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New data on glacier fluctuations during the climatic transition at ~4000 cal. yr BP from a buried log in the Forni Glacier forefield

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Abstract Glacier history can be reconstructed thanks to geomorphological documentation of previous advances, dating of glacial deposits, investigation of buried soils and included organic material which may be linked to vegetation dynamics. A buried log was retrieved at 2385 m a.s.l. on the North-East-facing slope of the upper Forni Valley (Italian Alps) where the homonymous valley glacier is located. The glacier forefield is currently facing an early successional forest expansion after the ongoing tongue retreat, mainly dominated by young *Picea abies* Karst. and *Larix decidua* Mill. specimens. From dendrochronological and radiocarbon analyses on the retrieved log, coupled with sedimentological and geopedological data, the past environmental and glacier conditions were reconstructed. The log belongs to the stone pine species (*Pinus cembra* L.), it has 283 tree rings and became buried in the deposit in the Subboreal, after 4201–4032 cal. yr BP, age of the outermost tree ring. The retrieved log reveals that during the Subboreal in the Forni Valley likely much older specimens of stone pine were present on the slopes, in strong contrast to present-day conditions. The log's tree-ring growth rates were similar to those presented during the Little Ice Age peak by stone pine trees of comparable age growing nowadays at the treeline.

Keywords Subboreal transition · Forni Glacier · buried log · *Pinus cembra* L. · Italian Alps

1 Introduction

The generalized glacier shrinkage that is affecting most of the debris-free glaciers in the European Alps and at the global scale is progressively changing the high-mountain landscape. Proglacial areas are progressively widening since the end of the Little Ice Age, occasionally exposing ancient forest remnants testifying to previous glacier advances (e.g. Craig and Smith 2013; Chernykh et al. 2013). Glacier terminus advances in fact generally destroy the geomorphological evidences (e.g. moraines) of previous minor advances and may bury the trees located in the proglacial areas and those growing on the valley slopes below the tongue's lateral margins. Moreover, climate-related gravity processes (e.g. debris flow), may also bury vegetation and trees on the valley slopes that then could be reworked by glaciers and enclosed in till. The glacier tongue recession and the erosional processes acting on slopes and valley floors frequently allow the retrieval of logs, stumps and roots formerly lying under till or colluvium, thus allowing the reconstruction of the past glacier history, especially for the more recent Little Ice Age fluctuations (e.g. Luckman 2000; Holzhauser and Zumbuhl 1999) thanks to the radiocarbon and dendrochronological dating (e.g.Pelfini 1999; Brauning 2006; Zhu et al. 2013).

Glacier tongue retreat has accelerated in the last decade since cumulative mean glacier mass balances are becoming more negative through time (Frezzotti and Orombelli 2014). The glacialized surface areas in the Alps have undergone a reduction of about 60% from 1850 to 1970s, increased of another 70% in 2003 and still increasing in the recent decade, depicting a situation which is worst than in the Middle Age and than 5000 years ago (Orombelli 2011; Frezzotti and Orombelli 2014).

Glacier fluctuations are usually followed also by responses in the biological systems. The improved temperature conditions at high altitudes are triggering an altitudinal rise of the treeline, especially in the inner portion of the Alpine mountain chain (Körner and Paulsen 2004; Holtmeier 2009; Leonelli et al. 2009a, 2011) However, due to the alpine farming decline, treeline altitudinal shifts may be traced back also to non-climatic inputs (Gehrig-Fasel et al. 2007). The widespread glacier retreat has favoured the creation of new habitats: glacier-free proglacial areas are typically colonized by animals and plants including trees which colonization patterns (ecesis), in relation to the glacier retreat phases, can be reconstructed through tree age estimations (Shroder 1980; Desloges and Ryder 1990; Mc Carthy and Luckman 1993; Garbarino et al. 2010).

The assessment of past climate variability is a crucial issue for the understanding of the ongoing warming phase compared to past conditions. Precise information can be derived from geomorphologic features as well as from several typologies of natural proxies that can be found in glacial and temperature-limited environments, both at high altitudes and latitudes (Kelly et al. 2004). Buried logs and stumps surely represent a precious source of information that may allow the assessment of both forest and glacier past size and features (Monegato et al.

2011). Subfossil wood (logs, stumps, roots, shrubs and branches) has become indeed a key element for reconstructing past glacial history in many sites on several mountain ranges thanks to radiocarbon dating and dendrochronological analysis (Luckman 1988; Schweingruber 1996; Hormes et al. 2001; Allen and Smith 2007; Coulthard et al. 2012). Many subfossil stems have been found in the inner flank of lateral moraines (Roethlisberger and Schneebeli 1979; Pelfini et al. 2009), in glacial lake deposits (Ravazzi et al. 2012; Trachsel et al. 2012) or in the glacial forefields (e.g. Baroni and Carton 1996; Nicolussi and Patzelt 2000; Joerin et al. 2008) allowing detailed palaeoenvironmental reconstructions. Moreover, supplementary data may be available considering the stratigraphic and sedimentological contexts of wood findings. Sedimentological analyses (e.g. Nicolussi and Patzelt 2000; Holzhauser 2002; Joerin et al. 2006; Ivy-Ochs et al. 2008, 2009) are useful to detect the surface processes responsible of the burying. In particular, pedosedimentary sequences, and especially the occurrence of buried soils, represent crucial tools for understanding the geomorphological and palaeoenvironmental processes occurred between two subsequent glacial advances, and therefore testifying to the existence of stable surfaces affected by pedogenesis during an ice-free phase (e.g. Mavris et al. 2011). In the European Alps, the study of glacial deposits and the retrieval of wood and peat remains allowed the identification and dating of past glaciations and glacier advances (e. g. Porter and Orombelli 1985; Kromer and Becker 1993; Deline and Orombelli 2005; Preusser et al. 2007; Starnberger et al. 2011; Nicolussi and Schlüchter 2012) and also the reconstruction of glacier length variations during the historical advancing phases (Holzhauser 2002).

