New data on glacier fluctuations during the climatic transition at ~4,000 cal. year BP from a buried log in the Forni Glacier forefield (Italian Alps)

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Abstract Glacier history can be reconstructed thanks to geomorphological documentation of previous advances, dating of glacial deposits, and investigation of buried soils and included organic material, which may be linked to vegetation dynamics. A buried log was retrieved at 2,385 m a.s.l. on the northeast-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 dendro-chronological 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 4,201–4,032 cal. year 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

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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, increase of another 70 % in 2003 and still increasing in the recent decade, depicting a situation which is worse than in the Middle Age and than 5,000 years ago (Orombelli 2011; Frezzotti and Orombelli 2014).

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Glacier fluctuations are usually followed also by responses in the biological systems. The improved temperature conditions at high altitudes trigger 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 favored the creation of new habitats: glacier-free proglacial areas are typically colonized by animals and plants including trees in 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), glacial lake deposits (Ravazzi et al. 2012; Trachsel et al. 2012) or the glacial forefields (e.g., Baroni and Carton 1996; Nicolussi and Patzelt 2000; Joerin et al. 2008) allowing detailed paleoenvironmental reconstructions. Moreover, supplementary data may be available considering the stratigraphic and sedimentological contexts of wood finds. Sedimentological analyses (e.g., Nicolussi and Patzelt 2000; Holzhauser 2002; Joerin et al. 2006; Ivy-Ochs et al. 2008, 2009) are useful for detecting 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 paleoenvironmental processes that 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 3,670 and 2,520 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 nineteenth 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
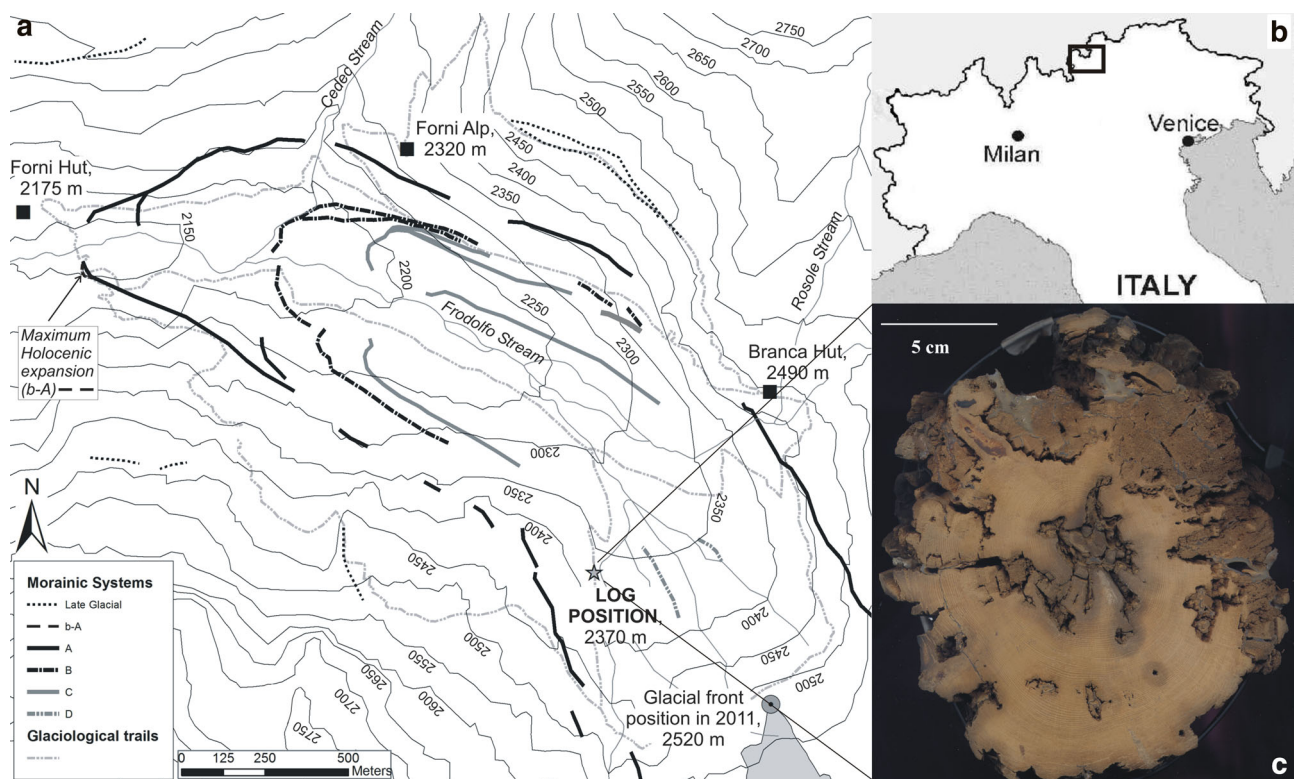
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Fig. 1 a Map of the Forni Glacier forefield with the location where the buried log was found, indicated by a *star* (coordinates: 5141023N, 621269E–UTM WGS84). *b-A*, i.e., before *A* maximum Holocene expansion; *A* Little Ice Age (LIA) moraine; *B* beginning of the twentieth 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

