, corresponding to the MIS 6 (Martinson et al., 1987). The top of these deposits is found at 70-45 m asl north-east of Venice while south-west its depth is comprised between 100 and 80 m asl (Massari et al., 2004; Pini et al., 2009; Fontana et al., 2010b).

The study area lies in the distal fine-grained sector of the megafan formed by the Brenta River (Mozzi et al, 2010, 2013).

The Middle and early Late Pleistocene stratigraphy of the area is poorly known, due to the lack in detailed stratigraphic studies deriving from the scarcity of deep cores available. Nevertheless, some valuable stratigraphic and paleontological information derived from two deep boreholes drilled in the thirties and fifties in the area of Padova (Accordi, 1950; Dieni and Proto Decima, 1960).

During the last 30 ka, the Brenta megafan experienced dramatic depositional changes in response to major climatic and environmental variations (Mozzi, 2005; Mozzi et al., 2013; Fontana et al., 2008 and 2010a; Rossato et al., 2018). A dominant depositional trend occurred during the aggradation phase of the LGM (26.5 – 17.5 cal ka BP), with sedimentation rates up to 3 m/ka (Rossato and Mozzi, 2016), that was followed by a sharp erosive phase during deglaciation at around 17.5 ka. This latter led to the cutting of incised valleys, subsequently filled by Late Glacial and Holocene deposits (Iliceto et al., 2001; Mozzi, 2005; Mozzi et al., 2010, 2013; Cucato et al., 2012; Ninfo et al., 2016).

3. Materials and Methods

We explored the suitability to paleoecological, paleontological and stratigraphic analysis of two deep boreholes drilled in the Brenta River megafan: the 130 m-long GER1 and the 103 m-long CB boreholes. Drilling sites are located in the Padova city center at 13 m asl and 15 km south of Padova at 4.2 m asl, respectively (Fig 1). Both the boreholes were drilled through continuous rotary drilling method. The recovery was almost total for both the core (about 98-99%), but about 15% of CB sediments were reworked.

We adopted a multidisciplinary approach to the study of the cores' stratigraphy and correlations, analyzing different proxies to allow the recognition of sedimentary environments, climatic and environmental conditions. The following proxies have been considered:

- lithofacies and their assemblages;
- major unconformities (soils and erosional surfaces);
- pollen and non-pollen palynomorphs (NPPs) content;
- macro- and micropaleontological content.

Radiocarbon dating was used to constrain the chronology of the upper parts of both cores.

3.1 Lithofacies analysis

Both stratigraphic successions were studied in detail through the macroscopic observation of the deposits. Different lithofacies were recognized based on grain size (Udden-Wentworth scale - Udden, 1914; Wentworth, 1922) and considering other sedimentological features such as sedimentary structures, distribution trend, fossil content, bioturbation, organic content, unconformities and paleosoils. The simplified lithostratigraphic description of the cores is reported in the stratigraphic logs (Fig. 2).

The paleosoils were described according to Jahn et al. (2006), based on the soil texture, color (Munsell Soil Color Charts), reaction to HCl 10% solution on a four-degree scale, and the presence of hard and soft carbonate concretions (Tab. 1). In order to allow comparison between different stages of soil development, the paleosoils were grouped in three classes as follows, using evidence of vertical carbonate leaching and precipitation along the soil profile: poorly developed, moderately developed, well developed.

The combined analysis of the lithofacies and main unconformities aimed at recognizing major stratigraphic units, as well as defining the different sedimentary environments.

3.2 Pollen and NPPs analysis

Peat intervals and fine-grained organic levels of both cores were systematically sampled for pollen analysis. 64 samples were processed for GER1 and 87 for CB (Fig. 2).

Preparation of samples followed standard methods (Faegri and Iversen, 1989), including HCl 10%, hot KOH 10%, sieving (Ø= 250 µm), HF 39% (hot for GER1 samples; cold for 48 hours for CB samples), acetolysis and sieving (Ø= 10 µm).

The amount of sediment treated per sample depends on the lithology: a volume of 1-3 cm^3 of organic-rich sediments, up to 10 cm^3 of organic poor-clay. *Lycopodium* spores were added to obtain estimates of palynomorph concentration per cm^3 of sediment according to Stockmarr (1971).

Identification was carried out under an optical microscope at a magnification of ×400, using Moore et al. (1991), Beug (2004), Reille (1992 – 1995) and the reference collection of the Lab. of Palynology at University of Padova. NPPs were identified on the basis of specialized literature reviewed by Miola (2012); however, only foraminifers were considered in the discussion since the main aim was the paleoclimatic reconstruction.

The preservation of the pollen types was analyzed according to Huntley and Birks (1983) and Berglund (1986).

At least 200 pollen grains were identified for each sample (GER1: min 202, max 3075, av. 844; CB: min 219, max 1279, av. 656). The pollen samples where Upland pollen sum (Poaceae, Alnus and Cichorioideae, Hygrophytes, Hydrophytes and undetermined excluded) was less than 100 grains were not represented in the pollen diagrams. In these samples the Upland pollen concentration was generally less than 500 grains/ml.

The pollen percentages are based on trees, shrubs, upland herbs (including xerophytes) (PS), with the exclusion of *Alnus glutinosa* type and Poaceae. The abundance of these taxa is quite variable and probably over-represents plants growing in local sedimentary environments, thus biasing the general trend of % curves of regional vegetation taxa (Faegri and Iversen, 1989). Moreover, we decided to use this PS to compare our data with two reference pollen records from the same geographical area (Pini et al., 2009; 2010), where the same PS has been used as basis for the percentage calculation. For this reason, also Cichorioideae have been excluded from the PS. Percentage of *Alnus*, Poaceae, Cichorioideae, Hydrophytes, Hygrophytes, undetermined (degraded) pollen and each group of NPPs have been calculated on the basis of PS plus the counts of each group.

Pollen diagrams were drawn using the software *Tilia 2.6.1* (Grimm, 1991-2019) and Adobe Illustrator CC2018 for further graphical processing (Figs. 3, 4).

3.3 Micropaleontological analysis

21 sediment samples for foraminifera analysis were taken from GER1 core (Fig. 2). The samples, with weight ranging between 100 and 200g, were dried at 50°C and washed through a 0.063mm mesh sieve. The fraction >0.063mm was examined at stereomicroscope.

Regarding the samples processing from CB core, the reader is referred to Cucato et al. (2012). Summarizing, 30 samples were washed in wet conditions, sieved through a 0.045 mm mesh sieve and stored in a 50% ethanol-50% water solution. The smaller mesh was selected to check the presence of testatae amoebae.

The semi-quantitative analysis for foraminifera assemblages was carried out through a stereomicroscope (in wet conditions for the CB samples) at specific level for both the cores.

3.4 Radiocarbon chronology (Tab. 1)

The chronology of the upper 35 meters of both cores was investigated through the radiocarbon dating of peat samples (Fig. 2). The dated samples were extracted from the inner part of the cores and wrapped in aluminum foil to avoid contamination. AMS dating of bulk samples was performed at the AMS Laboratory, ETH Zürich for GER1 core and by the Tandem Laboratory, University of Uppsala for CB core. ^{14}C ages were calibrated using the online radiocarbon calibration programme *OxCal* (version 4.3, calibration curve IntCal13; Bronk Ramsey, 2009). Tab. 1 summarizes the main information on the available radiocarbon chronology, i.e. dated levels and their provenance, type of material dated, lab code assigned to each sample, radiocarbon age and calibration.

4. Results and Discussion

4.1 Lithostratigraphy and sedimentary environments

The simplified lithostratigraphic logs of the sedimentary successions investigated in the GER1 and CB cores are reported in the Fig. 2.

Main stratigraphic units are outlined hereafter. The depths are relative to the ground surface.

4.1.1 Geriatrico 1 log (GER1)

Unit GER1 - I (130.00 – 118.65 m)

The bottom part of the unit is a 0.40-m thick medium-fine sand layer with scattered mud clasts and pebbles. Above this layer and up to 119.30 the unit consists of medium-fine gravel with sandy matrix. Finally, a sharp transition to silty clay – clay levels with rounded pebbles is observed.

Interpretation: infilling of a fluvial channel, incised within the alluvial plain during a deglaciation erosive phase, in agreement with what observed at the end of LGM in the Venetian plain (Iliceto et al., 2001; Mozzi, 2005; Mozzi et al., 2010, 2013; Cucato et al., 2012; Ninfo et al., 2016).

Unit GER1 - II (118.65 – 106.10 m)

The bottom of the unit corresponds to the base of a 0.4-m thick peat level, one of the thickest in the whole succession. Above it, alternations of silty and silty clay occur, sometimes organic or peaty and bioturbated, and fine sand which shows thin lamination mainly toward the top.

The upper part is characterized by the presence of five poorly developed paleosoils (Soils 1-5 – GER1, Tab. 2).

Interpretation: proximal floodplain with frequent crevasse splays and a transition to lacustrine conditions toward the top. The presence of soils embedded in the succession indicates recurrent periods of floodplain stability.

Unit GER1 - III (106.10 - 72.35 m)

Mainly fine-medium sand with silty intercalations and frequent bioturbation and shell fragments until about 100 m depth, followed by about ten meters of alternations between predominant silty levels, often laminated and rich in plant remains, and fine sand with frequent peat intervals. Until the unit top, alternation between fine – medium sand and silt with frequent millimetric plant remains and common parallel and cross laminations. At the top, the unit has a 0.5 m thick peat level, the thickest one of the whole sedimentary succession.

A bi-sequential moderately developed paleosoil (Soil 6-GER1) is present between 73.80 and 74.90 m depth (Tab. 2).

Interpretation: transition from an initial paralic environment such as a delta front, which evolves to delta and finally to alluvial plain conditions.

Unit GER1 - IV (72.35 - 50.15 m)

The unit bottom is represented by a sharp transition to medium-coarse sand, which is found as prevalent grain size until 63.00 m, in alternation with fine sand and silt.

Until the top, the sequence is characterized by the alternation between finer sediments with the prevalence of both sandy and clayey silt on fine sand and the presence of organic and peaty levels.

Between 50.40 and 50.15 m of depth frequent fresh-water shells fragments are found.

A well-developed soil (Soil 7-GER1) is found at the unit top (Tab. 2).

Interpretation: fluvial channel deposits with a transition to a proximal floodplain environment toward the top, within an aggrading alluvial plain.

Unit GER1 - V (50.15 – 30.00 m)

Mainly medium-fine silty sand with silty and clayey levels in the lower part of the unit, with a decrease of grain size and an increase of organic levels in the upper part. Here several peat intervals are present.

A bi-sequential moderately developed paleosoil (Soil 8-GER1) is found between 40.75 and 41.45 m of depth (Tab. 2).

An intercalation of organic carbonaceous matter in silt, sampled at 30.98 m of depth, yielded a radiocarbon age of 40595 ± 340 cal a BP.

Interpretation: alluvial floodplain sediments, deposited in an environment characterized by common crevasse splays, less frequent toward the top.

Unit GER1 - VI (30.00 – 13.65 m)

Mainly fine - medium sand, sometimes laminated, with subordinate silt intercalation until 23.00 meters depth, followed by an increase in silty fraction and the occurrence of several 3-4 cm thick peat levels.

Interpretation: transition from a fluvial channel with sandy bars to floodplain conditions characterized by sporadic swamping, within an aggrading alluvial plain.

A peat intercalation in organic fine sand, sampled at 20.80 m of depth, yielded and age beyond the limit of the ^{14}C method and it is interpreted as reworked, whereas a peat sample collected at 14.08 m has been dated 23187 ± 260 cal a BP.

Unit GER1 - VII (13.65 – 2.35 m)

Prevalent medium to coarse sand with common pebbles up to 2 cm. The base could be erosive and the upper part is composed by massive silt.

Interpretation: fluvial channel deposits, probably related to the infilling of a previous incised valley.

Unit GER1 - VIII (2.35 – 0.00 m)

Reworked anthropogenic fill.

4.1.2 Ca' Borille log (CB)

Unit CB - I (103.00 – 99.23 m)

Mainly fine-medium sandy succession with intercalations of sandy and clayey silt, rarely peaty silt. Frequent wood remains and arenaceous concretions containing pyrite. Short fining-upward intervals are recognized.

Interpretation: predominant alluvial floodplain deposits, deposited in an environment characterized by frequent crevasse splays.

Unit CB - II (99.23 – 85.62 m)

Grey and grey-greenish sandy sediments with subordinated intercalations of silt, sandy silt and clay. Persistent presence of mollusk shell fragments until 87 m depth, concentrated into two levels of biocalcirudite (between 99.00 and 98.55 m) containing prevalent *Glycimeris*, *Tellina*, *Chlamis*, *Cardium* and subordinated gastropod shell fragments, arenaceous – silty concretions covered by bryozoa and serpulids, and rare wood remains. The clayey levels show evidence of bioturbation.
Interpretation: proximal marine deposits pertaining to a succession evolving from a retro-barrier environment to shore-face conditions.

Unit CBB - III (85.62 – 73.08 m)
Fine sand to clay, often organized in fining-upward sequences. Several peat levels, with a maximum thickness of 0.25 m, are included in this unit. Frequent wood remains are present, mainly concentrated in the lower part of the unit. Toward the top some marine shell fragments with strong ornamentation (probably *Cardium*) occur. The entire unit is characterized by widespread bioturbation.
Interpretation: delta plain deposits.

Unit CB - IV (73.08 – 56.96 m)
Medium-coarse sand to clay, with common presence of peat intervals in the lower part of the unit. The bottom of the succession corresponds to the base of a 0.9 m thick peat level, the thickest one all along the succession. Other thinner peat intervals are found up to 68.00 m depth, while they are absent in the upper part of the unit.
A major erosive surface, representing the base of a channel body, is found at 60.50 m depth. The channel body is characterized by medium-coarse sand passing upward to fine sand with silt and clayey silt intercalations. The unit top is marked by a sharp passage from fine sand to clay with evidence of load deformation structures.
Interpretation: floodplain deposits with the establishment of a fluvial channel. The lower part of the unit can be attributed to an area distant from the river, where wetlands could develop. The middle

part of the unit corresponds to proximal floodplain conditions with abundant crevasse splay deposits, followed by the establishment of a channel body with sandy sedimentation.

Unit CB - V (56.96 – 50.67 m)

Mainly grey and grey-greenish clay and organic clay successions, sometimes organic, with thin parallel lamination. Sporadic presence of thin silt laminations between 56.00 and 55.00 m and toward the unit's top. Some peat intervals are found between 53.00 and 52.00 m. A moderately developed paleosoil (Soil 1-CB) is found between 50.60 and 52.00 m (Tab. 2).

Interpretation: lacustrine conditions evolving to wetland and finally to floodplain conditions.

Unit CB - VI (50.67 – 31.50 m)

The unit starts with a sharp transition to medium sand and it is characterized by cyclical grain size variations, with recurrent fining upward sequences with a medium or fine sandy base evolving to sandy silt, silt and clay or peat toward the top. Wood remains are frequent, mostly concentrated in the peat and organic clay levels.

A moderately developed paleosoil (Soil 2-CB) is found between 49.55 and 50.00 m of depth (Tab. 2). A peat sample collected at 33.54 m of depth has provide an age beyond the radiocarbon dating method.

Interpretation: alluvial plain deposits pertaining to a succession with recurrent transition between channel and overbank floodplain conditions.

Unit CB - VII (31.50 – 17.64 m)

Mainly medium sand with subordinate coarse sand and fine sand intercalation until 26.00 m, followed by prevalent fine sand with silt. Toward the top, organic silt and peat intervals occur. An erosive surface represents the unit bottom.

A peat sample collected at 17.70 m of depth yielded a radiocarbon age of 25201 ± 585 cal a BP.

Interpretation: these sediments represent the transition from a fluvial channel with sandy bars to floodplain conditions characterized by sporadic marsh conditions.