Logs can be preserved in till or buried in slope colluvium, coming from gravity processes, when located in protected positions with respect to the glacier flow. Different information can be obtained considering wood remnants in relation to their location: the last ring of *in situ* stumps, along the valley floor, provides the date of the glacier arrival while logs not *in situ*, when included in lateral moraines, may suggest glacier size in a dated period or they are helpful in reconstructing worsening climate phases linked to glacier advances when found in proglacial till deposits (e.g. Schweingruber 1996).

The aim of this paper is to show how even a single buried log finding can improve the knowledge on high-mountain past environmental evolution and, more in detail, on the reconstruction of past glacier extent and climatic and environmental factors driving glacier and slope processes dynamics. Our results derive from a recent retrieval of a buried log (Fig. 1c) found in 2011 thanks to the reworking of a tourist trail in the Forni Glacier forefield (Italian Alps), the largest Italian Valley Glacier.

2 Study Area

The Forni Glacier is located in the Central Italian Alps, in the Stelvio National Park. It lies on the northern slopes of the S. Matteo Mt., its elevation ranges between 3670 m and 2520 m a.s.l. (in 2011) and extends on a surface of 11.36 km^2 (D'Agata et al. 2014). As common in recently-deglacialized areas, local soils are poorly developed, especially along the main slopes. In the upper forefield area soils mostly correspond to Leptosols (ERSAF 2012), with very shallow A horizons over a deeper and extremely stony deposit (FAO 2006a); they can be defined as poorly developed soils or humiferous desaturated soils (i.e. ranker; according to Duchaufour 1983). On the contrary, the lower part of the Forni Valley, where a forest is present, is characterized by coniferous forest soils (ERSAF 2012) i.e. Podzols (FAO 2006b; Duchaufour 1983).

The Forni Glacier has been visited for scientific and tourist purposes since the middle of the 19th century (e.g., Omboni 1861; Stoppani 1865, 1875) and it has been deeply studied for several scientific purposes through time thus representing an important key site to understand the environmental and glacier responses to climate change in the central sector of the Southern European Alps (Fig. 1a).

The Forni Glacier past fluctuations are well documented by its moraine apparatus, and its Holocene maximum advance is testified to by the remnants of a terminal moraine (Fig. 1a, moraine ridge b-A), that is close to the Little Ice Age (LIA) maximum one, damming a small peat bog; the radiocarbon date obtained on the basal level of the pond (2670 ± 130 yr BP ^{14}C) provides a minimum age for a glacier advance (Orombelli and Pelfini 1985).

The outer moraine ridge (Fig. 1a, moraine ridge A) corresponds to the moraine built in the 19th century. On the basis of literature data it has been attributed to 1859 (Pelfini 1988), even if another hypothesis developed on the basis of lichenometry, but not supported by local historic data, attributed the ridge to an older phase (1819) (Pelfini 1992). The second moraine (Fig. 1a, moraine ridge B), located at the confluence with the lateral Cedech Valley, was referred to the advances occurred at the beginning of the 20th century: 1904 or 1913-1914. The third ridge (Fig. 1a, moraine ridge C), in the middle of the glacier forefield, is represented by a moraine abandoned by the glacier in 1926 (Desio 1967). Newly-formed and less elevated moraine ridges (Fig. 1a, moraine ridge D), nearer to the current position of the glacier terminus, testify to the last advance occurred in the 1974-1981 time interval (Citterio et al. 2007), before the ongoing accelerating phase of glacier shrinkage (D'Agata et al. 2014).

The glacier tongue retreat has been and is still accompanied by tree recolonization of the sandur. The Forni Glacier forefield is sparsely colonized by young trees mainly of Norway spruce (*Picea abies* Karst.) and European larch (*Larix decidua* Mill.), whereas Stone pine (*Pinus cembra* L.) specimens are only seldom present. Trees' mean age presents a negative gradient towards the glacier terminus, passing from about 50-70 years (at

2200 m a.s.l.) at about 2100 m from the glacier front to less than 10 years (at 2300 m a.s.l.) at about 900 m from the glacier front (Leonelli et al. unpublished data). Also tree height shows a negative trend, passing from 8-12 m to less than 1 m in the same positions as above. Outside the frontal Holocene moraines (Fig. 1a, moraine ridge A) stone pine trees form a pure forest, even if several barns and cattle grazing over centuries have altered its structure, especially at high-altitude, and has lowered the treeline at an altitude of 2300 m a.s.l.

The log was found at an altitude of 2385 m a.s.l., close to the point of coordinates 5141023 N, 621269 E – UTM WGS84, on the North-East-facing slope of the Forni Valley. The site is about 750 m far from the present glacier terminus. Its burial position was parallel to the slope, which presents an inclination of about 20-30°. The log, about 70 cm long x 25 cm diameter (measured on field), lied under 25 cm of mixed sediments and some portions around pith and the outer sections presented rotten wood.

3 Methods

Sedimentological and geopedological surveys were performed to describe the pedosedimentary sequence including the log and to collect sediment and soil samples. Then, the log was sampled and cut into several transversal disks in order to (i) identify the tree species, (ii) construct a ring-width individual mean curve, and (iii) extract a sample for radiocarbon dating.

More in detail for the construction of an individual mean curve of the log and for enhancing tree-ring visibility, the disk surfaces were prepared following standard methods (Stokes and Smiley 1968), then tree rings were measured to the nearest 1/100 mm with a measuring table (LINTAB; Frank Rinn, Heidelberg, Germany) together with the TSAP software package (Rinn 2005) along three different rays on both surfaces. The resulting six growth series were cross-dated visually and statistically (software COFECHA; Grissino-Mayer 2001), finally constructing a fluctuating mean curve for the retrieved log. This individual mean curve was then compared to the mean chronology constructed by selecting trees of the same species and of similar age (about 300 years), currently growing in the lower Forni Valley, outside the study site (Leonelli et al., 2009b). The 283 yr individual mean curve of the log was compared to the reference chronology mean growth in the 283 yr long period (1675-1957) centered over the period of minimum growth 1811-1821 AD corresponding to the LIA peak. A standardized mean curve for the log, based on the six growth series was also constructed, by applying a flexible spline with a 50% frequency cut–off at 100 yr to the growth series and then applying a biweight robust mean to the detrended growth indices (Cook and Briffa 1990).