advance is testified 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 (2,670 ± 130 year 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 nineteenth 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, referred to the advances that occurred at the beginning of the twentieth 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 that 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 toward the glacier terminus, passing from about 50–70 years (at 2,200 m a.s.l.) at about 2,100 m from the glacier front to less than 10 years (at 2,300 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 2,300 m a.s.l.

The log was found at an altitude of 2,385 m a.s.l., close to the point of coordinates 5141023N, 621269E—UTM

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WGS84, on the northeast-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 × 25 cm diameter (measured on field), lay under 25 cm of mixed sediments and some portions around the pith and the outer sections presented rotten wood (Fig. 1c).

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 to (1) identify the tree species, (2) construct a ring-width individual mean curve, and (3) 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-year individual mean curve of the log was compared to the reference chronology mean growth in the 283-year-long period (1675–1957) centered over the period of minimum growth at 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 cutoff at 100 year 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) was submitted to accelerator mass spectrometry (AMS) ^{14}C dating in order to obtain radiometric age ranges for the dendroclimatic curve. The sample for radiocarbon dating was mechanically separated 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 midpoint of the sampled interval. The analysis was 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 5,568 years; furthermore, the 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: (1) humified organic carbon was identified by means of the Walkley and Black (1934) method and results expressed as g/kg. (2) Calcium carbonate equivalents were chemically performed using a Dietrich–Frühling calcimeter (Gale and Hoare 1991). (3) Grain size analysis (Gale and Hoare 1991) were performed after removing organics by hydrogen peroxide (130 vol) treatment; sediments were wet sieved (grain size from 2,000 to 63 μm), then the silt plus clay fraction (<63 μm) was determined by Casagrande's aerometer on the basis of Stokes' law.

4 Results

The anatomical analysis revealed that the retrieved log belonged 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 analysis revealed that the minimum age of the log was 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., toward the inner, juvenile, portion of the log. Higher growth rates were also found toward 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 year 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 on mean 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
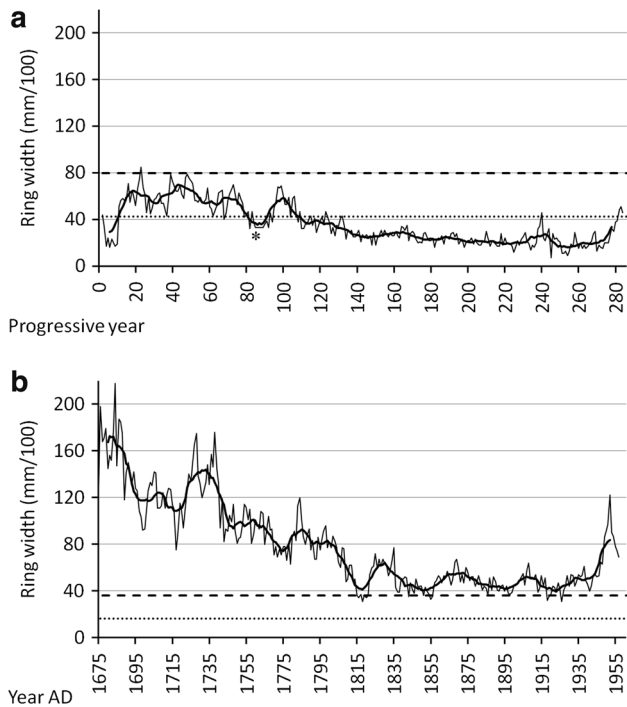
Fig. 2 The 283-year-long tree-ring width individual mean curve of the buried log (**a**) compared with the mean chronology of trees older than 283 years currently growing in the Forni Valley at the treeline, over the 283-year period (1675–1957 AD) centered on the LIA peak (**b**) (see "Methods" for details; data of 'FSN' site from Leonelli et al. 2009b). *Bold lines* indicate an 11-year running mean. *Dashed line* in **a** indicates the mean growth of the chronology in **b** over the whole 283-year period considered (and vice versa). The *dotted line* in **a** indicates the mean growth of the chronology depicted in **b** over the 11-year 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-year 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 suboptimal 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"