Unit CB - VIII (17.64 – 2.55 m)

The unit starts with a transition from peaty silt to fine sand and it is divided in 3 successions:

- 8a (17.64 – 12.94 m): parallel cross-laminated fine-medium sand with increasing silt laminations toward the top. At the top, a 7 cm thick silty clay, sometimes organic, layer is present with several plant remains and terrestrial gastropod shells (*Planorbis*);
- 8b (12.94 – 9.40 m): alternation between fine sand/silty fine sand and predominant silt or organic silt;
- 8c (9.40 – 2.55 m): predominance of silt and clay with peaty intercalations.

A well-developed paleosoil with gley pedofeatures (Soil 3-CB) is found between 2.90 and 3.60 m of depth (Tab. 2). A peat sample collected at 7.52 m of depth yielded a radiocarbon age of 21194 ± 505 cal a BP.

Interpretation: the lowermost sediments are interpreted as the result of a transition from a fluvial channel with sandy bars to levee's facies and, finally to low energy floodplain conditions (8a). The interpreted depositional environment of the middle part (8b) is a proximal floodplain with common crevasse splays, whereas in the upper part (8c) distal floodplain conditions are documented.

The paleosoil within succession 8c formed in poorly drained soil conditions.

Unit CB - IX (2.55 – 0.00 m)

Silty – clayey sediments affected by modern soil development (Soil 4-CB, Tab. 2).

Interpretation: distal floodplain deposits, documenting well developed soil formation relative to the present topographic surface. Due to pedogenic processes, the upper horizon (now partly destroyed by plowing) suffered from carbonate leaching, while in the lower ones an enrichment in calcium carbonate is found as Bk horizon.

4.2 Micropaleontological results

In GER1 core foraminifera were present only in 6 samples (104.65-104.75, 103.90-103.95, 98.75-98.80, 92.65-92.70, 82.30-82.35, 80.85-80.90), and they were only benthonic. Although the foraminiferal assemblages present in CB core were already reported in Cucato et al. (2012), it is worthy to remind that among the 30 analyzed samples only two, positioned in the lower part of the borehole (97.82 and 98.44m) contained foraminifera, again only benthonic.

For a more complete view, two biofacies (A and B) and an additional facies (C), without any biosome or bioclast, are distinguished and described below, which best reflect the content of all the examined samples of the two cores.

Biofacies A1 (GER1 104.65, 103.90, 98.75, 92.65, 82.30, 80.85 m)

The samples contain abundant fine sand along with plant remains, shell remains (ostracods) and bioclasts. *Ammonia beccarii tepida* is the most common species, accompanied by *Elphidium granosum*, and by sporadic specimens of *Ammonia beccarii*, *Quinqueloculina seminulum*, *Ammonia papillosa*, *Elphidium decipiens*, *Haynesina germanica*, *Rosalina globularis*, and *Elphidium advenum*. This biofacies may be referred to a transitional environment/lagoon.

Biofacies A2 (CB 98.44 and CB 97.82 m)

Foraminifers are not rare, although scattered within micaceous very fine sand and/or plant remains and in some case (CB 97.82 m) broken or blackened. Miliolids (*Quinqueloculina oblonga*, *Adelosina longirostra*, *Q. seminulum*, *Triloculina trigonula*, *Cornuspira involvens*) are common along with *E. advenum*, accompanied by *Ammonia perlucida*, *A. beccarii*, *R. globularis*, *Asterigerinata mamilla*, *Buccella granulata*, *Elphidium granosum* and rare specimens of *H. germanica*. This biofacies, suggests a very shallow marine environment (near-shore area, < 20-25 m water depth) and it can be equated to the biofacial unit II by Jorissen (1987). Indeed, this latter occupies the zone between 7.5

and 25 m depth with substrata generally coarse, rich in Ca carbonate, poor in organic matter and characterized by a benthonic foraminiferal assemblage mainly composed by *A. beccarii beccarii*, *A. beccarii tepida*, *E. advenum*, *Ammonia perlucida*, *A. longirostra*, *E. granosum*, *E. decipiens*, *T. trigonula*, *Nonion depressulum*. However, the presence of a prairie cannot be rule out in the paleoenvironment of the examined samples, because of the presence of the epiphytic taxa *A. mamilla*, *R. globularis* and *B. granulata*.

Biofacies B (CB 12.90, 11.35, 10.62, 8.41 m and GER1 108.30 m)

Foraminifera are absent, but scattered remains of other organisms (ostracods, otoliths, gastropods such as Planorbidae or *Hydrobia* spp) are present up to common. The samples show scarce presence of very fine sand while plant remains are in some case abundant. This biofacies may suggest a transitional to continental environment with low salinity/fresh water, and it can be ascribed to the interval 8.40-12.90 m in core CB and to the sample 108.30 m in core GER1.

Facies C1 (GER1 98.20, 97.10, 95.60, 94.00, 93.60, 91.50 m and CB 85.45, 82.84, 77.82, 75.60, 52.10, 49.10, 37.06 m)

This facies includes samples presenting abundant (or only) plant remains. Very fine sand is scarce. Samples with this content could reflect both marine/transitional and freshwater environments.

Facies C2 (GER1 109.73, 105.75, 103.30, 102.25, 100.20, 94.65, 78.67, 78.25 m and CB 91.42, 100.84, 92.90, 85.80, 80.85, 75.36, 64.60, 62.28, 56.10, 54.85, 52.40, 31.90, 31.63, 31.60, 7.80, 7.21, 5.50, 2.70 m)

The samples are composed by very fine sand (in some case with oxidized clasts), scarce or absent plant remains, no foraminifera and very rare (frequently absent) small shell fragments. The samples of this facies, barren in fossil remains, may suggest a continental/fluvial environment.

4.3. Palynological results

Selected percentage pollen records from both the cores are shown in Figs. 3 and 4, whereas the complete pollen diagrams are supplied as supplementary materials (Supplementary materials 1 and 2).

The preservation of pollen grains was often modest with high percentage of undeterminable grains (up to 50%, mainly broken saccate) for both the cores. Only 34 samples of GER1 core and 67 samples of CB core yielded a statistically significant (>100 grain/g) pollen sum (PS). The pollen spectra with a lower sum were considered sterile and excluded from the diagrams.

On the basis of the pollen assemblage of terrestrial plants, which give an indication of the regional vegetation, the pollen records were subjectively divided in zones, referring also to the stratigraphic data (see Section 4.1 and Fig. 2). The supplementary materials 3 and 4 report the percentage ranges and limits in table, facilitating the distinctions of pollen zones. Whilst in GER1 10 pollen zones were identified, 14 were determined in CB. In both cores the zones numbering increases toward the top.

The reconstruction of the regional vegetation and local plant communities of each core is summarized hereafter.

4.3.1 Geriatrico 1 core (GER1)

Due to the large number of sterile levels (30 samples out of 64 analysed samples) and the widespread occurrence of not analysed sandy layers (Fig. 2 and Tab. 2), the specific limits of the 10 pollen zones are based both on the pollen associations and the stratigraphic information (Section 4.1,). Moreover, large portions of the core are unfortunately devoid of pollen data (Fig. 3, supplementary material 1, 3). Hereafter we present a description of pollen zones, with indications of their stratigraphic boundaries and reconstructed regional and local vegetations. For some pollen zones, correlations with zones identified in other pollen records from the same region are proposed.

Zone GER1.1 (117.70 - 118.65 m) - Temperate mixed forest

Arboreal pollen (AP) is represented by thermophilous and mesophilous broadleaved trees with prevalent *Quercus* undiff., *Carpinus betulus*, *Tilia*, *Fraxinus* undiff. and *Fagus*. Other deciduous trees such as *Pterocarya*, *Ulmus/Zelkova*, *Zelkova*, *Carya* and *Betula* are present. Conifers are less represented, however *Pinus*, *Abies* and *Picea* are continuously recorded.

Among the sporadic taxa the occurrence of *Buxus*, present only here and in the GER1.5 pollen zone, stands out. Moreover, among non-arboreal pollen (NAP), to be reported is the co-occurrence of Chenopodiaceae and *Limonium*, which may testify to the presence of salt marshes, and the continuous presence of *Artemisia*. Hygrophytes, Hydrophytes and Polypodiaceae occur.

Zone GER1.2 (117.20 - 117.70 m) - Pinus *forest with* Picea *and rare broad-leaved trees*

AP reaches here its lowest percentage, however it is dominant on NAP. *Pinus* is the most represented taxon followed by *Picea*, whereas decreasing values of *Abies* and increasing values of *Betula* are recorded toward the top. Broad-leaved trees are less abundant if compared with the previous zone and mostly represented by *Quercus*, *Corylus* and *Tilia*.

Xerophilous/halophilous NAP elements are continuously present and represented by *Artemisia*, Chenopodiaceae and deteriorate, probably reworked, *Limonium*, with a peak at 117.32 m depth. Hygrophytes and Hydrophytes are also present.

Zone GER1.3 (99.30 - 100.50 m) - Mixed forest dominated by Pinus

This zone is separated from the previous one by 16.71 m of sediments; no pollen grains were found in 12 samples from the interval 114.75 - 105.48 m depth.

The zone is represented by only one sample (100.00 m) with an AP assemblage constituted by *Pinus* for half. *Fagus*, *Betula*, *Pterocarya*, *Abies* and *Carpinus betulus* are present, whereas thermophilous trees are well represented by *Quercus* and *Tilia*. Among NAP, Hygrophytes and Polypodiaceae are common whereas Hydrophytes, Poaceae, *Senecio* type and *Hypericum* are present with low percentages.

Zone GER1.4 (93.95 - 99.30 m) - Temperate broad-leaved forest with subordinate conifers

AP is heterogeneous and dominated by taxa of broad-leaved trees. Thermophilous trees are common with *Quercus*, *Ulmus/Zelkova*, *Corylus*, *Tilia* and *Fraxinus*. *Carpinus betulus* is continuously recorded and a distinct peak of *Fagus* occurs at 97.80 m depth. *Pinus* is always present with percentages ranging from 20% to 50%, whereas *Picea* occurs only at the bottom of the zone. The highest value of *Pinus* is record at 97.6 m depth along with *Betula*. Among the herbs, *Artemisia* occurs. Polypodiaceae are abundant whereas Poaceae, Hygrophytes and Hydrophytes are quite common. *Senecio* type, *Hypericum*, *Helleborus* undiff, *Saxifraga hirculus* and other herbs are rare or sporadic.

Zone GER1.5 (72.35 – 93.95 m) - Temperate broad-leaved forest with common conifers

The zone includes seven sterile samples and some sandy levels which lack pollen information (e.g., 75.34 – 78. 54; 83.16 – 88.39 m).

The zone is dominated by thermophilous trees pollen which reach a distinct peak at 88.40 m depth.

In respect to the prevoius zone, mesophilous taxa are more abundant with the continuous presence of *Fagus* and increased values of *Carpinus betulus*. *Abies* occurs, with values < 9%, and increased values of *Pinus* and *Picea* are recorded. *Betula* is still present with similar abundance. Among the sporadic taxa, *Buxus* occurs with very low percentage. Among the herbs Chenopodiaceae appear, whereas *Artemisia* percentage slightly increases.

Poaceae, Hygrophytes and Polypodiaceae are abundant. Other herbs are *Saxifraga hirculus* typ, Brassicaceae and *Senecio* type.

Zone GER1.6 (54.95 - 57.40) - Pinus *forest and steppic plant communities of cold and dry climate*

14.95 m of not analysed silt-sand layers separate this zone from the previous one.

The zone is represented by only one sample (57.36 m) because of the presence of four sterile samples (56.77, 56.36, 56.19, 55.65 m). Pollen concentration is low and the AP assemblage quite entirely represented by *Pinus* with low values of *Betula*. Pollen of broad-leaved thermophilous trees is absent. The zone records a climatic cooling and a dryness increasing, as testified by the absence of thermophilous and mesophilous trees and the presence of xerophityc herbs and shrubs (*Artemisia*, *Ephedra fragilis* type, Chenopodiaceae). Other common herbs are Poaceae and Hygrophytes.

Zone GER1.7 (43.40 – 45.40 m) - Temperate broad-leaved forest with Pinus*, gradually evolving to more open condition*

The zone is separated from the previous one by 9.55 m of prevalently silty-sandy layers. Two samples from organic clayey levels were collected at 54.56 and 52.05 m and yielded no pollen.

AP is heterogeneous with abundant *Pinus* and well represented mixed deciduous trees. The zone is characterized by a constantly decreasing values of *Pinus*, *Quercus*, *Fagus*, *Carpinus betulus* and *Ulmus/Zelkova* toward the top, whereas *Corylus*, *Tilia*, *Picea* and *Abies* remain stable and Hygrophytes increase. Although with low percentages, Poaceae, *Artemisia* and Brassicaceae are present, as well as Hydrophytes.

Zone GER1.8 (37.40 – 37.90 m) - Open pine-birch forest with temperate elements and steppic plant communities of cold and dry climate

Two sample (42.12, 41.34 m), collected in the 5.5 m thick interval separating this zone from the previous one, are sterile.

AP assemblage is rich of *Pinus* with abundant *Betula* and rare *Picea*. Few temperate deciduous trees (*Quercus, Tilia, Fagus, Carpinus betulus, Castanea sativa*) occur with low abundance.

Xerophytic herbs are well represented by the co-occurrence of *Artemisia* and Chenopodiaceae, alon with sporadicgrains of *Senecio* type, *Apiaceae*, *Valeriana officinalis* type, Hydrophythes and others.

Hygrophytes are common and Polypodiaceae occur with low percentage.

Zone GER1.9 (30.00 – 34.87 m) - Open pine-birch forest with steppic plant communities of cold and dry climate

This zone is separated from the previous one by 2.53 m of not analysed silt and sand.

AP values ranges between 65 and 90%, mostly represented by *Pinus*, *Juniperus*, *Betula* and *Picea*. Pollen of broad-leaved thermophilous and mesophilous trees is very rare and represented by few grains of *Carpinus betulus*, *Corylus*, *Quercus*, *Tilia* and *Cornus sanguinea*. Xerophytic herbs and shrubs are abundant with *Artemisia*, Chenopodiaceae and *Ephedra fragilis* type. Poaceae and Hygrophytes are also common, whereas Polypodiaceae are poorly represented. *Senecio* type, *Valeriana officinalis* type, *Saxifraga aizoides* type and Hydrophytes are rare.

Zone GER1.10 (13.97 – 14.40 m) - Steppe and xerophytic scrubs with conifer grooves

15.60 m of not analysed silt and sand separate this zone from the previous one.

The zone is represented by only one sample (13.98 m). The percentage of AP is relatively low (70%-80%) and dominated by *Pinus* but with lower values of *Juniperus*, *Betula* and *Picea* in respect to the previous zone. Xerophytic herbs and shrubs are still abundant with *Artemisia*, *Ephedra fragilis* type, Chenopodiaceae and *Valeriana officinalis* type. *Senecio* type is sporadic. Hygrophytes are common.

4.3.2 Cà Borille core (CB)

Due to the higher pollen concentration and lower number of sterile samples (26 samples out of 87 analyzed samples), the lower occurrence of wide sandy portions not analysed (Fig. 2) and the consequent major sampling concentration (61 samples in 103 m), this core allowed to distinguish 14 pollen zones in a more continuous way in comparison to GER1 core (Fig. 4, supplementary material 2, 4). However, the limits between the zones are defined both on stratigraphic and palynological data.

Zone CB1 (99.23 – 103.00 m) - Pinus *forest with xerophilous elements*

The zone is represented by only one sample (102.03 m) because of the presence of three sterile samples (102.05, 99.09, 99.05 m). AP assemblage is almost completely constituted by *Pinus* and unidentified broken saccate. Sporadic grains of *Picea* and *Fagus* occur. NAP is represented by Poaceae, xerophytic elements, Apiaceae and Hydrophytes.

Zone CB2 (98.70 - 99.23 m) – Open temperate broad-leaved forest

The AP assemblage reaches the lowest values of the whole core and is dominated by *Carpinus betulus* with subordinated *Quercus*, *Corylus*, *Cornus mas* and *Pinus*. Other mixed elements such as *Abies*, *Picea*, *Fagus*, *Ulmus*, *Salix*, *Fraxinus*, *Tilia* and *Acer* are sporadically present. NAP is principally represented by Chenopodiaceae, which co-occur with other xerophilous/halophilous taxa such as *Artemisia*, Asteraceae Cichorioideae and *Limonium*. Poaceae are also common, whereas Hygrophytes and Hydrophytes are rare.