- ^{14}C dating. A wood sample of a couple of tree rings (one wide and the following very narrow) has been submitted to accelerator mass spectrometry (AMS) ^{14}C dating in order to obtain radiometric age ranges for the dendroclimatic curve. Sample for radiocarbon dating was mechanically separated in order to include two single rings (namely the tree rings 58 and 59 in the growth curve derived from the log); the date obtained was considered to represent the mid-point of the sampled interval. The analyses were performed at the Center for Applied Isotope Studies of the University of Georgia (USA). The obtained uncalibrated age is expressed in radiocarbon years before 1950 (years BP), using the ^{14}C half-life of 5568 years; furthermore, radiocarbon result calibration (2σ) is reported according to IntCal13 (Reimer et al. 2013), with the CALIB Rev 7.0.2 software (Stuiver and Reimer 1993; Stuiver et al. 2014).

- Geopedological analyses. Field description of the pedosedimentary sequence including the sub-fossil wood sample and horizon designations are presented according to the guidelines proposed by FAO (2006a). The Munsell® (1994) nomenclature was used for color attributions. Some physical and chemical analyses were performed on bulk samples collected from the stratigraphic section: (i) Humified organic carbon was identified by means of the Walkley and Black (1934) method and results expressed as g/Kg. (ii) Calcium carbonate equivalents were chemically performed using a Dietrich–Frühling calcimeter (Gale and Hoare 1991). (iii) Grain-size analyses (Gale and Hoare 1991) were performed after removing organics by hydrogen peroxide (130 vol) treatment; sediments were wet sieved (grain size from 2000 to 63 μm), then the silt plus clay fraction (<63 μm) was determined by Casagrande's aerometer on the basis of Stokes's law.

4 Results

The anatomical analysis revealed that the retrieved log belongs to a specimen of *Pinus cembra* L., the most widespread species in the Forni Valley up to the Forni Hut (Fig. 1a).

4.1 Tree-ring individual mean curve

The dendrochronological analyses revealed that the minimum age of the log is 283 years (Fig. 2A). The respective tree-ring growth curves showed a typical age trend, with the largest tree rings in the oldest portion of the mean curve (Fig. 2A), i.e. towards the inner, juvenile, portion of the log. Higher growth rates were also found towards the most recent portion of the mean growth curve.

Comparing the log's growth with the growth of *P. cembra* trees currently growing at the treeline in the Forni Valley (Fig. 2B; Leonelli et al. 2009b), we found that the log's mean tree-ring growth over its 283 yr was similar to the growth comprising the cool period around 1816 AD. The tree-ring growth in the log was meanly 0.44 mm lower than the one in the reference period 1675-1957. Tree-ring growth rates in the log were meanly lower than the reference mean chronology and after the tree ring nr. 118 they were always lower than the growth rates recorded during the LIA peak, excluding the last few years (Fig. 2A).

The standardized mean curve (Fig. 3) shows over the 172 year-long time period (years nr. 18-189, where at least four series are present), three minima (around the years nr. 80; 130; 190) separated by 50-60 years with the most pronounced one around the ring nr. 80. The passage to wider rings was faster than the passages to the periods of minimum tree-ring width. The higher variability recorded up to the year nr. 17 and since the year nr. 190 is largely given by the too small sample depth.

The radiocarbon dating of the tree ring number 58 (and 59) gave the result of 3920±25 uncal. yr BP ($\delta^{13}C$ -24.3‰; pMC 61.39±0.19), corresponding to 4426–4257 cal. yr BP (2σ range). Since the tree lived at least for other 225 years from year nr. 58, the outermost and older tree ring visible in the log can be dated to 4201–4032 cal. yr BP.

4.2 Pedosedimentary sequence

In the analyzed pedosedimentary sequence the parent material is constituted of local metamorphic rocks, mostly micaschist rich in quartz, muscovite, chlorite and albite (Fig. 4; Appendix 1). Rock outcrops are common, while coarse surface fragments are abundant, in form of weakly weathered coarse gravel and stones. Evidences of slight mass movements are present.

The described sequence is composed of two pedosedimentary units consisting of poorly weathered soil horizons (Fig. 5, 6); at the top of the upper unit a sandy loam A horizon with sparse gravel is present, followed by two distinct AC horizons showing an increase in coarse gravel toward the bottom. The AC2 horizon includes the log. It lies on a buried 2AB horizon, which displays an incipient biochemical weathering; the 2AB horizon is underlain by two 2C horizons and they constitute the deeper pedosedimentary unit. In the 2C2 horizon an increase in the coarse gravel fraction is evident. Due to the limited thickness of the 2AB horizon it is possible to state that the deeper unit was truncated before the parent material of the upper unit was accumulated.

Laboratory analyses highlight a general decreasing trend with depth in the organic carbon content, ranging from 10.5 g/kg (A horizon) to 2 g/kg (2C2 horizon) (Fig. 5, 6); an exception is represented by the 2AB horizon, which shows a relative peak in the organic carbon content (8 g/kg), which is comparable (to some extent) with the superficial A horizon. In the whole pedosedimentary sequence calcium carbonate equivalents content is low (4%), while the highest value was measured in the AC1 horizon (10%). Grain size analyses substantiate the presence of two distinct pedostratigraphic units as suggested by the field description: in fact, gravel increases with depth, from about 30% to about 60%, in each of the identified units. As regards of the fine earth cumulative curves, all described horizons are poorly sorted and dominated by sand; the 2AB horizon is the exception, showing a clear decrease in the sand fraction and a corresponding increase in the coarse and medium silt fractions (Fig. 6).

5 Discussion

The presence of the log dating to 4201–4032 cal. yr BP buried in the Forni Glacier forefield adds new information about a crucial phase of the Holocene, encompassing part of the Subboreal and an early stage of the Neoglacial.

Presently the valley slope is characterized only by very young trees, mainly sparse larches, while the retrieved log is evidence of a *Pinus cembra* specimen of about 300 years old. Nowadays old stone pine trees can be found only outside the glacier forefield, in the area external to the LIA moraine ridge and about 2 km from the glacier front. Within the limits of the LIA moraines only younger trees are growing and close to the log site only sparse trees <1 m height are present.