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 $3,920 \pm 25$ uncal. year BP (δ^{13}C-24.3 ‰; pMC 61.39 ± 0.19), corresponding to 4,426–4,257 cal. year BP (2σ range). Since the tree lived at least for another 225 years from year nr. 58, the outermost and older tree ring visible in the log can be dated to 4,201–4,032 cal. year 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
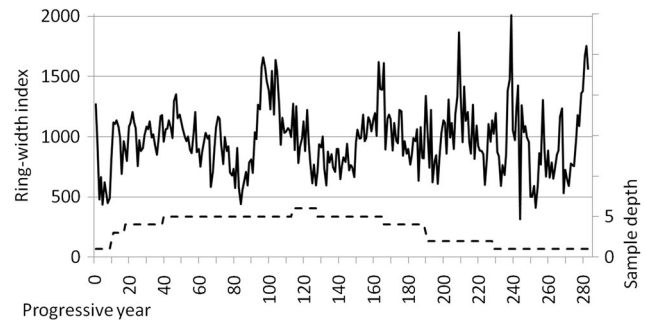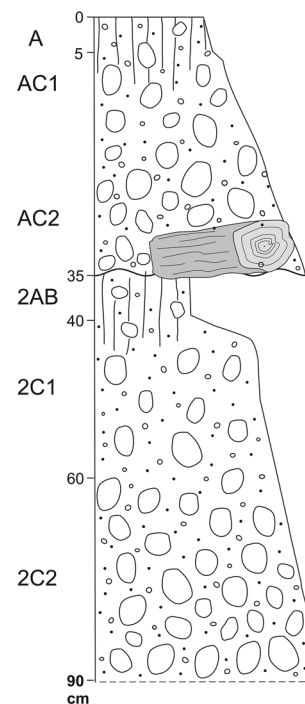
(Fig. 4; "Appendix"). Rock outcrops are common, while coarse surface fragments are abundant, in the form of weakly weathered coarse gravel and stones. Evidences of slight mass movements are present.

The described sequence is composed of two pedosedimentary units consisting of poorly weathered soil horizons (Figs. 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

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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
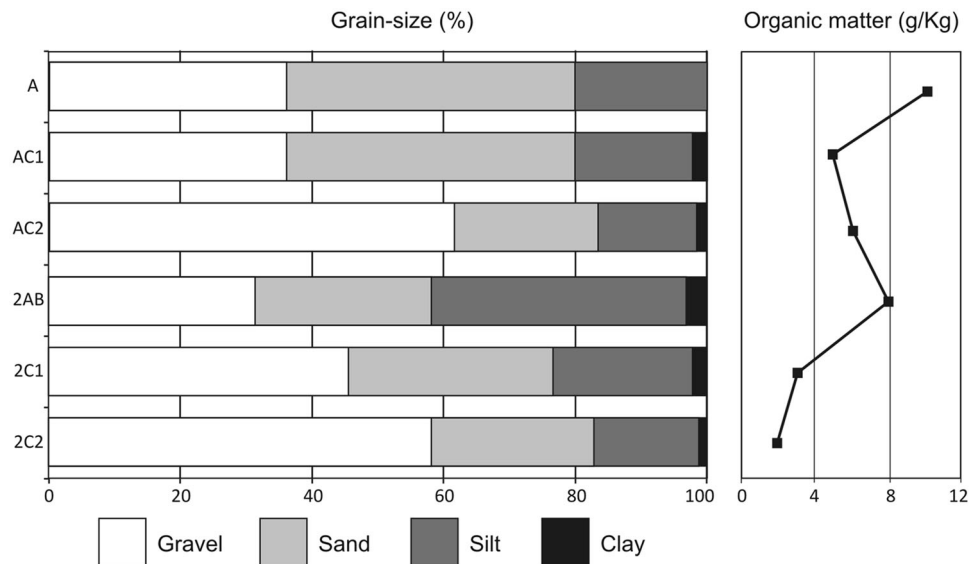
two 2C horizons and constitutes the deeper pedosedimentary unit. In the 2C2 horizon an increase in the coarse gravel fraction is evident. Due to the limited thickness of the 2AB horizon, it is possible to state that the deeper unit was truncated before the parent material of the upper unit was accumulated.