Zone CB3 (80.92 - 85.62 m) - Temperate mixed forest

This zone is separated from the previous one by 13.08 m of not analysed sandy layers.

With the exception of the sample at 83.18 m depth where AP is about 30%, AP is higher than in the previous zone and is dominated by *Quercus* in the lower part, *Carpinus betulus* in the middle and *Fagus* in the upper part of the zone. Other thermophilous trees and shrubs such as *Corylus* and *Ulmus* are common, whereas the conifers are poorly represented although continuously present, in particular *Pinus* percentage does not exceed 20%. Among the rare taxa, *Buxus* is recorded. NAP is represented by a very high variety of taxa; the most common are Hygrophytes, Poaceae, Apiaceae, *Aster* type, *Sinapis* type (Brassicaceae), Labiatae A group. The pollen assemblage of the sample at 83.18 m is dominated by Chenopodiaceae, Poaceae and *Limonium.* Among AP assemblage, *Carpinus betulus* is dominant with subordinated *Quercus*, *Corylus* and *Fagus*.

Zone CB4 (76.94 - 78.26 m) - Open pine-birch forest with residual stands of temperate broad-leaved trees

A layer of 2.66 m of sands separate this zone from the previous one.

The zone includes four sterile samples (78.24, 78.14, 77.91, 77.79 m). The pollen assemblage of the unique sample (77.66 m) is mainly constituted by Poaceae.

AP is represented by *Pinus*, *Betula* and subordinated *Picea*. Sporadic *Quercus* and *Fagus,* rare *Carpinus betulus* and *Tilia* are also present.

Zone CB5 (71.57 - 76.94 m) - Temperate broad-leaved forest

AP is mostly represented by temperate broad-leaved trees with *Quercus* followed by *Fagus*, *Carpinus betulus*, *Corylus* and *Ulmus* slightly decreasing from the middle toward the top of the pollen zone. Conifers are poorly but continuously present whereas *Betula* appears at the top, where *Pinus* and broken saccate are more abundant. Among the rare and sporadic taxa, the presence of *Buxus* and *Vitis vinifera* stands out.

NAP is dominated by Poaceae with common Chenopodiaceae. At 74.42 m the rare presence of *Limonium* is recorded in correspondence with Dinoflagellates and IOLs of foraminifers.

This zone presents some similarities with the pollen zone AZ51 of the AzzanoX core in which an open broad-leaved forest with dominant deciduous *Quercus* with *Fagus* and scattered conifers is recorded. That interval is moreover characterized by the presence of pollen types of salt marshes (Pini et al., 2009).

Zone CB6 (67.70 - 71.57 m) - Conifer forest with birch and residual stands of temperate broad-leaved trees

AP is mainly constituted by *Pinus* and broken saccate whose abundance vary irregularly along the zone. *Abies*, *Picea* and *Betula* are also common and more abundant than temperate broad-leaved trees and shrubs (*Fagus, Carpinus betulus, Corylus, Cornus mas, Ulmus, Fraxinus*), which decrease toward the top of the zone. Rare grains of *Olea europaea* occur at 70.40 m depth. Among NAP, Poaceae are abundant and followed by *Artemisia*, whose percentage increases upward. Other herbs are Hygrophytes, Apiaceae, Chenopodiaceae, *Sinapis* type (Brassicaceae).

Zone CB7 (60.49 - 61.13 m) - Pinus *forest and steppic plant communities of cold and dry climate*

This zone is separated from the previous one by 6.57 m of prevalent sandy layers. Four samples within this interval were sterile (65.00, 64.54, 62.30, 61.15 m).

The zone includes two samples with AP almost completely constituted by *Pinus* and broken saccate. *Picea* and *Betula* are present with low percentage. Very rare are thermophilous trees. NAP is not well represented, including Hygrophytes and Poaceae with subordinated xerophytic herbs such as *Artemisia* and Chenopodiaceae. The pollen assemblage may be correlated to zones AZ53-54 of AzzanoX core which are referred to a phase of cool and dry climate (Pini et al., 2009). Moreover, this zone is very similar to the GER1.6 zone.

Zone CB8 (50.67 - 52.55 m) – Temperate broad-leaved forest

This zone is separated from the previous one by 7.94 m of sediments devoid of pollen information: between 56.96 and 60.49 m of depth sandy layers occur and between 55.13-53.74 m depth 4 samples yielded very low pollen sums.

The zone is characterized by AP dominated by thermophilous and mesophilous broad-leaved trees and shrubs such as *Carpinus betulus*, *Quercus*, *Ulmus*, *Corylus*, *Cornus mas* and others. Conifers are continuously present, although with low percentage increasing toward the top. *Buxus* reaches the highest value of the core in this zone (10%), *Fagus* does not exceed 2%, and rare grains of *Olea europaea* are recorded between 52.04 and 51.94 m of depth. NAP presents a great variety of taxa, the most represented are Poaceae, Hygrophytes, *Artemisia*, Apiaceae and Chenopodiaceae.

The zone presents similarities with the pollen zone AZ55 of AzzanoX core which is referred to a broad-leaved thermophilous forest under interglacial climate conditions, with dominant *Quercus* and rare *Fagus* (Pini et al., 2009). The presence of Buxus and *Olea europaea* in the frame of a mixed forest with abundant *Carpinus betulus and Quercus* recalls the FDP 11d-f zones of Fimon – Ponte sulla Debba core (Pini et al., 2010).

Zone CB9 (45.73 - 46.00 m) - Pinus *forest with scattered* Picea *and xerophytic elements*

This zone is separated from the previous one by 4.67 m of sediment that provide two sterile samples (49.96, 47.25 m), and is constituted by only one sample (45.81 m).

AP is represented by *Pinus* and abundant broken saccate with *Picea* and few grains of *Abies*. Broad-leaved trees and shrubs are still present, although with lower abundance in respect to the previous zone, with the exception of *Fagus* and *Tilia* which are more abundant. NAP is represented by Poaceae with *Artemisia* and Chenopodiaceae. The zone is constituted by only one sample; the pollen spectrum might reflect colder and dryer climatic conditions, similar to those recorded in the pollen zone AZ57 of the AzzanoX core (Pini et al., 2009) as well FDP 11g-12 zone of Fimon – Ponte sulla Debba core (Pini et al., 2010).

Zone CB10 (41.68 - 45.73 m) - Temperate mixed forest

AP is mainly represented by thermophilous and mesophilous broad-leaved trees and shrubs with dominant *Carpinus betulus* followed by *Quercus*, *Fagus*, *Ulmus*, *Corylus* and *Tilia*. Among the conifers, *Picea* and *Pinus* are the most represented, although with low percentage, followed by *Abies*. NAP shows great heterogeneity of upland herbs with dominant *Poaceae* as well as common Hygro- and freshwater Hydrophytes. The presence of quite abundant *Fagus* and the absence of *Buxus*, are the main remarkable differences with the CB8 zone. These features, in addition to the occurrence of the sequence CB8-CB9 suggest a comparison with the pollen zone AZ59 of the AzzanoX core (Pini et., 2009), even if the latter records higher percentage of *Pinus*. However, the presence of temperate taxa and the expansion of *Fagus* are coherent. Similarly, the zone recalls the upper part of the superzone FDP 13 of Fimon – Ponte sulla Debba core (Pini et al., 2010), although *Picea* and *Abies* are in this last record better represented.

Zone CB11 (40.00 - 41.68 m) - Open pine forest with Picea *and xerophytic scrubs*

AP shows values < 70% and toward the top of the zone, it is subordinate to NAP. It is constantly dominated by *Pinus* with abundant broken saccate and common *Picea*. Temperate taxa are almost completely absent. NAP is dominated by Poaceae and *Asteraceae* undiff. with a great variety of less represented upland herbs taxa. Hydro- ad Hygrophytes are present with low percentage values. At the depth of 40.01 m a peak of Chenopodiaceae and *Limonium* is recorded along with rare foraminifers. A remarkable percentage of undetermined pollen occurs here, due to pollen preservation issues.

Despite the absence of *Betula*, this pollen assemblage recalls the AZ61 and FDP14 zones of the AzzanoX and Fimon – Ponte sulla Debba cores (Pini et al., 2009; 2010), which documents a forest withdrawal and the expansion of herbaceous steppic and xerophilous elements.

Zone CB12 (33.52 - 40.00 m) - Mixed broad-leaved forest with Picea

AP ranges between 40% and 90% and is mainly represented by broad-leaved trees and shrubs. *Quercus*, *Carpinus betulus* and *Ulmus* are co-dominant and followed by *Fagus*, *Corylus* and *Tilia*. *Pinus* and *Picea* are quite well represented, whereas *Betula* is scarcely present as well as *Abies*. Among rare taxa, *Castanea sativa* and *Vitis vinifera* are recorded. NAP is mainly represented by Poaceae and Hygrophytes. A peak of *Aster* type with Chenopodiaceae and *Limonium* is recorded at the bottom of the zone.

The zone presents some similarities with AZ62 zone of AzzanoX core (Pini et al., 2009), except for the low *Betula* occurrence, with the FDP15a zone of Fimon – Ponte sulla Debba core (Pini et al., 2010) and the Rugo5 zone of the Valeriano Creek succession (Monegato et al., 2010).

Zone CB13 (31.50 - 33.52 m) - Open pine forest with steppic plant communities of cool and dry climate

AP is almost completely constituted by *Pinus* and broken saccate with *Betula* and *Picea*. Temperate trees are almost completely absent with the exception of *Tilia* and extremely rare grains of *Carpinus betulus* and *Quercus*.

NAP is dominated by Poaceae and Hygrophytes with few taxa of xerophilous herbs.

The cold pollen assemblage with the presence of reduced warm temperate taxa and the persistence of *Tilia* up to 5%, recalls the FDP16a zone of Fimon – Ponte sulla Debba core (Pini et al., 2010a).

Zone CB14 (7.35 – 25.05 m) - Open pine-birch forest with plant communities of cool and dry climate

This zone is separated from the previous one by 6.45 m of not analysed medium-coarse sand.

AP is mainly constituted by *Pinus*, broken saccate, and *Betula*. *Corylus* and *Picea* sporadically occur whereas other temperate taxa such as *Tilia*, *Cornus sanguinea* and *Quercus* are extremely rare in the lower part of the zone. Among NAP, Poaceae, *Artemisia*, Chenopodiaceae, Apiaceae and *Aster* type are well represented. Hygrophytes are also present. The overall abundance of *Pinus*, grasses and xerophytes with the low persistence of thermophilous trees and shrubs recalls the AZ68 zone of AzzanoX core where the sporadic presence of temperate taxa is related to long-distance transport or to reduced refugial populations (Pini et al., 2009). Similar features are recorded in GER1.10 zone.

5. Correlation between GER1 and CB cores, climate stratigraphy and landscape reconstruction

Information retrieved from palaeoecological records are relevant for the chrono-biostratigraphic correlations among sites at regional and continental scales (Müllenders et al., 1996; Tzedakis et al., 2001; Pini et al., 2009, 2010; Monegato et al., 2010).

The pollen records of GER1 and CB cores testify to alternating phases of cool to warm temperate forest and open vegetation, including xerophytic shrubs and steppe communities (Figs. 3, 4). These changes are mostly related to the Middle and Late Pleistocene glacial-interglacial cycles (Lisiecki and Raymo, 2007; Wagner et al., 2019). Since both successions are mainly represented by fluvial deposits with proximal marine intercalations, percentage changes may be referred to either vegetation or pollen source changes and variations of pollen deposition/preservation potential, depending on, e.g., variations in the fluvial/tidal regime and depositional/taphonomical processes. Unfortunately, wide portions of both successions resulted barren in pollen content and, thus, our pollen records are not continuous. However, long chronological discontinuities within the sedimentary succession can be excluded because of the long-lasting subsidence of the Venetian plain (Massari et al., 2004; Barbieri et al., 2007).

The chrono-biostratigraphic correlation between the GER1 and CB cores - and their integration with global marine records (Lisiecki and Raymo, 2005) and alpine chronostratigraphy (Chaline and Jerz, 1984) - are possible only merging all available multiproxy information (Figs. 5, 6). Applying such integrated approach, three main chronological and stratigraphic constrains were recognized (Figs. 2, 5):

i) the first constrain is provided by the LGM aggradation phase. The great fluvial aggradation phase of the Brenta River megafan during this cold period (Iliceto et al., 2001; Mozzi, 2005; Mozzi et al., 2010; Ninfo et al., 2016; Rossato and Mozzi, 2016; Rossato et al., 2018) is well recognized in the sandy deposits of the stratigraphic units CB-VII, CB-VIII and GER1-VI. In CB core this sedimentation phase is constrained by two radiocarbon dates and its onset is marked by an erosional surface corresponding to the base of a fluvial channel. At the top of CB-VIII unit there is a well-developed soil (Soil 3-CB, Tab. 2), that was interpreted as the “caranto” paleosoil (Cucato et al., 2012; Mozzi et al., 2003; Mozzi et al., 2013). The thick sandy body recorded in GER1-VI unit is attributed to the LGM thanks to two radiocarbon dates. Here, the top of the succession (GER1-VII and GER1-VIII units) corresponds to the filling of the post-LGM incised valley of Padova (Cucato et al., 2012; Mozzi et al., 2013);

ii) the second constrain for the correlation between CB and GER1 core is a major paleosoil encountered in both cores (Soil 7-GER1, Soil 2-CB; Tab. 2). In CB core, this paleosoil lies within the uppermost relative warm phase, indicated by the pollen records of pollen zones CB8-CB12, and can be ascribed to the MIS 5. Instead, in GER1, it lies slightly below the uppermost relative warm phase, indicated by pollen zone GER1.7. Due to its stratigraphic positions, this sedimentary hiatus can be correlated with the erosional event observed in the Friulian plain (Pini et al., 2009; Monegato et al., 2010) and attributed to the MIS 5d glacioeustatic fall (Waelbroeck et al., 2002). Whilst in AzzanoX core this erosional surface cuts only part of the sediments associated to the pollen zones attributed to the Eemian Interglacial (Pini et al., 2009), in the Valeriano Creek succession the erosion was sufficiently strong to remove all the Eemian sediments (Monegato et al., 2010). The same erosional event is recorded also in the Lake Fimon, where the water level drop and the reduction of the lake surface occurred as a consequence of established dry conditions (Pini et al., 2010);

iii) the third main constrain for the correlation of GER1 and CB cores is the presence of a marine transgression corresponding to the base of penultimate warm (fully interglacial) phase recorded in both the cores (pollen zones GER1.3-GER1.5 and pollen zones CB2-CB5). The marine intercalations, attributed to open bay to lagoon conditions thanks to the micropaleontological content (biofacies A1 and A2) and the presence of marine mollusk shell fragments, are correlated through the lower part of GER1-III unit and CB-II unit.

The palynological results were entered in the correlation framework obtained from these three constrains, in order to reconstruct the climatostratigraphy of the two cores and to understand the environmental evolution of the Venetian plain since the Middle Pleistocene (Figs. 5, 6). For better clarity, we opted to discuss the meaning and correlation of the different palynological zones in the following paragraphs from the top down, i.e., in inverse stratigraphic order.

5.1 The Last Glacial Maximum (LGM)

The interpretation of the upper parts of the cores, chronologically well-framed thanks to radiocarbon dating, represents one of the correlation constrains described above. The palynological information confirm cold conditions ascribable to the LGM for comparison with other data in the area of Padova an in the whole Venetian plain (Müllenders et al., 1996; Miola et al., 2003, 2006; Mozzi et al., 2003). Indeed, the vegetation reconstructed in GER1.10 and CB14 zones is dominated by xerophytic herbs and shrubs with conifer grooves; this last persisted in the foreland also during the advanced stages of the LGM, as similarly showed for the Friulian plain (Monegato et al., 2007; Pini et al., 2009) and from the paleoclimatic simulations of Barron and Pollard (2002), which foresee a steep precipitation gradient across the Alps during MIS 3 and the LGM, allowing the survival of woody species on the southern side of the Alps.