Surely a single buried log does not allow to assess the possible presence of a forest growing on the valley slopes; nevertheless in several cases single retrievals or few radiocarbon dates allowed to add new information about local glacier histories (e.g Baroni and Carton 1990,1996 for the Adamello Presanella group; Porter and Orombelli 1985 for the Rutor glacier in the Western Italian Alps).

Our findings support the hypothesis that, before the log was included in the deposit, the Forni Valley was likely characterized by the presence of much older Stone pine trees than nowadays, dating back to the early Subboreal. The retrieved log could belong to a sparse tree coverage or to an even older and developed forest in the middle Holocene under a warm Atlantic climate (Ravazzi and Aceti 2004; Tinner 2007) as well demonstrated, for example, in the Central Eastern Alps. Therein, in the Kauner valley (Austria), a Stone pine treeline was found higher than its modern limit at 2370 m a.s.l. (Nicolussi et al. 2005). In this valley, based on radiocarbon dating of subfossil logs, a downvalley shift of about -100 m up to about 2200 m a.s.l. has been presumed for the period 4050–3750 cal. yr BP (Nicolussi et al. 2005), likely meaning a climate worsening condition also over the region of the Forni Valley.

We have no information about the size of the Forni Glacier in the Subboreal, but the retrieval of the buried log and its comparison with the evidence dating to the last decades suggest that about 4000 years ago the glacier terminus was placed at an altitude at least higher than 2300 m. A retreating phase for that period has been recognized for other Alpine glaciers (e.g. Joerin et al. 2008, Nicolussi and Patzelt, 2000). Important information to support this hypothesis can be carried out from geopedological analyses, which suggest magnitude and rates of processes driving soil development closely linked to climate conditions. The parent material of both identified pedosedimentary units is heterometric, including angular pebbles in a sandy loam matrix; these sedimentological characteristics are compatible both with slope sediments or till deposited laterally on the lower portion of the valley slope so it is difficult make a distinction among the two kind of processes. Nevertheless, it is worth to notice that the log was found lying upon the residual 2AB horizon of a truncated soil, which origin required an exposed and stable surface under climatic conditions promoting biochemical weathering. Such conditions lasted enough to permit the genesis of soil horizons possibly more mature than the one at the present day surface that formed in the last decades. This evidence further supports the occurrence of a stable geomorphic surface at the time of the growth of the log and the occurrence of a soil supporting the growth of well-developed sparse trees or even of a forest in the upper Forni Valley. On the contrary, after this phase, a cooling trend may have promoted surface instability causing the tree death and the subsequent burying of the log. Enhanced instability of the slopes and the increased runoff during the Subboreal cooling phase are testified in other sites of the Alps and the Apennine (e.g., Bertolini et al. 2004; Mayewski et al. 2004; Arnaud et al. 2005; Borgatti and Soldati 2010; Cremaschi and Nicosia 2012). We cannot identify if the burying was directly caused by a glacier advancing phase or by a slope process as the pedological analysis do not allow to distinguish between slope deposit and reworked till. However, the log was surely under the glacier body during the LIA, as evidenced by the higher altitude of the LIA lateral moraine (Fig. 1). In recent times the portion of slope where it was retrieved was abandoned by glacier ice since about the 1960s, when the glacier terminus in the valley bottom was at about 2300 m a.s.l. By analyzing high-resolution aerial photos and orthophotos for the period 1954-2007, we found that the area where the log was retrieved was still ice covered in 1954. Nevertheless the log site is located close to the 1954 glacier boundary and then probably the surface was abandoned by ice some years later, thus suggesting that the surface was exposed since the beginning of the 1960s. Moreover the debris layer covering the retrieved log is thick enough to suggest that the log has been uninterruptedly buried in the deposit since the Subboreal, and more precisely since 4201–4032 cal. yr BP, age of the outermost tree ring.

Comparing the log’s tree-ring growth with those of Stone pine trees of similar age growing nowadays at the treeline, trees that can be found only outside the study site, we found that the log’s mean tree-ring growth was similar to the growth comprising the coldest period of the Little Ice Age (LIA peak, around 1816 AD). Even if a single tree retrieval is surely not sufficient to assess past climate conditions (and low growth rate can be caused by several factors), it is interesting to note the very low tree-ring growth rates recorded over the analyzed 283 years of growth. For this reason we cannot exclude that these growth patterns could have been controlled only by climate conditions; however tree growth at these altitudes is mainly controlled by temperature. Moreover, a non-climatic suppressed growth should be linked to the presence at that times of a close forest, which at the moment seems unlikely, given the retrieval of only this isolated buried log. The narrower tree rings, which may correspond to the coolest period, were recorded around the year nr. 80 (i.e. 4404-4235 cal. yr BP).

Considering that the innermost tree ring dated to 4483-4314 cal. yr BP, it is probable that the tree germinated about 4500 cal. yr BP and it was buried at least 283 years later, about 4000 cal. yr BP, living in a cold climate. The late-Holocene climatic transition at about 4000 cal. yr BP is recognized as a period of complex climatic change from the Holocene Climatic Optimum (Mayewski et al. 2004; Magny et al. 2009), and it is characterized by drying and cooling climate: the so called ‘4000 BP event” started about 4400 yr BP and ended about 3800 yr BP (Perry and Hsu 2000; Drysdale et al. 2006; Magny et al. 2009; Liu and Feng 2012). For what concerns the southern side of the Alps a key site is represented by the Miage Glacier in the Mt. Blanc Massif, where glacier advances have been detected at 4800–4600 cal. yr BP (early Neoglacial) and around 2500 cal. yr BP (Deline and Orombelli 2005). Moreover, glacier advancing phases have been recognized in the Russian Altai (4900 to 4200 cal. years BP; Akkem stage) according to Agatova et al. (2012), prior than 3000 ^{14}C yr BP in northern British Columbia Coast Mountains according to Jackson et al. (2008), in 3167–2737 cal. yr BP for the Scimitar in British Columbia Coast Mountains, Canada according to Craig and Smith (2013).