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) (Figs. 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) to the superficial A horizon. In the whole pedosedimentary sequence, calcium carbonate equivalent 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 the fine earth cumulative curves, all described horizons are poorly sorted and dominated by sand; the 2AB horizon is an 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 4,201–4,032 cal. year 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
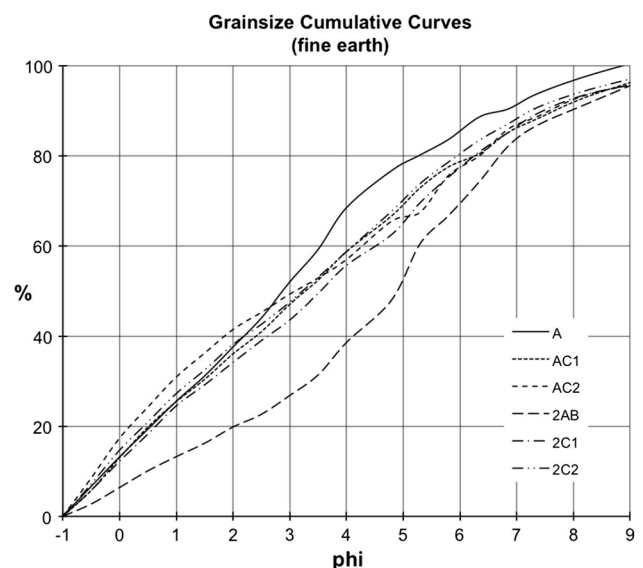

Fig. 6 Grain size cumulative curves (fine earth) for each horizon. Note the increase in silt and clay in the 2AB horizon

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 grow and close to the log site only sparse trees <1 m height are present.

Surely, a single buried log does not allow assessing the possible presence of a forest growing on 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 2,370 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 2,200 m a.s.l. has been presumed for the period 4,050–3,750 cal. year 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 4,000 years ago the glacier terminus was placed at an altitude at least higher than 2,300 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 and till deposited laterally on the lower portion of the valley slope, so it is difficult make a distinction between the two kinds of processes. Nevertheless, it is worth noticing that the log was found lying upon the residual 2AB horizon of a truncated soil, the origin of which 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 few 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 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 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 pedological analysis does not allow distinguishing 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 2,300 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 4,201–4,032 cal. year BP, the 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., 4,404–4,235 cal. year BP).

Considering that the innermost tree ring dated to 4,483–4,314 cal. year BP, it is probable that the tree germinated about 4,500 cal. year BP and was buried at least 283 years later, about 4,000 cal. year BP, living in a cold climate.

The Late Holocene climatic transition at about 4,000 cal. year BP is recognized as a period of complex climatic change from the Holocene Climatic Optimum (Mayewski et al. 2004; Magny et al. 2009) and is characterized by drying and cooling climate: the so-called "4,000 BP event" started about 4,400 year BP and ended about

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3,800 year 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 4,800–4,600 cal. year BP (early Neoglacial) and around 2,500 cal. year BP (Deline and Orombelli 2005). Moreover, glacier advancing phases have been recognized in the Russian Altai (4,900–4,200 cal. years BP; Akkem stage) according to Agatova et al. (2012), prior to 3,000 ^{14}C year BP in northern British Columbia Coast Mountains according to Jackson et al. (2008), and in 3,167–2,737 cal. year 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 4,200 cal. year 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 toward 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 4,201–4,032 cal. year BP. Its retrieval and the following dendrochronological, pedological and geomorphological analyses allow to add new information about the local climate and 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 (1) when the tree grew, a stable climatic phase allowing soil development was present; (2) a climate worsening, also likely responsible for 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 smaller than the present 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 proposed here, even if based on a single retrieved log, underlines the importance of spot findings for past glacier fluctuation reconstruction. This is

confirmed by the dating of the basal peat layer of the small peat bog dammed by the frontal moraine of the Forni Glacier, giving the minimum age 2,670 ± 130 year 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.