5.2 The Middle Würm and the identification of Early-Middle Würm boundary

The palynological signal of the stadial phases of the Middle Würm is generally similar to the LGM one, and not always is easily distinguished from the interstadial phases features (Pini et al., 2009). The millennial-scale climatic oscillations characterizing MIS 3 and MIS 4 are only identified in high-resolution pollen records in Western and Southern Europe, where the sampling resolution is below 300 yr (Allen et al., 2000; Tzedakis et al., 2004; Sánchez Goñi et al., 2008; Wohlfarth et al., 2008; Badino et al., 2019). Pollen zones GER1.8, GER1.9 and CB13 reflect open conifer-birch forest with abundant steppic and xerophytic communities and very rare temperate taxa, either reworked or referred to long-distance transport. The typical alternation between mixed conifer - *Betula* forest and expansion phases of steppic communities, recorded in the master cores of Venetian Friulian plain (AzzanoX and Fimon - Ponte sulla Debba cores), is unrecognizable here. However, these zones can be attributed to the Middle Würm (i.e., ca 35-75 ka) thanks to radiocarbon dating: in CB core a radiocarbon date allows to fix the base of LGM (Ua-24602 sample, Tab. 1), in GER1 core the sample ETH-74713 provides a radiocarbon age fully falling in the MIS 3.

Middle Würm is thus considered to include the upper parts of GER1-V and CB-VI stratigraphic units. The lower limit, currently set around 70 ka BP (Chaline and Jerz, 1984), is here based on the relative expansion of thermophilous threes recorded in CB12 pollen zone, whereas in GER1 core is assumed to correspond with the Soil 8-GER1, probably including the part of the second post-Eemian interstadial.

The modest thickness of the deposits associated to the MIS 3/4 is coherent with what observed in AzzanoX core (Pini et al., 2009) and in some other cores of the Friulian plain (CNC4, LUG, VV, PCN) where the lagoon deposits of the Tyrrhenian transgression are found few meters below the MIS 3 deposits, suggesting the existence of a sedimentary gap which comprises large part of Middle Würm (Feruglio, 1936; Fontana et al., 2010a, 2010b).

5.3 Identification of the Eemian Interglacial and vegetation changes during the stadial-interstadial sequence in the Early Würm

The deposits associated to the lower part of GER1-V (37.40-50.15 m of depth) and the upper part of GER1-IV (50.15-54.95 m of depth) stratigraphic units, as well the lower part of CB-VI (33.52-50.67 m of depth) and the upper part of CB-V (50.67-52.55 m of depth) stratigraphic units, are embedded between the Middle Würm deposits and a deeper, pronounced cold phase (pollen zones GER1.6 and CB7). The vegetation successions of pollen zones GER1.7 and CB12-CB8, are the uppermost ones to present a more or less marked occurrence of temperate taxa.

In the circumalpine region, the Eemian Interglacial is characterized by high afforestation (AP>85%) with dominance of thermophilous and mesophilous trees and shrubs with abundant *Carpinus* and *Quercus* and low occurrence of *Fagus* (Woillard, 1978; Müllenders et al., 1996; Reille et al., 1998; Drescher-Schneider, 2000; Pini et al., 2009, 2010). The CB8 pollen zone reflects this condition and is topped by the paleosoil (Soil 2-CB, Tab. 2) related to the glacioeustatic sea-level drop coincident with MIS 5d and described as one of our three correlation constrains. GER1 core does not present a pollen zone with similar vegetation assemblage, however, two sterile levels (54.56 m, 52.02 m of depth) occurs immediately below the paleosoil (Soil 7-GER1) correlated with Soil 2-CB. Likely, the pedogenetic processes of oxidation may have deteriorated the pollen content, determining the absence of pollen within the deposits associated to the last interglacial. Above this stratigraphic unconformity, an alternation between arboreal cool and warm phases is recorded, more pronounced in CB core, probably due to the higher sampling frequency. Conditions of persistent afforestation, with changes in forest composition and phases with slightly minor opening of forest canopy are coherent with what recorded in the Early Würm of the Venetian plain (Pini et al., 2010), and may reflect the post-Eemian stadial-interstadial sequence.

In CB core, the pollen zone CB9 seems to represent a *Pinus*-*Picea* open forest that can be associated to the first stadial occurred after the Eemian Interglacial, whereas the CB10 pollen zone indicates a new phase of mixed forest dominated by warm-temperate broad-leaved trees and characterized by the expansion of *Fagus*. Since the occurrence of *Fagus* allows to distinguish post-Eemian interstadial from the last Interglacial (Tzedakis et al, 2001; Magri et al., 2006; Pini et al., 2009, 2010), CB10 pollen zone is attributed to the first post-Eemian interstadial (related to MIS 5c). *Carpinus*, abundant during the Eemian, is still a main forest tree, whereas *Abies* is present with low percentage. Based on the stratigraphic position and the similar pollen assemblage, we correlate GER1.7 pollen zone to the same interstadial. The forest canopy experienced an opening reduction in CB11 pollen zone, which is characterized by *Pinus* dominance with xerophytic elements. The almost total absence of warm-temperate taxa suggests a relatively cold and dry phase ascribable to the second post-Eemian stadial (related to MIS 5b), not identified in GER1 core, during which one of the most extreme trees population crashes is assumed (Tzedakis et al., 2003).

A controversial point is the punctual presence of halophytes within CB11 zone, which is unlikely related to salt marshes or microtidal flooding processes since, according to Antonioli et al. (2004), at global scale, the sea level dropped at about -60 m below the present position during MIS 5d, rising to -20 m during the subsequent interstadials (MIS 5c and MIS 5a). Moreover, the micropaleontological data, although not abundant, indicate a continental environment. Broad-leaved temperate forest expands again in pollen zone CB12 but not as extensively as during the Eemian and the first post-Eemian interstadial, coherently with the vegetation association observed during the second post-Eemian interstadial in AzzanoX and Lake Fimon records (Pini et al., 2009, 2010). In GER1 core MIS 5a is not supported by palynological data, probabily due to the pedogenic processes associated to Soil 8-GER1 development.

The Early Würm misses here the continuative abundance of *Picea*, recorded in the circumalpine records (Pini et al., 2009).

5.4 Vegetation and fluvioglacial aggradation evidence during the penultimate glaciation

Between 54.95 and 72.35 m of depth, GER1 core presents a prevalently medium-coarse fluvial sand unit characterized by the presence of organic and peaty intercalations (stratigraphic unit GER1-IV). The lithofacies suggest similarities with the glaciofluvial aggradation phase occurred during the LGM, an interpretation supported also by the few available palynological information in the upper part of the stratigraphic unit, which indicate cold and dry continental climatic conditions (pollen zone GER1.6).

Similar features are recorded in the upper part of CB-IV stratigraphic unit, which also shows the establishment of a sandy channel body, and CB7 pollen zone, reflecting a *Pinus* forest with scattered *Picea* and xerophytic shrubs.

This alluvial interval is constrained at the top by the Eemian forest succession in CB core and by the deposits ascribed to MIS 5e in GER1 core. Below, there are the thick stratigraphic units GER1-III and CB-II, characterized at the bottom by the marine intercalation that constitutes our third main correlation constrain.

These considerations support the attribution of this interval to the penultimate glaciation (54.95-72.35 m of depth in GER1 core and 52.55-67.70 m in CB core), during which the full glacial conditions led to high sediment yield from the outwash streams, fed by the Alpine glaciers reaching the frontal position in the piedmont area (Venzo, 1977; Carton et al., 2009; Rossato et al., 2013). In this context the Venetian-Friulian plain aggraded up to 20-30 m (Fontana et al., 2010a).

Whilst in GER1 core the beginning of the penultimate glaciation is fixed in coincidence with the abrupt transition to prevalently sandy fluvial aggradation (72.35 m of depth), in CB it is identified by the pollen assemblage of zone CB6. Indeed, it shows an interstadial signature with persistent temperate taxa in low percentage, likely framed within the millennial climatic oscillations occurred during the early MIS 6, before the extreme cooling (pollen zone CB7) coinciding with the beginning of the penultimate glacial maximum (i.e. about 150 ka; Martrat et al., 2004).

5.5 Evidence of a sea level highstand and identification of MIS 7

The depositional, macro- and micropaleontological data of GER1-III and CB-II stratigraphic units (biofacies A1 and A2), highlights the presence of a paralic environment, probably recording a transgression-regression cycle, although a clear ravinement surface is not identified. These deposits are characterized by a pollen content typical of a temperate climate in both the cores (GER1.3-5 and CB2-5 pollen zones). Assuming prevalently continuous sedimentation, we refer this interval to MIS 7, as it is overlaid in both the cores by a pronounced cold phase (pollen zones GER1.6 and CB7) followed by the Eemian Interglacial (pollen zone CB8). This interpretation is consistent with the AzzanoX core succession, in which a clear bathymetric curve for MIS 7 is reconstructed, whereas continuous continental conditions are observed throughout the last interglacial (Pini et al., 2007, 2009). Although the co-dominance *Abies-Fagus*, diagnostic of the late MIS 7, is not recorded neither in GER1 nor in CB cores, the association of *Fagus* with frequent *Carpinus betulus* supports the attribution to the MIS 7 (Tzedakis et al., 2001). Whilst in GER1 core the pollen samples frequency is too low for identifying the stadial-interstadial succession visible in pollen records attributed to MIS 7, in CB core the samples are enough to hypothesize a climatic sequence. In particular, the open vegetation reflected by the pollen zone CB4 is consistent with a stadial phase, likely framed as substage b. Indeed, according to Tzedakis et al. (2003) the persistence of significant tree population is recorded in Mediterranean records, in accordance with continuous moisture availability during this period, contrary to what observed during substage 7d (Reille and de Beaulieu, 1995; Reille et al., 1998). The stadial interval thus identified, is embedded between two temperate phases (pollen zones CB2-3 and CB5). Pollen zone CB3 shows the largest and floristically diverse forest expansion of MIS 7 interval, with thermophilous elements abundance values among the highest in the whole core. A similar situation is observed during substage c in Valle di Castiglione and Tenaghi Philippon pollen records (Van der Wiel and Wijstra, 1987; Follieri et al., 1988; Tzedakis et al., 2003). Pollen zone CB2 shows low AP sum; however, it presents a clear *Carpinus betulus* dominance, attributable to MIS 7c according to Tzedakis et al. (2001), and is associated with the paralic deposits of stratigraphic unit CB-II and separated from the upper zone by a 13.08 m-thick interval of shore-face sand. The amplitude of sea-level changes during MIS 7 is still poorly understood (Bard et al., 2002), however according to Dutton et al. (2009), the MIS 7.3 highstand was lower than the MIS 7.5 and MIS 7.1 highstands at Argentarola Cave (central Italy). Nevertheless, the lack of major unconformities, the strong interstadial signature of pollen zones CB2-3 and the evident absence of a pronounced cold and dry phase attributable to substage d, allows to hypothesize the correspondence of pollen zones CB2-3 to MIS 7c and CB5 to MIS 7a.

5.6 Pre-MIS 7/8 continental deposits

GER1 and CB cores have a depth difference of 15.65 m, which prevents the chrono-biostratigraphic correlation of the GER1 basal units.

Below the MIS 7 proximal marine deposits, CB core shows a 3.77 m-thick basal unit constituted by alluvial sediments (CB-I stratigraphic unit) characterized by pollen originating from a pine forest (CB1 pollen zone). Despite the presumed stratigraphic continuity, the attribution of this interval to the early MIS 7 is excluded, as the pollen signature of the unique sample does not reflect neither the extremely dry and cold vegetation of the substage 7d, nor the substage 7e warm phase (Follieri et al., 1988; Reille et al., 1998; Tzedakis et al., 1997, 2001, 2003). A clear attribution to the marine isotopic stage is difficult, however MIS 8 may be supposed. The limited thickness of the fluvial deposits attributed to MIS 8 is coherent with the limited extent of this glaciation in Europe in respect to MIS 6 (Batchelor et al., 2019).

A similar pollen zone is not observed in GER1 core, where a 11.11 m-thick alluvial interval barren in pollen separate the MIS 7 paralic deposits from an important organic level rich in pollen. This last shows a mixed temperate forest (pollen zone GER1.1) evolving to a conifer-dominated one (pollen zone GER1.2), not interpretable as MIS 8 because of the abundance of broad-leaved trees, hence older than this stage. Referring to the Central-European records (e.g, Reille and de Beaulieu, 1995; Reille et al., 1998), coherently with what was done for AzzanoX core (Zanferrari et al., 2008), the continuous presence of *Pterocarya* in the lower zone GER1.1, recalls the MIS 11 interstadials. Nevertheless, we should consider the complex stratigraphic distribution of this taxon in the Mediterranean area (Tzedakis et al., 2001), where it makes the last appearance in MIS 11c in southeast Greece (Okuda et al., 2001), whereas it persists during MIS 9e at Tenaghi Philippon (Van der Wiel and Wijstra, 1987) and throughout MIS 7 at Valle di Castiglione (Follieri et al., 1988). Moreover, the great *Abies* expansion observed during the Holstein/Praclaux Interglacial in all the available records (Tzedakis et. al, 2001; Zanferrari et al., 2008) misses in GER1 core, whereas the supposed presence of two species of *Abies* (i.e., *Abies* and *Abies* cfr. based on morphological and morphometrical features) is observed in pollen zones GER1.1, GER1.2, GER1.3. up to GER1.5.

On the other hand, according to Tzedakis et al. (2003), MIS 11 shows two peaks of temperate taxa (MIS 11a, c) and a *Pinus* dominated substage (MIS 11b), which may recall GER1.2 pollen zone.

The ambiguity in chronologically framing the upper peak of *Pterocarya* is observed also in the nearby and deeply studied Venezia1 core (Müllenders et al., 1996; Kent et al., 2002; Massari et al., 2004), where it occurs in correspondence of a transgressive surface at 262 m of depth. In this core, the available magnetostratigraphic and biostratigraphic constrains allow to relate sapropel VS02 to the Sb, to assign it an age of 0.597 Ma (Langereis et al., 1997) and to fix the Eemian transgression at 79 m of depth. Kent et al. (2002) proposed two alternative age models for the section of the Venezia1 core above 572.4 m. The first model, justified by a linear subsidence rate of 180 m/Ma, considers the transgression with the last occurrence of *Pterocarya* coincident with the transition between MIS 12 and MIS 11. Consequently, in the Venezia1 core the transition between MIS 8 and MIS 7 corresponds with a transgression surface at 152 m of depth, about 50 m deeper than in GER1 and CB core; moreover, the Venezia1 core record assumes that *Pterocarya* disappeared in the Venetian plain after MIS 11.

Age Model 2 assumes that the stratigraphically-highest occurrence of *Pseudoemiliana lacunosa* at 562.4 m corresponds with its last appearance datum, an event considered to be globally synchronous and associated with the upper part of MIS 12 (Thierstein et al., 1977). According to this model, supported by an irregular subsidence pattern with an average rate of 360 m/Ma, the transgressive surface rich in *Pterocarya* corresponds with the transition between MIS 8 and MIS 7 which is thus located about 160 m below the GER1 and CB one. Moreover, according to this age model, *Pterocarya* persisted in the Venetian plain even after MIS 11.

Assuming the validity of one or the other model for the Venice area significantly changes the interpretation of the pollen zones GER1.1 and GER1.2. Age Model 1 allows to assume that the occurrence of *Pterocarya* in GER1 core is coincident or older to its last appearance during MIS 11 in the Venetian plain. This interpretation is justified assuming large sedimentary gaps in the depth interval where 5 paleosoils are observed in unit GER1-II. On the other hand, our observations suggest that these paleosoils are poorly developed (Tab. 2) and unlikely represent large gaps, inducing to consider a stratigraphic continuity and to adopt the Age Model 2. Since according to this model, *Pterocarya* is present after MIS 11, pollen zones GER1.1 and GER1.2 would coincide with MIS 9. Nevertheless, the consequent depth difference between the first MIS 7 surface transgression in Venezia1 and the MIS 7.3 one in GER1-CB cores (about 160 m) seems to be too significant.