According to Walker et al. (2012) a widespread aridification recognized at mid/low-latitude in different environments occurred 4200 cal. yr BP, thus determining the Middle–Late Holocene Boundary; however, this period was characterized by a generalized climatic instability including cooler and wetter conditions in Europe. Evidence of this climate transition is reported also by other authors, who identify it as a Holocene transition towards more unsteady climatic conditions (e.g. Sandweiss et al. 1999; Mayewski et al. 2004; Anderson et al. 2007; Magny et al. 2009).

6 Conclusions

The buried log retrieved in the Forni Valley dated back to 4201–4032 cal. yr BP. Its retrieval and the following dendrochronological, pedological and geomorphological analyses carried out allow to add new information about the local climate, the environmental conditions during the Subboreal and to hypothesize a glacier front past position. A single buried log is not sufficient for assessing the presence of a mature forest, however its presence and the integrated results deriving from the different investigation methods allow to state that i) when the tree grew, a stable climatic phase allowing soil development was present; ii) a climate worsening, also likely responsible of a glacier advance, caused tree death probably in relation to gravity or glacial processes. The Forni

Glacier, presently the widest Italian valley glacier, during the Subboreal transition was likely advancing after reaching an area likely smaller than nowadays during the previous warmer climate phase. More data would be necessary to better characterize the climatic and environmental transition and to compare the local situation to the one emerging on the southern side of the European Alps.

The reconstruction here proposed even if based on a single retrieved log, underlines the importance of spot findings for past glacier fluctuations reconstruction. This is confirmed by the dating of the basal peat layer of the small peat bog dammed by the frontal moraine of Forni Glacier, giving the minimum age 2670±130 yr BP; this ^{14}C date allowed to date for the first time on the southern side of the Alps the maximum Holocene advance of the Forni Glacier (Orombelli and Pelfini 1985).

The present results underline the importance of multidisciplinary approaches for the comprehension of the past environmental evolution to better understand the ongoing changes in glacial environments and to hypothesize the possible environmental responses to future climate change.

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Appendix: description of the horizons of the pedosedimentary sequence

A (0-5 cm); very wet; pale olive (5Y 6/4) dry, and olive (5Y 4/3) moist; sandy loam with subangular medium gravel, slightly weathered; medium granular structure, weak; common macropores; few fine roots; gradual to diffuse, smooth boundary to:

AC1 (5-20 cm); moist; light yellowish brown (2.5Y 6/3) dry, and olive (5Y 4/4) moist; sandy loam, with common subangular medium gravel and few subangular coarse gravel, both slightly weathered; fine granular structure, weak; common macropores; few fine roots; gradual to diffuse, smooth boundary to:

AC2 (20-35 cm); moist; olive (5Y 5/4) dry, and olive (5Y 4/3) moist; sandy loam with dominant subangular coarse gravel, weathered; fine granular structure, weak; few macropores; few fine roots; gradual to diffuse, irregular boundary to:

2AB (35-37 cm); moist; light brownish gray (2.5Y 6/2) dry, and olive (5Y 4/4) moist; silt loam with many subrounded medium gravels weathered; fine granular loose structure; weak; common macropores; few fine roots; gradual to diffuse, smooth boundary to:

2C1 (37-61 cm); moist; pale olive (5Y 6/3) dry, and olive (5Y 4/4) moist; sandy loam with common subrounded coarse gravels weathered; fine granular structure; weak; few macropores; few fine roots; gradual to diffuse, smooth boundary to:

2C2 (61-91+ cm); moist; pale olive (5Y 6/4) dry, and olive (5Y 4/4) moist; sandy loam with many subrounded coarse gravels weathered; fine granular structure,; weak; few macropores; few fine roots; lower boundary not exposed.

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Figure captions

Fig. 1 (a) Map of the Forni Glacier forefield with the location where the buried log was found, indicated by the star (coordinates: 5141023 N, 621269 E -UTM WGS84). b-A i.e. before A = maximum Holocene expansion; A = Litlle Ice Age (LIA) moraine; B = beginning of the 20th century: 1904 or 1913-1914; C= 1926 glacier expansion; D= 1974-1981 glacier expansion; (b) illustrates the position of the study area in a regional context. (c) Transversal section of the retrieved log after its drying that caused a partial shrinkage of the rotten portions.

Fig. 2 The 283 year long tree-ring width individual mean curve of the buried log (A) compared with the mean chronology of trees older than 283 years currently growing in the Forni Valley at the treeline, over the 283 yr period (1675-1957 AD) centered on the LIA peak (B) (see methods for details; data of 'FSN' site from Leonelli et al. 2009b). Bold lines indicate a 11-yr running mean. Dashed line in A indicates the mean growth of the chronology in B over the whole 283 yr period considered (and vice versa). The dotted line in A indicates the mean growth of the chronology depicted in B over the 11 yr period of minimum growth 1811-1821 AD; in B it indicates the mean growth of the individual mean curve depicted in A over the 11 yr period of minimum growth (tree rings no. 251-261).

Fig. 3 The tree-ring standardized mean curve derived from the measurements along three rays on two transversal surfaces. The different consistency of the sample depth over time is due to the sub optimal log preservation conditions.

Fig. 4 A sketch of the pedosedimentary sequence including the log; for the description of the horizons the reader is referred to the text and Appendix.

Fig. 5 Results of the geopedological analyses (grain size and organic matter content) carried out on the pedosedimentary sequence; note the high amount of gravel along the whole sequence and the high content of organic matter in the 2AB horizon.

Fig. 6 Grain size cumulative curves (fine earth) for each horizon. Note the increase in silt and clay in the 2AB horizon.