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.

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.

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.

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.

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.

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.

References

Agatova AR, Nazarov AN, Nepop RK, Rodnight H (2012) Holocene glacier fluctuations and climate changes in the southeastern part of the Russian Altai (South Siberia) based on a radiocarbon chronology. Quat Sc Rev 43:74–93

Allen SM, Smith DJ (2007) Late Holocene glacial activity of Bridge Glacier, British Columbia Coast mountains. Can J Earth Sci 44(12):1753–1773

Anderson DG, Maasch KA, Sandweiss DH, Mayewski PA (2007) Climate and cultural change: Exploring Holocene transitions. In: Anderson DG, Maasch KA, Sandweiss DH (eds) Climate changes & cultural dynamics: a global perspective on mid-Holocene transitions. Academic Press, Salt Lake City, pp 1–23

Arnaud F, Revel M, Chapron E, Desmet M, Tribovillard N (2005) 7200 years of Rhône river flooding activity in Lake Le Bourget, France: a high-resolution sediment record of NW Alps hydrology. Holocene 15:420–428

Baroni C, Carton A (1990) Holocene variations of the Vedretta della Lobbia, Adamello Group, central Alps. Geogr Fis Din Quat 13(2):105–119

Baroni C, Carton A (1996) Geomorphology of the upper Val di Genova (Adamello Group. Central Alps. Geogr Fis Din Quat 19(1):3–17

Bertolini G, Casagli N, Ermini L, Malaguti C (2004) Radiocarbon data on Lateglacial and Holocene landslides in the Northern Apennines. Nat Hazards 3:645–662

Borgatti L, Soldati M (2010) Landslides as a geomorphological proxy for climate change: a record from the Dolomites (northern Italy). Geomorphology 120(1–2):56–64

Brauning A (2006) Tree-ring evidence of "Little Ice Age" advances in southern Tibet. The Holocene 16(3):369–380

Chernykh DV, Galakhov VP, Zolotov DV (2013) Synchronous fluctuations of glaciers in the Alps and Altai in the second half of the Holocene. The Holocene 23(7):1074–1079

Citterio M, Diolaiuti G, Smiraglia D, Agata C, Carnielli T, Stella G, Siletto GB (2007) The fluctuations of Italian glaciers during the last century: a contribution to knowledge about Alpine glacier changes. Geogr Ann A 89(3):164–182

Cook ER, Briffa KR (1990) Data analysis. In: Cook ER, Kairiukstis LA (eds) Methods of dendrochronology. Applications in the environmental sciences, Kluwer Academic, Boston, pp 97–162

Coulthard B, Smith DJ, Lacourse T (2012) Dendroglaciological investigations of mid- to late-Holocene glacial activity in the Mt. Waddington area, British Columbia Coast Mountains, Canada. Holocene 23(1):93–103

Craig JA, Smith DJ (2013) Late Holocene glacial history of Scimitar Glacier, Mt. Waddington area, British Columbia Coast Mountains, Canada. Can J Earth Sci 50(12):1195–1208

Cremaschi M, Nicosia C (2012) Sub-Boreal aggradation along the Apennine margin of the Central Po Plain: geomorphological and geoarchaeological aspects. Géomorphologie 2:155–174

D'Agata C, Bocchiola D, Maragno D, Smiraglia C, Diolaiuti GA (2014) Glacier shrinkage driven by climate change in the Ortles-Cevedale Group (Stelvio National Park, Lombardy, Italian Alps) during half a century (1954–2007). Theoretical Applied Climatology 116:169–190

Deline P, Orombelli G (2005) Glacier fluctuations in the western Alps during the Neoglacial, as indicated by the Miage morainic amphitheatre (Mont Blanc massif, Italy). Boreas 34(4):456–467

Desio A (1967) I ghiacciai del Gruppo Ortles-Cevdeale. Comitato Glaciologico Italiano, Turin, Vol. 1 and 2

Desloges JR, Ryder JM (1990) Neoglacial history of the Coast Mountains near Bella Coola, British Columbia. Can J Earth Sci 27:281–290

Drysdale R, Zanchetta G, Hellstrom J, Maas R, Fallick A, Pickett M, Cartwright I, Piccini L (2006) Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone. Geology 34:101–104