The discussion therefore remains open, since the only palynological data available is insufficient to certainty frame this interval and the closer deep information from the Venezia1 core are still debated (Kent et al., 2002; Massari et al., 2004).

The gravelly basal portion of GER1 (stratigraphic unit GER1-I) misses palynological and micropaleontological information. The unique stratigraphic data seems to refer these deposits to the infilling of a fluvial incised channel, established within the alluvial plain during a deglaciation erosive phase related to a glacial interval older than MIS 8.

6. Conclusions

The sedimentary successions of GER1 and CB cores provide a new, continuous archive of the long-term sedimentary, climatic and environmental evolution of the south-eastern Alpine foreland, allowing to investigate the Middle-Upper Pleistocene and to reconstruct the climate history of the Central Venetian plain since MIS 7. Palynological analysis in GER1 brings new data on the debate on the pre-Eemian evolution of the Venetian plain (e.g., Kent et al., 2002; Massari et al., 2004) and the chronology of the last occurrence of *Pterocarya* in the southern alpine area, as this core yielded a deep stratigraphic interval rich in this taxon and older than MIS 8, not yet definitively interpreted as for its chronology.

The stratigraphic and paleontological analyses show that both cores mainly cross alluvial deposits, with evidence of one proximal marine intercalation. Unconventionally, the palynostratigraphic method was applied to both core successions, which were simultaneously interpreted due to their proximity, merging all available multiproxy information in order to reconstruct the climatic and stratigraphic evolution of the basin.

Despite the presence of paleosoils, erosional surfaces and levels barren in pollen, an overall stratigraphic continuity was recognized in the successions. The joint interpretation of the two cores allowed to design a robust chronological model that comprises the last two glaciations (i.e., MIS 6 and 2).

The palynological data allow to link the stratigraphic units to major climatic fluctuations, indicating the unique transgression interval as the interglacial MIS 7.3 (i.e about 220-210 ka BP), and to highlight the continuous continental conditions of the area of Padova during the Last Interglacial, in agreement with what observed in the Friulian Plain (Pini et al., 2009). The robust stratigraphic correlation between GER1 and CB cores and the correlation with the reference records in the Venetian-Friulian plain (Zanferrari et al., 2008; Pini et al., 2009, 2010; Monegato et al., 2010, 2011), allow to identify the Eemian level in the composite section, even if GER1 core lacks the related palynological information. The stratigraphic positions of the stadials and interstadials phases were also outlined basing on the integration of lithostratigraphic and palynostratigraphy information.

The palynological constrains allow to chronologically frame two important phases of glaciofuvial aggradation, correlating them to the last two glacial culminations. The penultimate glacial culmination (i.e. late MIS 6, about 148-135 ka BP) is embedded between the late MIS 7 and the Eemian deposits, whereas the LGM (i.e. 26.5-19 ka cal BP) follows the Eemian deposition and is further constrained by radiocarbon dating. The Middle Würm is underrepresented with no evidence for a glacial acme during MIS 4.

The occurrence of hiatuses and levels poor in pollen deeper than the MIS 8 deposits in GER1 prevents the certain attribution of the lower two pollen zones to either MIS 11 or MIS 9. This question, still unsolved, would require further studies on others pollen-rich, deeper successions, not yet available in the area.

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References

Accordi, B., 1950. Esame geologico-paleontologico di un pozzo terebrato a Cartura (Padova). Mem. Ist. Geol. Univ. Padova, 16, 1-19.

Allen, J.R.M., Watts, W.A., Huntley, B., 2000. Weichselian palynostratigraphy, palaeovegetation and palaeoenvironments; the record from Lago Grande di Monticchio, southern Italy. Quatern. Int. 73/74, 91-110.

Antonioli, F., Bard, E., Silenzi, S., Potter, E.K., Improta, S., 2004. 215-kyr history of sea level based on submerged speleothems. Global Planet. Change 43, 57-68.

Avanzini, M., Bargossi, G.M., Borsato, A., Selli, L., 2010. Note Illustrative della Carta Geologica d'Italia alla scala 1: 50.000, Foglio 060- Trento, ISPRA-Servizio Geologico d'Italia, Trento.

Badino, F., Pini, R., Ravazzi, C., Margaritora, D., Arrighia, S., Bortolinia, E., Figusa, C., Biagio Giaccio, B., Luglia, F., Marciania, G., Monegato, G., Moronic, A., Negrino, F., Oxilia, G., Peresani, M., Romandini, M., Ronchitelli, A., Spinapolice, E.E., Zerboni, A., Benazzi, S., 2019. An overview of Alpine and Mediterranean palaeogeography, terrestrial ecosystems and climate history during MIS 3 with focus on the Middle to Upper Palaeolithic transition. Quatern. Int., ISSN 1040-6182. https://doi.org/10.1016/j.quaint.2019.09.024.

Barbieri, C., Di Giulio, A., Massari, F., Asioli, A., Bonato, M., Mancin, N., 2007. Natural subsidence of Venice area during the last 60 My. Basin Res. 19/1, 105-123.

Bard, E., Antonioli, F., Silenzi, S., 2002. Sea-level during the penultimate interglacial period based on submerged stalagmite from Argentarola Cave (Italy). Earth Plan. Sci. Lett. 196 (3-4), 135-146.

Barron, E., Pollard, D., 2002. High-resolution climate simulations of Oxygen Isotope Stage 3 in Europe. Quaternary Res. 58, 296-309.

Batchelor, C.L., Margold, M., Krapp, M., Murton, K.D., Dalton, A.S., Gibbard, P.L., Stockes, C.R., Murton, J.B., Manica, A., 2019. The configuration of Northern Hemisphere ice sheets through the Quaternary. Nat. Commun. 10, 3713, https://doi.org/10.1038/s41467-019-11601-2.

Berglund, B.E., 1986. Handbook of Holocene palaeoecology and palaeohydrology.Wiley-Interscience; John Wiley & Sons Ltd., Chichester. J. Quaternary Sci., 1: 86-87. doi:10.1002/jqs.3390010111.

Beug, H.J., 2004. Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Verlag Dr. Friedrich Pfeil, München.

Bortolami, G.L., Carbognin, L., Gatto, P., 1984. The natural subsidence in the Lagoon of Venice, Italy. Land Subsidence, IAHS Publications 151, 777-785.

Braconnot, P., Otto-Bliesner, B., Harrison, S., Joussaume, S., Peterchmitt, J.-Y., Abe-Ouchi, A., Crucifix, M., Driesschaert, E., Fichefet, Th., Hewitt, C.D., Kageyama, M., Kitoh, A., Laîné, A., Loutre, M.-F., Marti, O., Merkel, U., Ramstein, G., Valdes, P., Weber, S.L., Yu, Y., Zhao, Y., 2007. Results of PMIP2 coupled simulations of the Mid-Holocene and Last Glacial Maximum – Part 1: experiments and large-scale features, Clim. Past 3, 261-277, https://doi.org/10.5194/cp-3-261-2007.

Bronk Ramsey, C., 2009. Bayesian analysis of radiocarbon dates. Radiocarbon 51(1), 337-360.

Carbognin, L., Tosi, L., 2002. Interaction between climate changes, eustasy and land subsidence in the North Adriatic Region, Italy. Marine Ecology 23 (Suppl. 1), 38-50.

Carton, A., Bondesan, A., Fontana, A., Meneghel, M., Miola, A., Mozzi, P., Primon, S., Surian, N., 2009. Geomorphological evolution and sediment transfer in the Piave River watershed (north-eastern Italy) since the LGM. Géomorphologié: relief, Processus. Environment 3, 37-58.

Castiglioni, G.B., 1999. Geomorphology of the Po Plain. Geogr. Fis. Din. Quat. (Suppl. 3), 7-20.

Chaline, J., Jerz, H., 1984. Arbeitsergebnisse der Subkomission für Europäische Quartärstratigraphie: Stratotypen des Würm-Glazials (Bericht SEQS 5). Eiszeitalter und Gegenwart 34, 185-206.

Clark, P., Dyke, A., Shakun, J., Carlson, A., Clark, J., Wohlfarth, B., Mitrovica, J., Hostetler, S., McCabe, A., 2009. The Last Glacial Maximum. Science 325, 710-714,

Cucato, M., De Vecchi, G.P., Mozzi, P., Abbà, T., Paiero, R., Sedea, R. (Eds.), 2012. Note Illustrative della Carta geologica d'Italia alla scala 1:50.000, Foglio 147 Padova Sud. ISPRA-Servizio Geologico d'Italia – Regione Veneto. LTS Land Technology & Services, Padova e Treviso.

Dieni, I., Proto Decima, F., 1960. Studio paleontologico - stratigrafico di un pozzo perforato nell'orto Botanico dell'Università di Padova: Memorie Acc. Patavina di SS. LL. AA; Classe di SC. Mat. e Nat. 73, 3-16.

Drescher-Schneider, R., 2000. The Riss-Würm interglacial from West to East in the Alps: an overview of the vegetational succession and climatic development. Geologie en Mijnbouw. Netherlands Journal of Geosciences 79 (2/3), 233-239, doi: 10.1017/S0016774600023672.

Duprat- Oualid, F., Rius, D., Bégeot, C., Magny, M., Millet, L., Wulf, S., Appelt, O., 2017. Vegetation response to abrupt climate changes in Western Europe from 45 to 14.7k cal a BP: the Bergsee lacustrine record (Black Forest, Germany). J. Quaternary Sci., 32: 1008-1021. https://doi.org/10.1002/jqs.2972.

Dutton, A., Bard, E., Antonioli, F., Esat, M.T., 2009. Phasing and amplitude of sea-level and climate change during the penultimate interglacial. Nature Geoscience 2, 355-359 https://doi.org/10.1038/ngeo470.

Fægri, K., Iversen, J., 1989. Textbook of pollen analysis. 4th ed. by K. Fægri, P.E. Kaland & K. Krzywinski. John Wiley & Sons, Chichester.

Feruglio, E., 1936. Sedimenti marini nel sottosuolo della bassa pianura friulana. Boll. Soc. Geol. It. 55(1), 129-138.

Follieri, M., Magri, D., Sadori, L., 1988. 250,000-year pollen record from Valle di Castiglione (Roma). Pollen Spores 30, 329-356.

Fontana, A., Mozzi, P., Bondesan, A., 2008. Alluvial megafans in the Venetian - Friulian Plain (north-eastern Italy): evidence of sedimentary and erosive phases during Late Pleistocene and Holocene. Quatern. Int. 189, 71-90.

Fontana, A., Mozzi, P., Bondesan, A., 2010a. Late Pleistocene evolution of the Venetian - Friulian Plain. Rendiconti Lincei Scienze Fisiche e Naturali 21, Supp. 1, 181-196.

Fontana, A., Bondesan, A., Meneghel, M., Toffoletto, F., Vitturi, A., Bassan, V., 2010b. Note illustrative della Carta Geologica d'Italia alla scala 1:50.000. Foglio 107, Portogruaro. ISPRA-Regione del Veneto, Roma.

Fontana, A., Mozzi, P., Marchetti, M., 2014. Alluvial fans and megafans along the southern side of the Alps. Sediment. Geol. 301, 150-171.

Garzanti, E., Vezzoli, G., Andò, S., 2011. Paleogeographic and paleodrainage changes during Pleistocene glaciations (Po Plain, Northern Italy). Earth Science Rev. 105(1-2), 25-48. doi: 10.1016/j.earscirev.2010.11.004.

Grimm, E., 1991-2019. Tilia, Version 2.6.1 Illinois State Museum, Research and Collection Center, Springfield.

Grüger, E., 1989. Palynostratigraphy of the last interglacial/glacial cycle in Germany. Quatern. Int. 3/4, 69-79.

Heiri, O., Koinig, K. A., Spötl, C., Barrett, S., Brauer, A., Drescher-Schneider, R., Gaar, D., Ivy-Ochs, S., Kerschner, H., Luetscher, M., Moran, A., Nicolussi, K., Preusser, F., Schmidt, R., Schoeneich, P., Schwörer, C., Sprafke, T., Terhorst, B., Tinner, W., 2014. Palaeoclimate records 60-8 ka in the Austrian and Swiss Alps and their forelands. Quaternary Sci. Rev. 106, 186-205. https://doi.org/10.1016/j.quascirev.2014.05.021.

Huntley, B. & Birks, H. J. B. 1983. An atlas of past and present pollen maps for Europe: 0-13,000 years ago. Cambridge: University Press. Antiquity, 58(223), 154-155. doi:10.1017/S0003598X00051814.

Iliceto, V., Meloni, F., Mozzi, P., Rizzetto, F., 2001. Il sottosuolo della Cappella degli Scrovegni a Padova. Geol. Tec. Ambient. 9, 3-17.

Jahn, R., Blume, H.P., Asio, V.B., Spaargaren, O., Schad, P., Langohr, R., Brinkman, R., Nachtergaele, F.O., Pavel Krasilnikov, R., 2006. Guidelines for Soil Description. FAO, Rome, p. 97.

Jorissen, F.J., 1987. The distribution of benthic foraminifera in the Adriatic Sea. Mar. Micropalaeontol. 12(1), 21-48.

Kent, D.V., Rio, D., Massari, F., Kukla, G., Lanci, L., 2002. Emergence of Venice during the Pleistocene. Quaternary Sci. Rev. 21, 1719-1727.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic $\delta^{18}O$ records. Paleoceanography 20, PA1003, doi: 10.1029/2004PA001071.

Lisiecki, L.E., Raymo, M.E., 2007. Plio-Pleistocene climate evolution: trends and transitions in glacial cycle dynamics. Quaternary Sci. Rev. 26, 1-2, 56-69. https://doi.org/10.1016/j.quascirev.2006.09.005.

Löfverström, M., 2020. A dynamic link between high-intensity precipitation events in southwestern North America and Europe at the Last Glacial Maximum. Earth Planet. Sci. Lett. 534, 116081.

Löfverström, M., Caballero, R., Nilsson, J., Kleman, J., 2014. Evolution of the large-scale atmospheric circulation in response to changing ice sheets over the last glacial cycle. Clim. Past 10, 1453-1471. doi:10.5194/cp-10-1453-2014.

Luetscher, M., Boch, R., Sodemann, H., Spötl, C., Cheng, H., Edwards, R.L., Frisia, S., Hof, F., Müller, W., 2005. North Atlantic storm track changes during the Last Glacial Maximum recorded by Alpine speleothems. Nat. Commun. 6, 6344. doi: 10.1038/ncomms7344.

Magri, D., Vendramin, G.G., Comps, B., Dupanloup, I., Geburek, T., Gömöry, D., Latalowa, M., Litt, T., Paule, L., Roure, J.M., Tantau, I., van der Knaap, W.O., Petit, R.J., Beaulieu, J.-L. de, 2006. A new scenario for the Quaternary history of European beech populations: palaeobotanical evidences and genetic consequences. New Phytologist 171, 199-221.

Mancin, N., Di Giulio, A., Cobianchi, M., 2009. Tectonic vs. climate forcing in the Cenozoic sedimentary evolution of a foreland basin (Eastern Southalpine system, Italy). Bas. Res. 21(6), 799-823. doi: 10.1111/j.1365-2117.2009.00402.

Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore, T.C., Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. Quaternary Res. 27,1-29.

Martrat, B., Grimalt, J.O., Lopez-Martinez, C., Cacho, I., Sierro, F.J., Flores, J.A., Zahn, R., Canals, M., Curtis, J.H., Hodell, D.A., 2004. Abrupt temperature changes in the western Mediterranean over the past 250,000 years. Science 306, 1762-1765.

Massari, F., Grandesso, P., Stefani, C., Jobstraibizer, P.G., 1986. A small polyhistory foreland basin evolving in a context of oblique convergence: the Venetian basin (Chattian to Recent, Southern Alps, Italy). in: Allen, P.A., Homewood, P. (Eds.), Foreland Basins. Blackwell Publishing Ltd, Oxford, United Kingdom. doi:10.1002/9781444303810.ch7.

Massari, F., Rio, D., Serandrei Barbero, R., Asioli, A., Capraro, L., Fornaciari, E., Vergerio, P.P., 2004. The environment of Venice area in the past two million years. Palaeogeogr. Palaeoclimatol. Palaeoecol. 202, 273-308.