Figure_1

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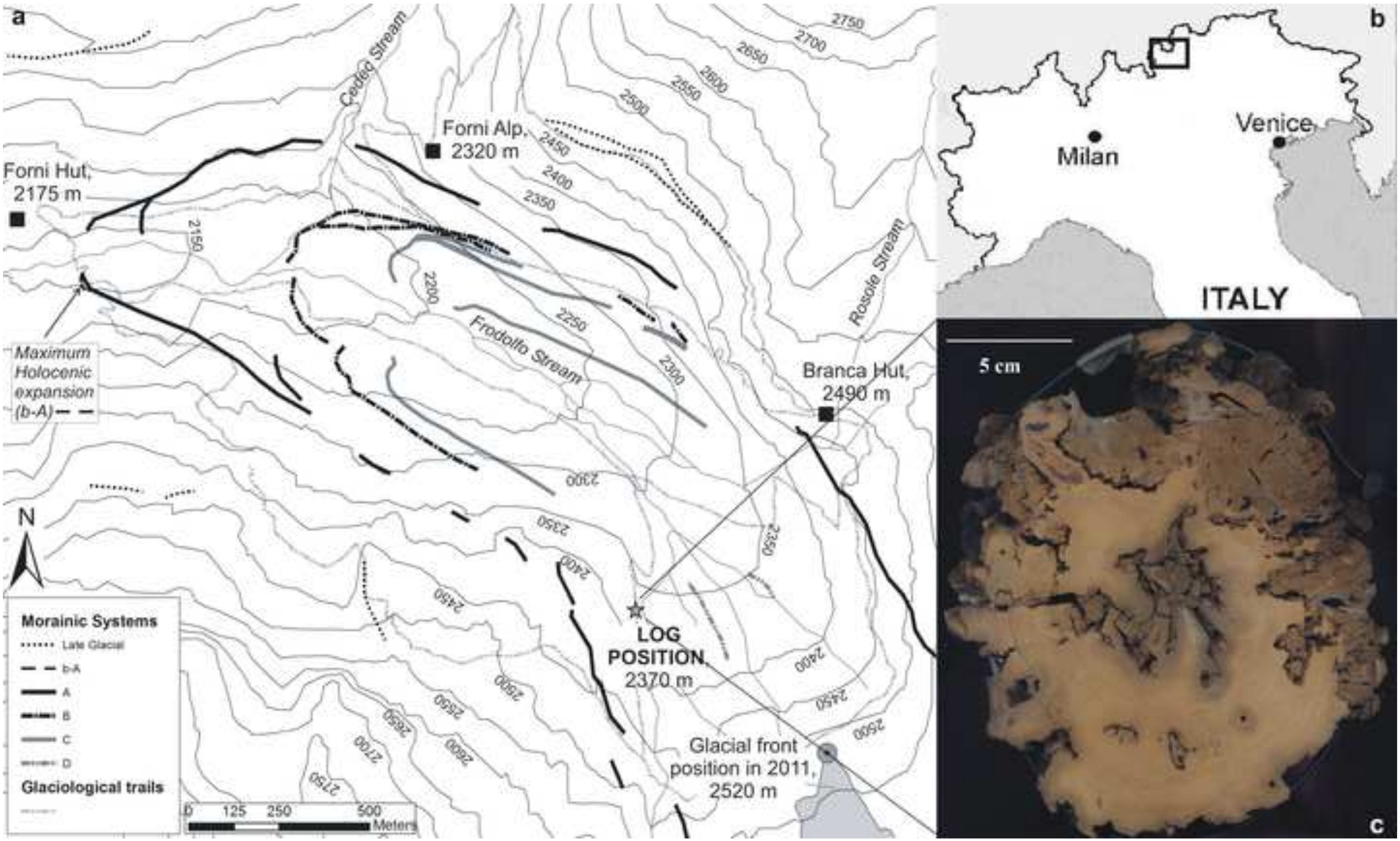

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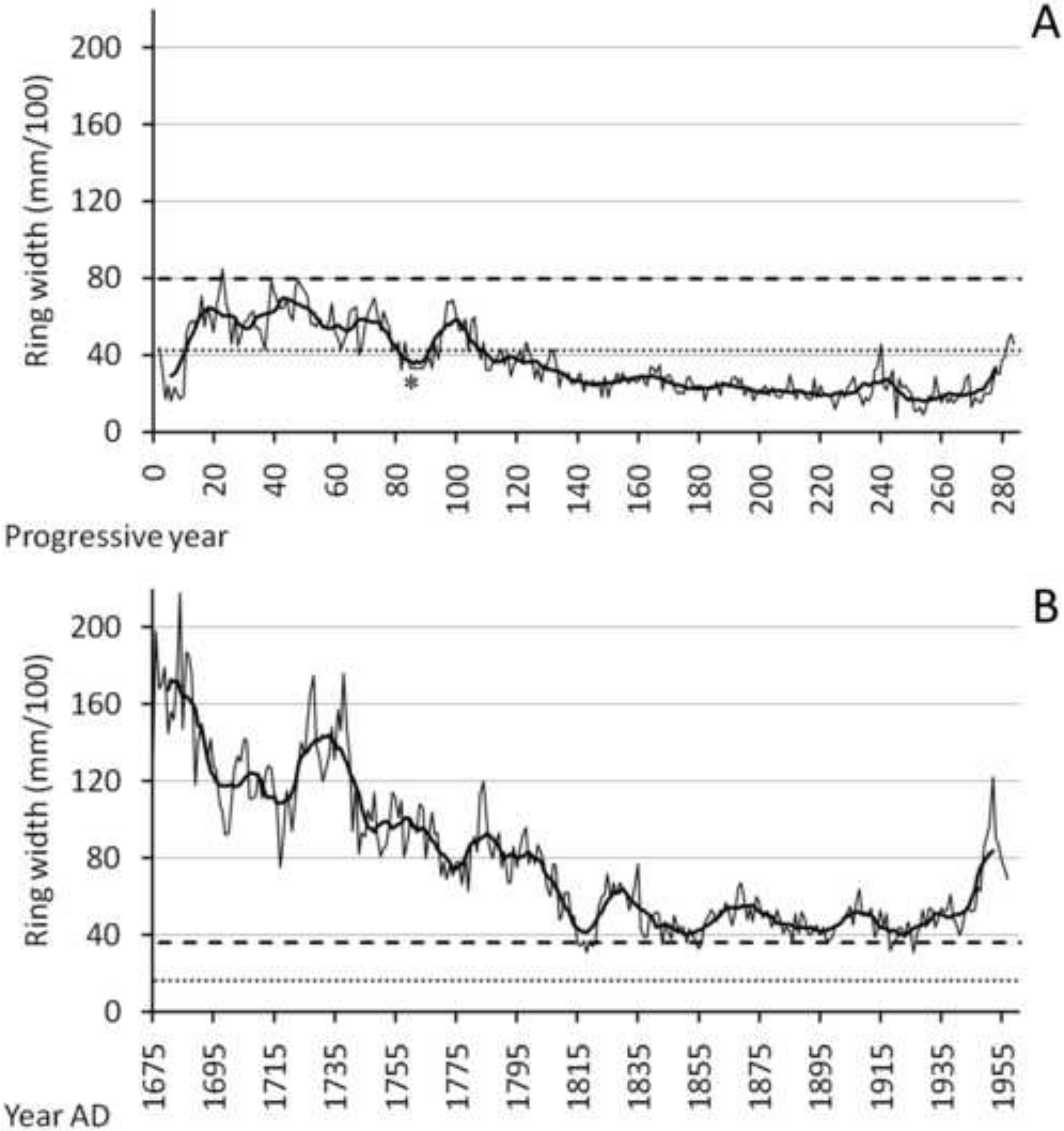