Miola, A., Albanese, D., Valentini, G., Corain, L., 2003. Pollen data for a biostratigraphy of LGM in the Venetian Po Plain. Il Quaternario 16, 21-26.

Miola, A., Bondesan, A., Corain, L., Favaretto, S., Mozzi, P., Piovan, S., Sostizzo, I., 2006. Wetlands in the Venetian Po Plain (north-eastern Italy) during the Last Glacial Maximum: vegetation, hydrology, sedimentary environments. Rev. Palaeobot. Palyno. 141(1), 53-81.

Miola, A., 2012. Tools for Non-Pollen Palynomorphs (NPPs) analysis: A list of Quaternary NPP types and reference literature in English language (1972–2011). Rev. Palaeobot. Palyno., 186, 142-16.

Monegato, G., Ravazzi, C., Donegana, M., Pini, R., 2007. Evidence of a two-fold glacial advance during the Last Glacial Maximum in the Tagliamento end moraine system (eastern Alps). Quaternary Res. 68, 284-302.

Monegato, G., Lowick, S.E., Ravazzi, C., Banino R., Donegana, M., Preusser, F., 2010. Middle to Late Pleistocene chronology and palaeoenvironmental evolution of the south-eastern Alpine Foreland: the Valeriano Creek succession (NE Italy). J. Quaternary Sci. 25, 617-632.

Monegato, G., Pini, R., Ravazzi, C., Reimer, P. J., Wick, L., 2011. Correlating Alpine glaciation with Adriatic sea-level changes through lake and alluvial stratigraphy, J. Quaternary Sci. 26, 791-804. https://doi.org/10.1002/jqs.1502.

Monegato, G., Ravazzi, C., Culiberg, M., Pini, R., Miloš, B., Calderoni, G., Jež, J., Perego, R., 2015. Sedimentary evolution and persistence of open forests between the south-eastern Alpine fringe and the Northern Dinarides during the Last Glacial Maximum. Palaeogeogr. Palaeoclimatol. Palaeoecol. 436. 23-40.

Monegato, G., Scardia, G., Hajdas, I., Rizzini, F., Piccin, A., 2017. The Alpine LGM in the boreal ice-sheets game. Sci. Rep.-UK, 7, 2078. https://doi.org/10.1038/s41598-017-02148-7.

Moore, P.D., Webb, J.A., Collinson, M.E., 1991. Pollen Analysis. Blackwell Scientific Publications, Oxford.

Mozzi, P., Bini, C., Zilocchi, L., Becattini, R., Mariotti Lippi, M., 2003. Stratigraphy, paleopedology and palynology of Late Pleistocene and Holocene deposits in the landward sector of the lagoon of Venice (Italy), in relation to the caranto level. Il Quaternario 16 (1Bis), 193-210.

Mozzi, P., 2005. Alluvial plain formation during the Late Quaternary between the southern Alpine margin and the Lagoon of Venice (northern Italy). Geogr. Fis. Din. Quat. (Suppl. 7), 219-230.

Mozzi, P., Piovan, S., Rossato, S., Cucato, M., Abbà, T., Fontana, A., 2010. Palaeohydrography and early settlements in Padua (Italy). Il Quaternario 23, 387-400.

Mozzi, P., Ferrarese, F., Fontana, A., 2013. Integrating digital elevation models and stratigraphic data for the reconstruction of the post-LGM unconformity in the Brenta alluvial megafan (North-Eastern Italy). Alp. Mediterr. Quat. 26, 41-54.

Müllenders, W., Favero, V., Coremans, M., Dirickx, M., 1996. Analyses polliniques de sondages à Venise. In: Gullentops, F. (Ed.), Pleistocene palynostratigraphy. Aardkundige Mededelingen 7, 87-117.

Müller, U.C., Pross, J., Bibus, E., 2003. Vegetation response to rapid climate change in Central Europe during the past 140,000 yr based on evidence from the Füramoos pollen record. Quat. Res. 59, 235-245.

Muttoni, G., Carcano, C., Garzanti, E., Ghielmi, M., Piccin, A., Pini, R., Rogledi, S., Sciunnach, D., 2003. Onset of major Pleistocene glaciations in the Alps. Geology 31, 989-992.

Ninfo, A., Mozzi, P., Abbà, T., 2016. Integration of LiDAR and cropmarks remote sensing for the study of fluvial and anthropogenic landforms in the Brenta-Bacchiglione alluvial plain (NE Italy). Geomorphology. http://dx.doi.org/10.1016/j.geomorph.2015.11.006.

Okuda, M., Yasuda, Y., Setoguchi, T., 2001. Middle to Late Pleistocene vegetation history and climatic changes at Lake Kopais, southeast Greece. Boreas 30, 73-82.

Pini, R., Ravazzi, C., Donegana, M., 2007. Gli ultimi cinque cicli climatici nella successione sedimentaria della pianura friulana. In: Carli, B., Cavarretta, G., Colacino, M., Fuzzi, S. (Eds.), Clima e cambiamenti climatici: le attività di ricerca del CNR, pp. 169-172.

Pini, R., Ravazzi, C., Donegana, M., 2009. Pollen stratigraphy, vegetation and climate history of the last 215 ka in the Azzano Decimo core (plain of Friuli, north-eastern Italy). Quat. Sci. Rev. 28, 1268-1290.

Pini, R., Ravazzi, C., Reimer P.J., 2010. The vegetation and climate history of the last glacial cycle in a new pollen record from Lake Fimon (southern Alpine foreland, N-Italy). Quat. Sci. Rev. 29, 3115-3137.

Pola, M., Ricciato, A., Fantoni, R., Fabbri, P., Zampieri, D., 2014. Architecture of the western margin of the North Adriatic foreland: the Schio-Vicenza fault system. Italian J. Geosci. 133, 223-234.

Reille, M., 1992e1995. Pollen et spores d'Europe et d'Afrique du Nord. Laboratoire de Botanique historique et Palynologie, Marseille.

Reille, M., de Beaulieu, J.-L., 1995. Long Pleistocene pollen records from the Praclaux Crater, south-central France. Quaternary Res. 44, 205-215.

Reille, M., Andrieu, V., de Beaulieu, J.-L., Guenet, P., Goeury, C., 1998. A long pollen record from Lac du Bouchet, Massif Central, France for the period 325 to 100 ka (OIS 9c to OIS 5e). Quat. Sci. Rev. 17, 1107-1123.

Rossato, S., Monegato, G., Mozzi, P., Cucato, M., Gaudioso, B., Miola, A., 2013. Late Quaternary glaciations and connections to the piedmont plain in the prealpine environment: the middle and lower Astico Valley (NE Italy). Quatern. Int. 288, 8-24.

Rossato, S., Mozzi, P., 2016. Inferring LGM sedimentary and climatic changes in the southern Eastern Alps foreland through the analysis of a 14C ages database (Brenta megafan, Italy). Quat. Sci. Rev. 148, 115-127.

Rossato, S., Carraro, A., Monegato, G., Mozzi, P., Tateo, F., 2018. Glacial dynamics in pre-Alpine narrow valleys during the Last Glacial Maximum inferred by lowland fluvial records (northeast Italy). Earth Surf. Dynam. 6, 809-828, 2018 https://doi.org/10.5194/esurf-6-809-2018.

Sánchez Goñi, M.F., Landais, A., Fletcher, W.J., Naughton, F., Desprat, S., Duprat, J., 2008. Contrasting impacts of Dansgaard-Oeschger events over a western European latitudinal transect modulated by orbital parameters. Quat. Sci. Rev. 27, 1136-1151.

Sidall, M., Stocker, T.F., Spahni, R., Blunier, T., McManus, J., Bard, E., 2006. Using a maximum simplicity paleoclimate model to simulate millennial variability during the last four glacial cycles: Quat. Sci. Rev. 25, 3185-3197.

Spötl, C., Holzkämper, S., Mangini, A., 2007. The last and the penultimate interglacial as recorded by speleothems from a climatically sensitive high-elevation cave site in the Alps. In: Sirocko, F., Claussen, M., Sánchez Goñi, M.F., Litt, T. (Eds.), The Climate of Past Interglacials. Development in Quaternary Science, vol. 7. Elsevier, pp. 471-491.

Spötl, C., Reimer, P.J., Starnberger, R., Reimer, R. 2013. A new radiocarbon chronology of Baumkirchen, stratotype for the onset of the Upper Würmian in the Alps. J. Quater. Sci. 28, 552-558.

Stefani, C., Fellin, M.G., Zattin, M., Zuffa, G.G., Dalmonte, C., Mancin, N., Zanferrari, A., 2007. Provenance and paleogeographic evolution in a multi-source foreland: the Cenozoic Venetian-Friulian Basin (NE Italy). J. Sediment. Res. 77, 867-887. https://doi.org/10.2110/jsr.2007.083.

Stockmarr, J., 1971. Tablets with spores used in absolute pollen analysis. Pollen et Spores 13, 615-621.

Toscani, G., Marchesini, A., Barbieri, C., Di Giulio, A., Fantoni, R., Mancin, N., Zanferrari, A., 2016. The Friulian-Venetian Basin I: architecture and sediment flux into a shared foreland basin. It. J. Geosci. 135. 1-54. 10.3301/IJG.2015.35.

Tzedakis, P.C., Andrieu, V., de Beaulieu, J.-L., Crowhurst, S., Follieri, M., Hooghiemstra, H., Magri, D., Reille, M., Sadori, L., Shackleton, N.J., Wijmstra, T.A., 1997. Comparison of terrestrial and marine records of changing climate of the last 500,000 years. Earth Planet. Sci. Lett. 150, 17 1-176.

Tzedakis, P.C., Andrieu, V., Beaulieu, J.-L. de, Birks, H.J.B., Crowhurst, S., Follieri, M., Hooghiemstra, H., Magri, D., Reille, M., Sadori, L., Shackleton, N.J., Wijmstra, T.A., 2001. Establishing a terrestrial chronological framework as a basis for biostratigraphical comparisons. Quat. Sci. Rev. 20, 1583-1592.

Tzedakis, P.C., McManus, J.F., Hooghiemstra, H., Oppo, D.W., Wijmstra, T.A., 2003. Comparison of changes in vegetation in northeast Greece with records of climate variability on orbital and suborbital frequencies over the last 450 000 years. Earth Planet. Sci. Lett. 212, 197-212.

Tzedakis, P.C., Frogley, M.R., Lawson, I.T., Preece, R.C., Cacho, I., de Abreu, L., 2004. Ecological thresholds and patterns of millennial scale climate variability: the response of vegetation in Greece during the Last Glacial period. Geology 32 (2), 109-112.

Udden, J.A., 1914. Mechanical composition of clastic sediments. Bull. Geol. Soc. Am. 25, 655-744.

Van der Wiel, A.M., Wijstra, T.A., 1987. Palynology of the lower part (78-120 m) of the core Tenaghi Philippon II. Middle Pleistocene of Macedonia. Rev. Palaeobot. Palyno. 52, 89-117.

Venzo, S., 1977. I depositi quaternari e del neogene superiore nella bassa valle del Piave da Quero al Montello e del Paleopiave nella valle del Soligo (Treviso), Memorie Istituti Mineralogia Geologia Università di Padova 30, 1-64.

Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E., Labracherie, M., 2002. Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records. Quat. Sci. Rev. 21, 295-305.

Wagner, B., Vogel, H., Francke, A., Friedrich, T., Donders, T., Lacey, J.H., Leng, M., Regattieri, E., Sadori, L., Wilke, T., Zanchetta, G., Albrecht, C., Bertini, A., Combourieu-Nebout, N., Cvetkoska, A., Giaccio, B., Grazhdani, A., Hauffe, T., Holtvoeth, J., Joannin, S., Jovanovska, E., Just, J., Kouli, K., Kousis, I., Koutsodendris, A., Krastel, S., Lagos, M., Leicher, N., Levkov, Z., Lindhorst, K., Masi, A., Melles, M., Mercuri, A.M., Nomade, S., Nowaczyk, N., Panagiotopoulos, K., Peyron, O., Reed, J.M., Sagnotti, L., Sinopoli, G., Stelbrink, B., Sulpizio, R., Timmermann, A., Tofilovska, S., Totti, P., Wagner-Cremer, F., Wonik, T., Zhang, X., 2019. Mediterranean winter rainfall in phase with African monsoons during the past 1.36 million years. Nature 573, 256-260. https://doi.org/10.1038/s41586-019-1529-0.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. J. Geology 30, 377-392.

Wohlfarth, B., Veres, D., Ampel, L., Lacourse, T., Blaauw, M., Preusser, F., Andrieu- Ponel, V., Kéravis, D., Lallier-Vergès, E., Björck, S., Davies, S.M., Beaulieu, J.-L., de Risberg, J., Hormes, A., Kasper, H.U., Possnert, G., Reille, M., Thouveny, N., Zander, A., 2008. Rapid ecosystem response to abrupt climate changes during the last glacial period in western Europe, 40-16 ka. Geology 36 (5), 407-410.

Woillard, G., 1978. Grande Pile Peat Bog: A Continuous Pollen Record for the Last 140,000 Years. Quaternary Res. 9(1), 1-21. doi: 10.1016/0033-5894(78)90079-0.

Zanferrari, A., Avigliano, R., Fontana, A., Paiero, G., (Eds) 2008. Note Illustrative della Carta Geologica d’Italia alla scala 1:50.000: Foglio 087 “San Vito al Tagliamento”. Graphic Linea, Tavagnacco.

Figure captions

Fig. 1

Location of the Geriatrico 1 (GER1) and Cà Borille (CB) cores and the reference records of the Venetian-Friulian plain discussed in the text (base map modified from Fontana et al., 2008).

Fig. 2

Stratigraphic logs of Geriatrico 1 (GER1) and Cà Borille (CB) cores. Calibrated ^{14}C ages, identified stratigraphic units as well all the treated pollen and micropaleontological samples are reported. The dashed line indicated the main stratigraphic correlation discussed in the text.

Fig. 3

Overview pollen diagram of Geriatrico 1 (GER1) core with selected % records. *Alnus*, Poaceae, Cichorioideae, hydrophytes and hygrophytes are excluded from the Upland Pollen Sum. Only pollen samples with Upland Pollen Sum greater than 100 grains are reported. Black dots indicate percentage values < 1%.

Hydrophytes include *Hydrocaris*, *Menyanthes trifoliata*, *Myriophyllum spicatum* type, *Myriophyllum verticillatum* type, *Nuphar*, *Nymphaea alba* and *Potamogeton natans*.

Hygrophytes include Cyperaceae, *Lythrum salicaria* type, *Sparganium* type and *Typha latifolia* type.

Fig. 4

Overview pollen diagram of Cà Borille (CB) core with selected % records. *Alnus*, Poaceae, Cichorioideae, hydrophytes and hygrophytes are excluded from the Upland Pollen Sum. Only pollen samples with Upland Pollen Sum greater than 100 grains are reported. Black dots indicate percentage values < 1%.

Hydrophytes include *Callitriche*, *Menyanthes trifoliata*, *Myriophyllum alterniflorum* type, *Myriophyllum spicatum* type, *Myriophyllum verticillatum* type, *Nuphar*, *Nymphaea alba*, *Potamogeton subg. P.* type, *Stratiotes aloides* and *Trapa natans*.

Hygrophytes include *Alisma plantago aquatica*, Cyperaceae, *Filipendula* cf. *ulmaria*, *Hottonia palustris*, *Lythrum salicaria* type, *Sparganium* type, *Thalictrum* and *Typha latifolia* type.

Fig. 5

Stratigraphic and chronological correlation between Geriatrico 1 (GER1) and Cà Borille (CB) cores, based on the multi-proxy information. Specific percentage pollen histograms are selected and integrated with stratigraphic and micropaleontological data.

Pinus: cumulative percentage of *Pinus cembra*, *Pinus diploxylon* and *Pinus haploxylon*.

Broad-leaved trees and shrubs: cumulative percentage of *Carpinus* type, *Buxus*, *Cornus mas* type, *Cornus sanguinea* type, *Corylus*, *Fagus sylvatica* type, *Frangula alnus*, *Fraxinus*, *Olea europea*, *Quercus robur* group, *Tilia*, *Ulmus*, *Ulmus-Zelkova*, *Vitis vinifera* and *Zelkova*.

Xerophytes: cumulative percentage of *Artemisia*, Chenopodiaceae, *Ephedra distachya* type, *Ephedra fragilis* type, *Hippophae rhamnoides*.

Fig. 6

Correlation between playnological and stratigraphic data of Geriatrico 1 (GER1) and Cà Borille (CB) cores and the global marine records over the last 220 ka. The selected percentage pollen records of Fig. 5 are plotted against a temporal y axis and compared with the marine $\delta^{18}O$ LR04 stack curve by Lisiecki and Raymo (2005). The marine-transitional intervals are correlated with the curve of global sea-level oscillations by Waelbroeck et al. (2002).

Table captions

Tab. 1

Radiocarbon dates obtained for GER1 and CB cores. AMS: Accelerator Mass Spectrometry (ETH Zürich for GER1 and Tandem Laboratory, University of Uppsala for CB core). 14C ages are calibrated with the online calibration programme OxCal (version 4.3, calibration curve IntCal13; Bronk Ramsey, 2009).

Tab. 2

The main features of paleosoils within the GER1 and CB stratigraphic successions. Estimate of the degree of soil development: * poorly developed; ** moderately developed; *** well developed.

Fig.1

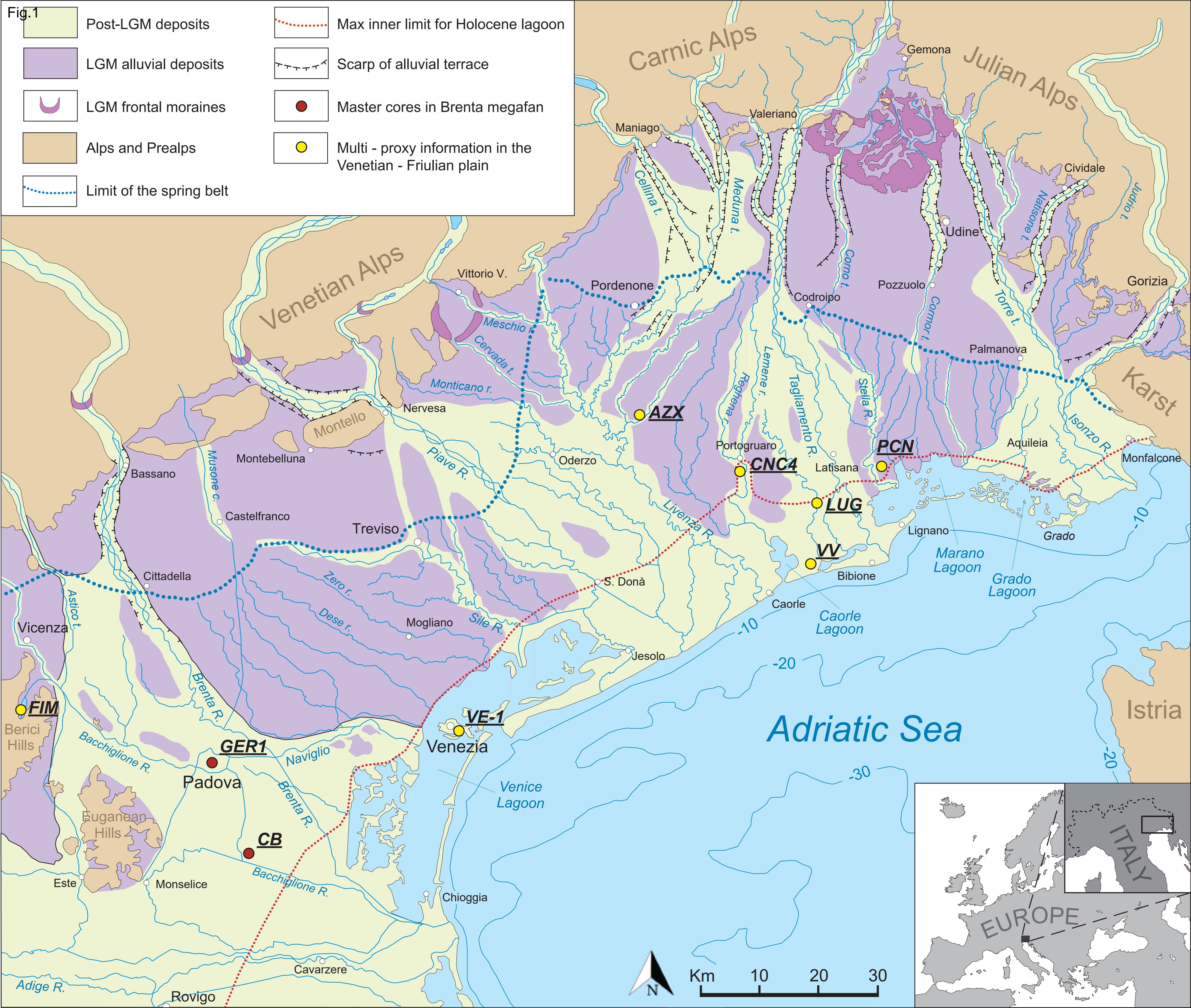

Post-LGM deposits
LGM alluvial deposits
LGM frontal moraines
Alps and Prealps
Limit of the spring belt
Max inner limit for Holocene lagoon
Scarp of alluvial terrace
Master cores in Brenta megafan
Multi - proxy information in the Venetian - Friulian plain
Carnic Alps
Julian Alps
Venetian Alps
Karst
Istria
Adriatic Sea
Gemona
Valeriano
Maniago
Cividale
Udine
Pordenone
Vittorio V.
Codroipo
Pozzuolo
Gorizia
Palmanova
Nervesa
Montello
Montebelluna
Bassano
Oderzo
Portogruaro
Latisana
Aquileia
Monfalcone
Castelfranco
Treviso
Cittadella
S. Donà
Vicenza
Mogliano
Caorle
Bibione
Lignano
Grado
Jesolo
Venezia
Padova
Berici Hills
Euganean Hills
Este
Monselice
Chioggia
Cavarzere
Rovigo
AZX
CNC4
PCN
LUG
VV
VE-1
FIM
GER1
CB
Cellina t.
Meduna t.
Corno t.
Cormor t.
Torre t.
Natisone t.
Judrio t.
Meschio
Cervada t.
Monticano r.
Piave R.
Musone c.
Reghena
Lemene r.
Tagliamento R.
Stella R.
Isonzo R.
Livenza R.
Zero r.
Dese r.
Sile R.
Astico t.
Brenta R.
Bacchiglione R.
Naviglio
Adige R.
Marano Lagoon
Grado Lagoon
Caorle Lagoon
Venice Lagoon
-10
-20
-30
Km
10
20
30
N
ITALY
EUROPE

Fig.2

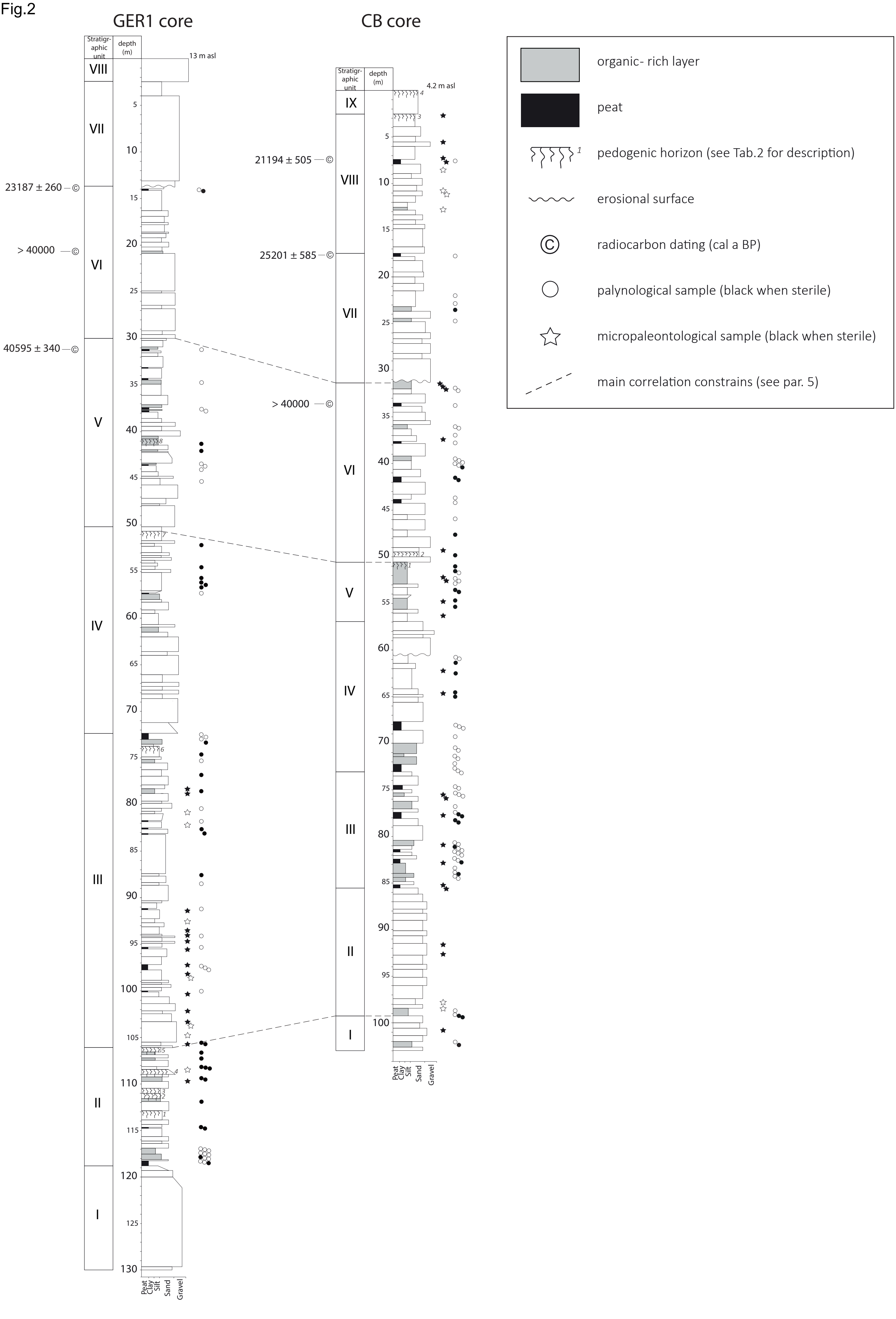

GER1 core
CB core
Stratigraphic unit
depth (m)
13 m asl
4.2 m asl
23187 ± 260
> 40000
40595 ± 340
21194 ± 505
25201 ± 585
> 40000
Peat
Clay
Silt
Sand
Gravel
organic- rich layer
peat
pedogenic horizon (see Tab.2 for description)
erosional surface
radiocarbon dating (cal a BP)
palynological sample (black when sterile)
micropaleontological sample (black when sterile)
main correlation constrains (see par. 5)

Fig.3

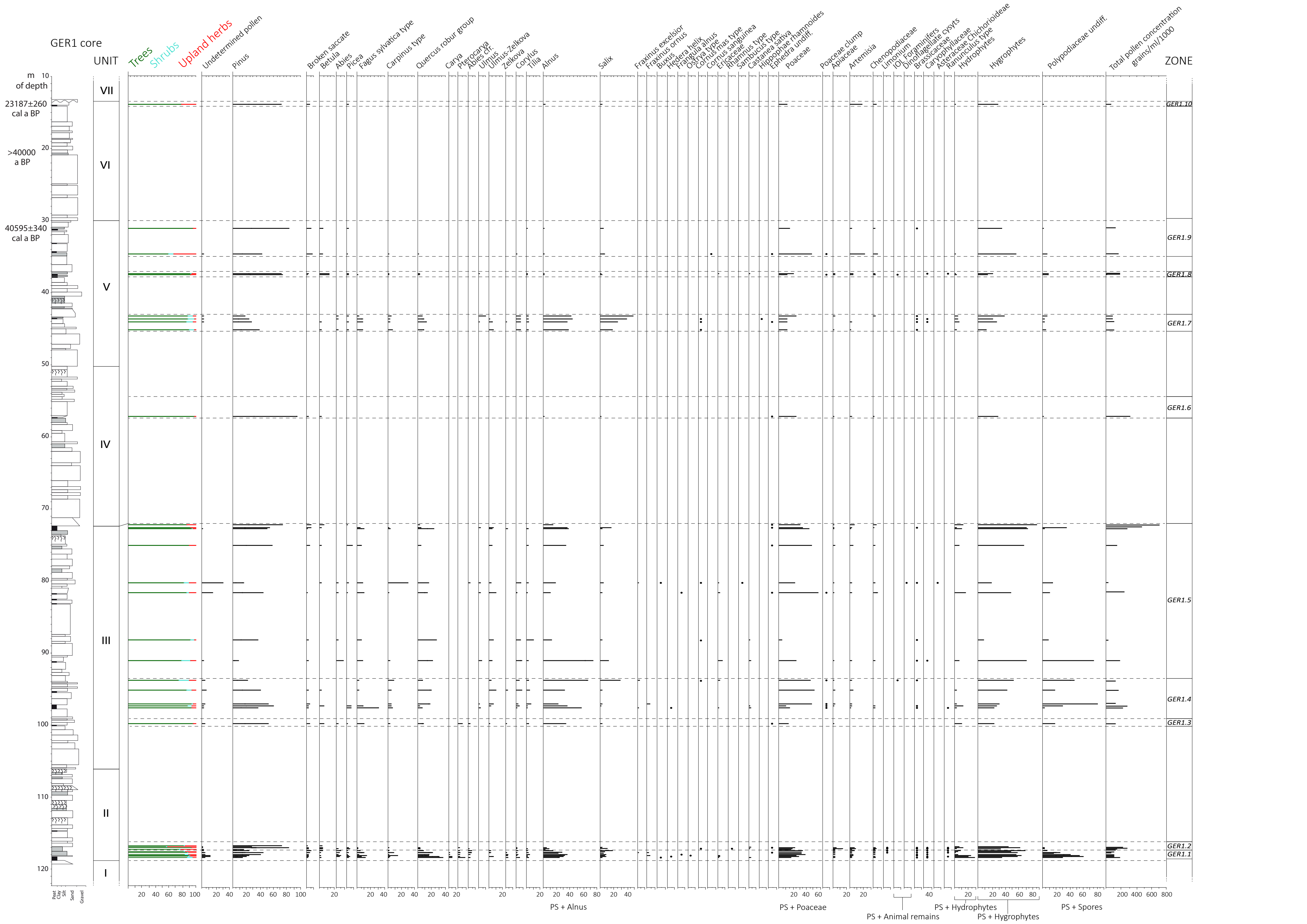

GER1 core
m of depth
UNIT
ZONE
23187±260 cal a BP
>40000 a BP
40595±340 cal a BP
VII
VI
V
IV
III
II
I
Trees
Shrubs
Upland herbs
Undetermined pollen
Pinus
Broken saccate
Betula
Abies
Picea
Fagus sylvatica type
Carpinus type
Quercus robur group
Carya
Pterocarya
Abies cfr.
Ulmus
Ulmus-Zelkova
Zelkova
Corylus
Tilia
Alnus
Salix
Fraxinus excelsior
Fraxinus ornus
Buxus
Hedera helix
Frangula alnus
Ostrya type
Cornus mas type
Cornus sanguinea
Ericaceae
Rhamnus type
Sambucus type
Castanea sativa
Hippophae rhamnoides
Ephedra undiff.
Poaceae
Poaceae clump
Apiaceae
Artemisia
Chenopodiaceae
Limonium
IOL Foraminifers
Dinoflagellate cysyts
Brassicaceae
Caryophyllaceae
Asteraceae Chichorioideae
Ranunculus type
Hydrophytes
Hygrophytes
Polypodiaceae undiff.
Total pollen concentration grains/ml/1000
GER1.10
GER1.9
GER1.8
GER1.7
GER1.6
GER1.5
GER1.4
GER1.3
GER1.2
GER1.1
Peat
Clay
Silt
Sand
Gravel
PS + Alnus
PS + Poaceae
PS + Animal remains
PS + Hydrophytes
PS + Hygrophytes
PS + Spores