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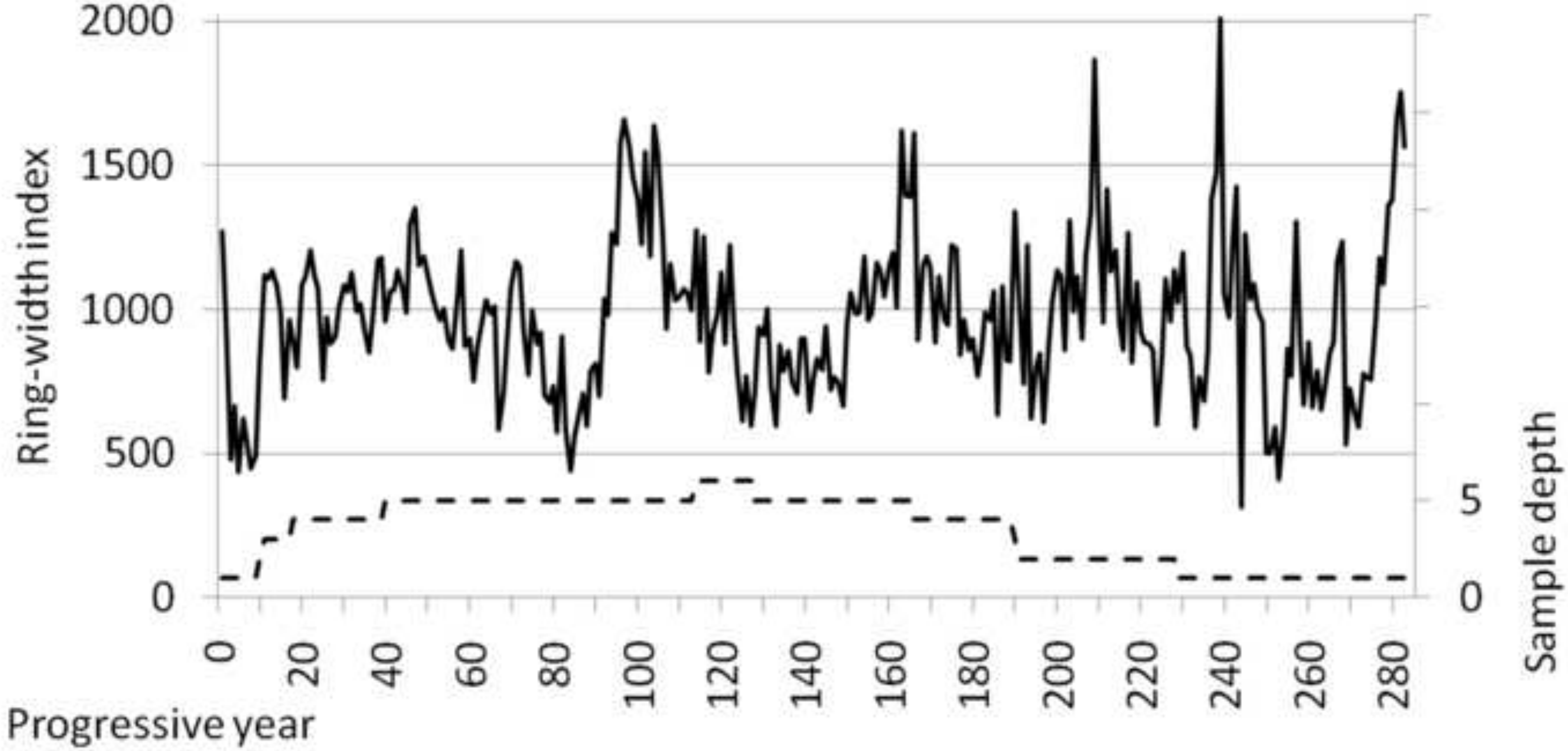