Fig.4

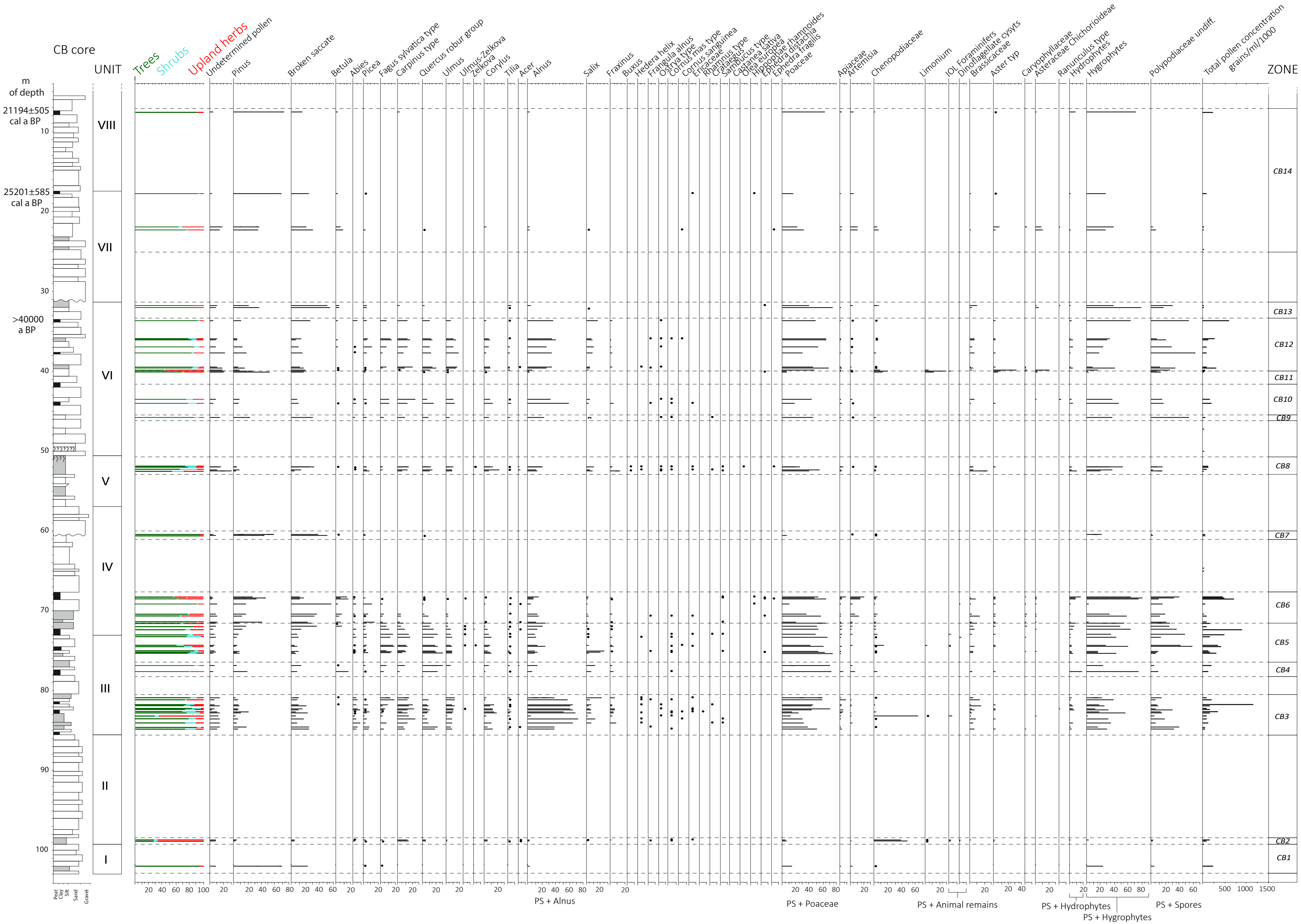

CB core
m of depth
21194±505 cal a BP
25201±585 cal a BP
>40000 a BP
Peat
Clay
Silt
Sand
Gravel
UNIT
I
II
III
IV
V
VI
VII
VIII
Trees
Shrubs
Upland herbs
Undetermined pollen
Pinus
Broken saccate
Betula
Abies
Picea
Fagus sylvatica type
Carpinus type
Quercus robur group
Ulmus
Ulmus-Zelkova
Zelkova
Corylus
Tilia
Acer
Alnus
Salix
Fraxinus
Buxus
Hedera helix
Frangula alnus
Ostrya type
Cornus mas type
Cornus sanguinea
Ericaceae
Rhamnus type
Crataegus
Sambucus type
Castanea sativa
Olea europea
Hippophae rhamnoides
Ephedra distachia
Ephedra fragilis
Poaceae
Apiaceae
Artemisia
Chenopodiaceae
Limonium
IOL Foraminifers
Dinoflagellate cysyts
Brassicaceae
Aster typ
Caryophyllaceae
Asteraceae Chichorioideae
Ranunculus type
Hydrophytes
Hygrophytes
Polypodiaceae undiff.
Total pollen concentration grains/ml/1000
ZONE
CB1
CB2
CB3
CB4
CB5
CB6
CB7
CB8
CB9
CB10
CB11
CB12
CB13
CB14
PS + Alnus
PS + Poaceae
PS + Animal remains
PS + Hydrophytes
PS + Hygrophytes
PS + Spores
500
1000
1500

Fig.5

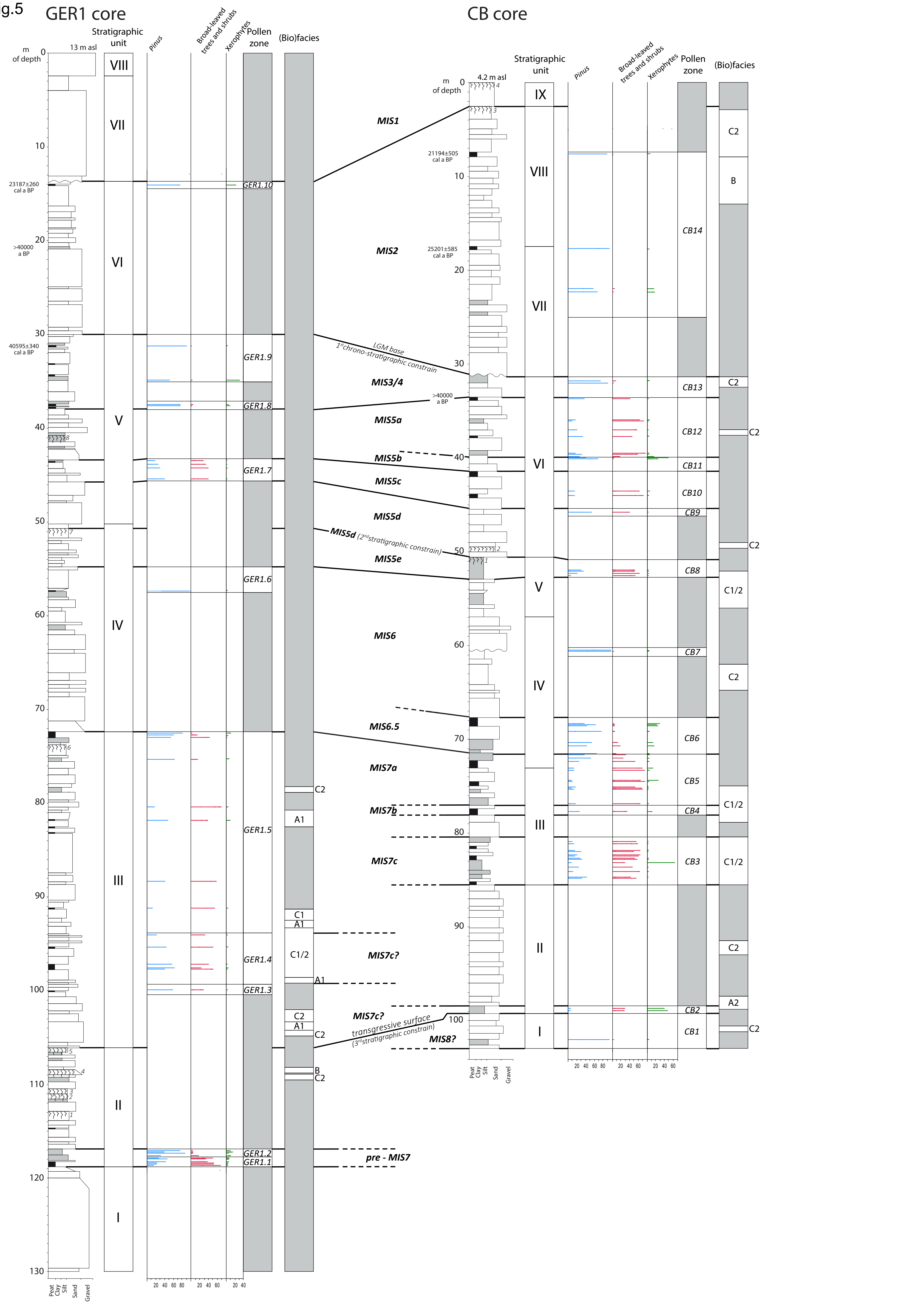
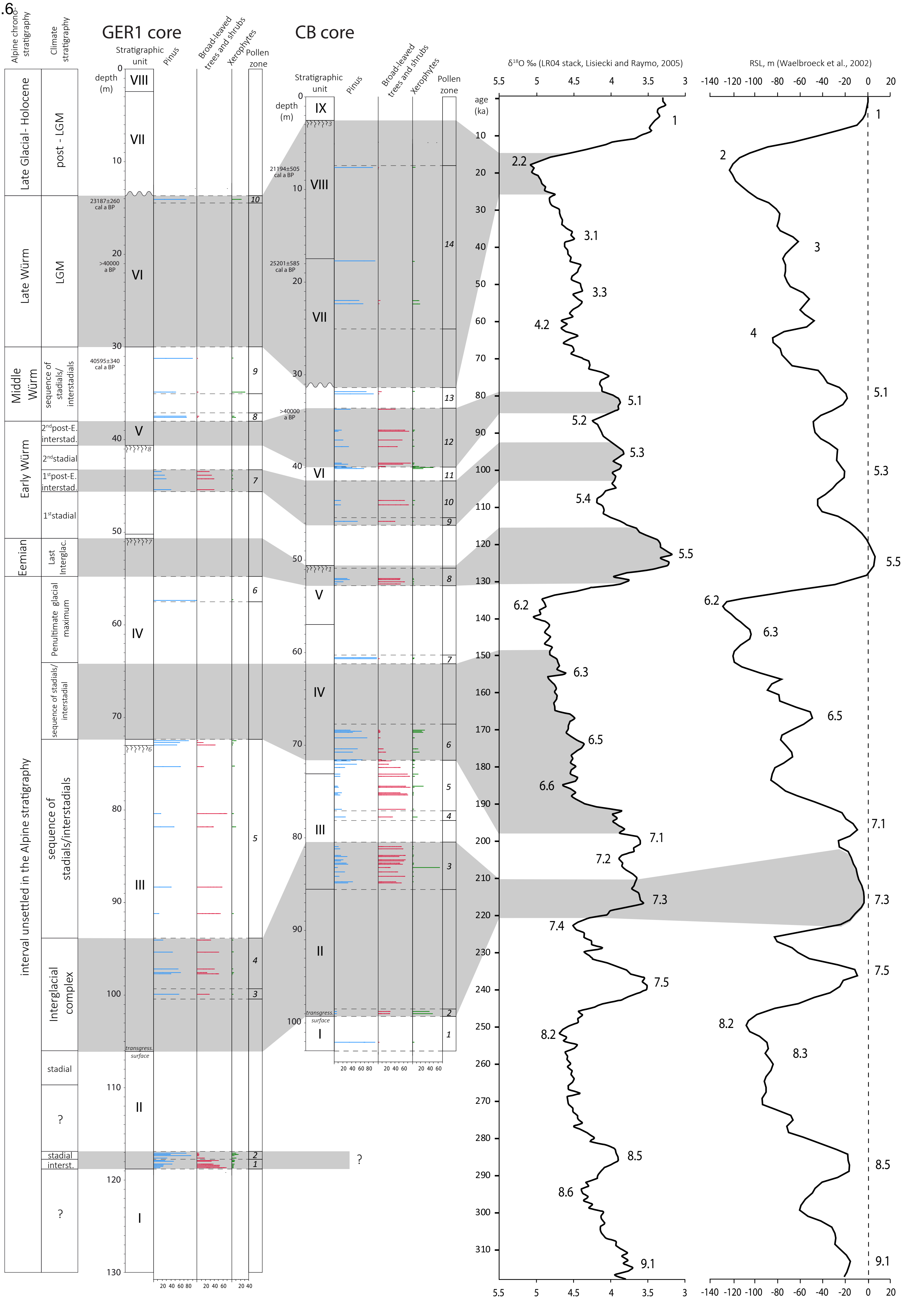

GER1 core
CB core
Stratigraphic unit
Pinus
Broad-leaved trees and shrubs
Xerophytes
Pollen zone
(Bio)facies
m of depth
13 m asl
4.2 m asl
VIII
VII
VI
V
IV
III
II
I
IX
23187±260 cal a BP
>40000 a BP
40595±340 cal a BP
21194±505 cal a BP
25201±585 cal a BP
GER1.10
GER1.9
GER1.8
GER1.7
GER1.6
GER1.5
GER1.4
GER1.3
GER1.2
GER1.1
CB14
CB13
CB12
CB11
CB10
CB9
CB8
CB7
CB6
CB5
CB4
CB3
CB2
CB1
C2
B
C1/2
A1
C1
A2
MIS1
MIS2
LGM base
1st chrono-stratigraphic constrain
MIS3/4
MIS5a
MIS5b
MIS5c
MIS5d
MIS5d (2nd stratigraphic constrain)
MIS5e
MIS6
MIS6.5
MIS7a
MIS7b
MIS7c
MIS7c?
transgressive surface
(3rd stratigraphic constrain)
MIS8?
pre - MIS7
Peat
Clay
Silt
Sand
Gravel
20 40 60 80
20 40 60
20 40

Fig.6



GER1 core
CB core
Alpine chronostratigraphy
Climate stratigraphy
Stratigraphic unit
depth (m)
Pinus
Broad-leaved trees and shrubs
Xerophytes
Pollen zone
δ18O ‰ (LR04 stack, Lisiecki and Raymo, 2005)
RSL, m (Waelbroeck et al., 2002)
age (ka)
Late Glacial - Holocene
post - LGM
Late Würm
LGM
Middle Würm
sequence of stadials/ interstadials
Early Würm
2nd post-E. interstad.
2nd stadial
1st post-E. interstad.
1st stadial
Eemian
Last Interglac.
interval unsettled in the Alpine stratigraphy
Penultimate glacial maximum
sequence of stadials/ interstadial
sequence of stadials/interstadials
Interglacial complex
stadial
?
stadial
interst.
23187±260 cal a BP
>40000 a BP
40595±340 cal a BP
21194±505 cal a BP
25201±585 cal a BP
transgress. surface

Tab.1

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Table
Tab. 1.docx

Tab.2

Click here to access/download
Table
Tab. 2.docx

Declaration of interests

☒ 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.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Author Statement

All authors contributed substantially to the research. Arianna Marcolla: Investigation, Data analysis, Writing – Original draft preparation; Antonella Miola: Investigation, Methodology, Data analysis; Paolo Mozzi: Conceptualization, Investigation, Writing – Review & Editing; Giovanni Monegato: Conceptualization, Validation, Writing – Review & Editing; Alessandra Asioli: Investigation, Data analysis; Roberta Pini: Validation; Cristina Stefani: Conceptualization, Supervision.

Supplementary material 3

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e-Component (supplementary data)
Supplementary material 3.docx