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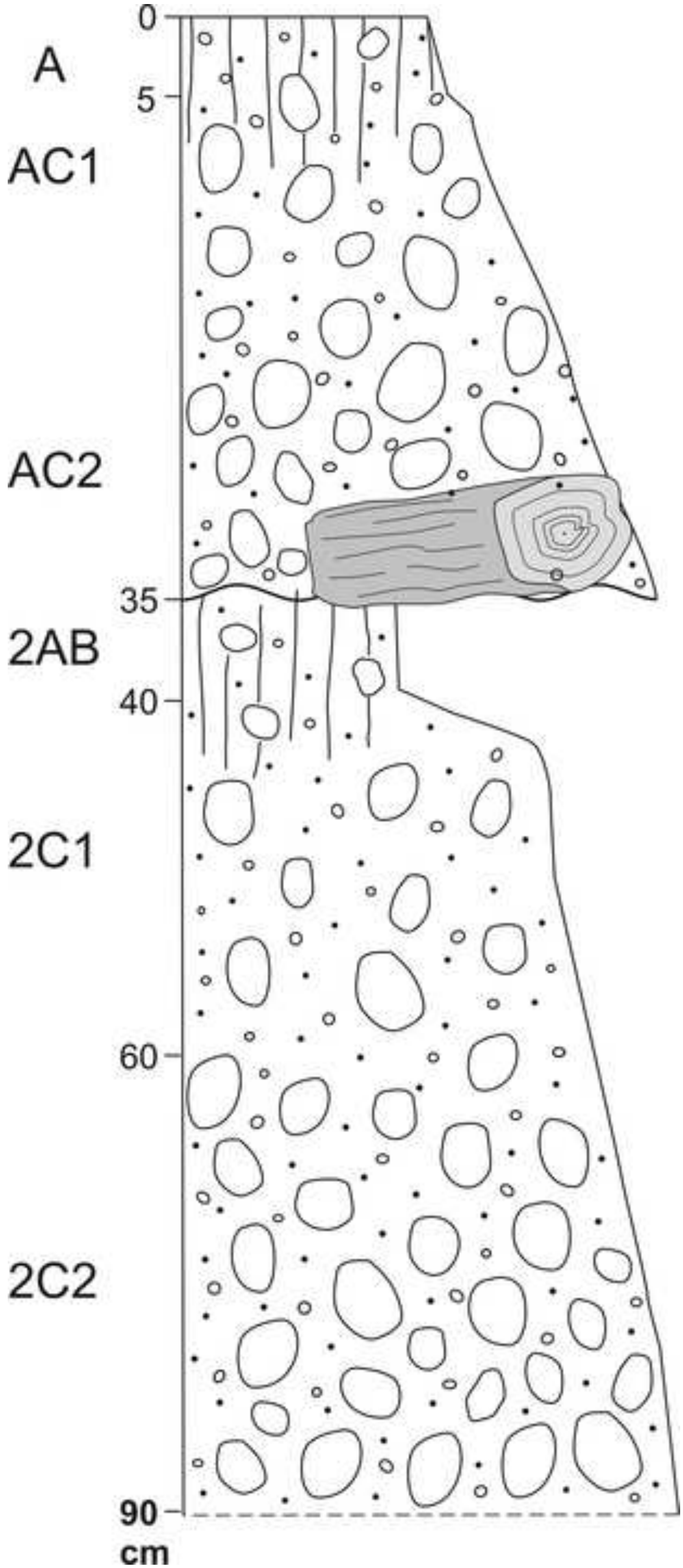

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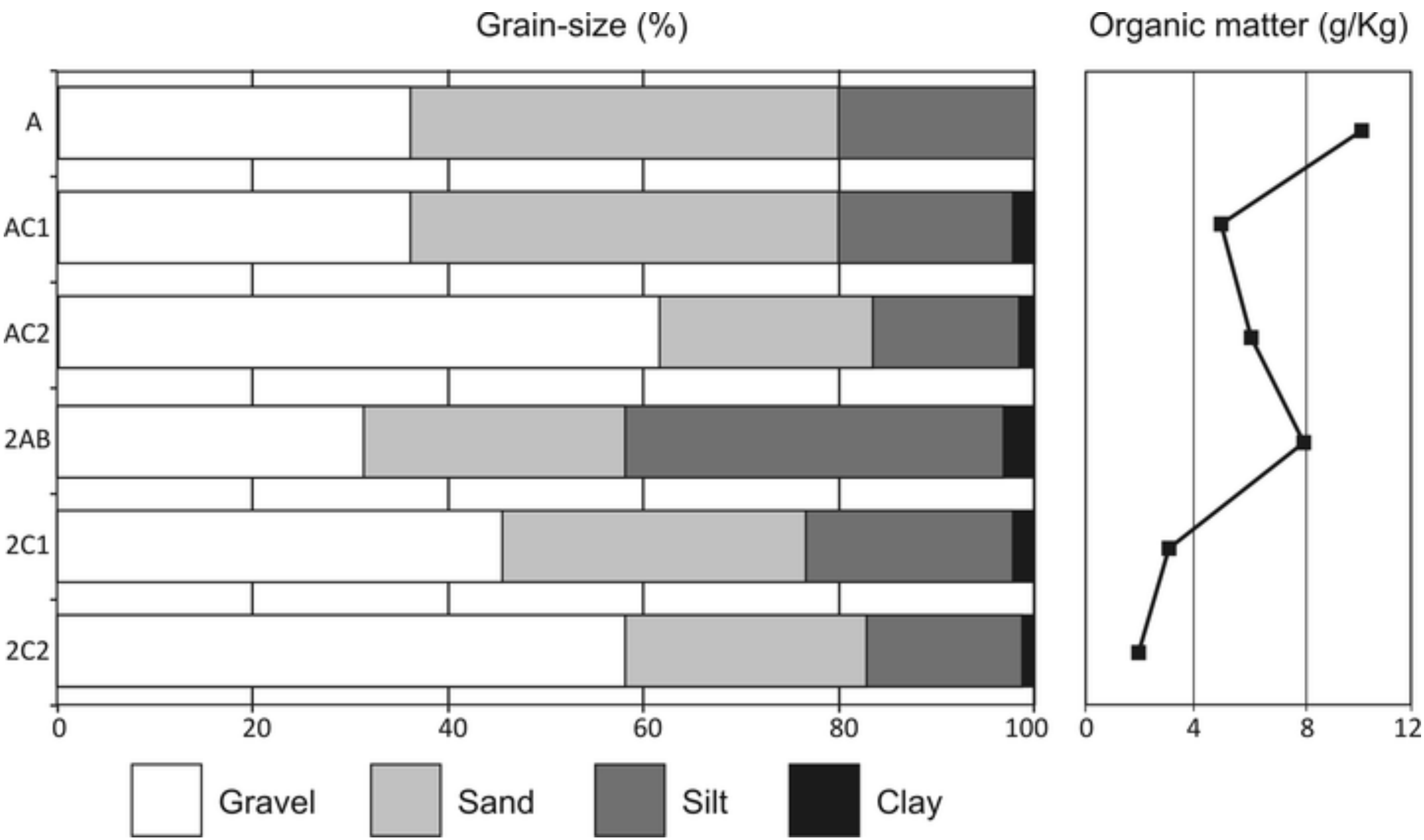

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