Duchaufour P (1983) Pedologie: 1. Pedogenese et classification, Paris, p 59

ERSAF (2012) http://www.ersaf.lombardia.it

FAO (2006a) Guidelines for soil description. Food and Agriculture Organization of the United Nations, Rome, p 109

FAO (2006b) World reference base for soil resources. World Soil Resources Reports 103. Food and Agriculture Organization of the United Nations, Rome

Frezzotti M, Orombelli G (2014) Glaciers and ice sheets: current status and trends. Rend Fis Acc Lincei 25:59–70

Gale SJ, Hoare PG (1991) Quaternary sediments. Belhaven Press, NY, p 372

Garbarino M, Lingua E, Nagel TA, Godone D, Motta R (2010) Patterns of larch establishment following deglaciation of Ventina glacier, central Italian Alps. For Ecol Manag 259:583–590

Gehrig-Fasel J, Guisan A, Zimmermann N (2007) Tree line shifts in the Swiss Alps: climate change or land abandonment? J Veg Sci 18:571–582

Grissino-Mayer HD (2001) Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. Tree-Ring Res 57:205–221

Holtmeier FK (2009) Mountain timberlines: Ecology, patchiness and dynamics. Springer, NY, p 438

Holzhauser H (2002) Dendrochronological evaluation of fossil wood to reconstruct Holocene history. Schweiz Z Forstw 153(1):17–28

Holzhauser H, Zumbuhl HJ (1999) Glacier fluctuations in the Western Swiss and French Alps in the 16th century. Clim Change 43(1):223–237

Hormes A, Müller BU, Schlüchter C (2001) The Alps with little ice: evidence for eight Holocene phases of reduced glacier extent in the Central Swiss Alps. Holocene 11(3):255–265

Ivy-Ochs S, Kerschner H, Reuther A, Preusser F, Heine K, Maisch M, Kubik PW, Schlüchter C (2008) Chronology of the Last Glacial cycle in the European Alps. J Quaternary Sci 23(6–7):559–573

Ivy-Ochs S, Kerschner H, Maisch M, Christl M, Kubik PW, Schlüchter C (2009) Latest Pleistocene and Holocene glacier variations in the European Alps. Quaternary Sci Rev 28(21–22):2137–2149

Jackson SI, Laxton SC, Smith DJ (2008) Dendroglaciological evidence for Holocene glacial advances in the Todd Icefield area, northern British Columbia Coast Mountains. Can J Earth Sci 45(1):83–98

Joerin UE, Stocker TF, Schluchter C (2006) Multicentury glacier fluctuations in the Swiss Alps during the Holocene. Holocene 16(5):697–704

Joerin UE, Nicolussi K, Fischer A, Stocker TF, Schlüchter C (2008) Holocene optimum events inferred from subglacial sediments at Tschierva Glacier. Eastern Swiss Alps. Quaternary Sci Rev 27(3–4):337–350

Kelly MA, Buoncristiani JF, Schlüchter C (2004) A reconstruction of the Last Glacial Maximum (LGM) ice-surface geometry in the western Swiss Alps and contiguous Alpine regions in Italy and France. Eclogae Geol Helv 97:57–75

Körner C, Paulsen J (2004) A world-wide study of high altitude treeline temperatures. J Biogeography 31:713–732

Kromer B, Becker B (1993) German oak and pine ^{14}C calibration, 7200-9439 BC. In: Stuiver M., Long A, Kra RS (ed) Calibration. Radiocarbon 35(1):125–135

Leonelli G, Pelfini M, Morra di Cella U (2009a) Detecting climatic treelines in the Italian Alps: the influence of geomorphological factors and of human impacts. Phys Geogr 30(4):338–352

Leonelli G, Pelfini M, Battipaglia G, Cherubini P (2009b) Site-aspect influence on climate sensitivity over time of a high-altitude *Pinus cembra* tree-ring network. Clim Change 96(1–2):185–201

Leonelli G, Pelfini M, Morra di Cella U, Garavaglia V (2011) Climate warming and recent treeline shift in the European Alps: the role of geomorphological factors in high-altitude sites. Ambio 40:264–273

Liu F, Feng Z (2012) A dramatic climatic transition at ∼4000 cal. year BP and its cultural responses in Chinese cultural domains. The Holocene 22(10):1181–1197

Luckman BH (1988) Dating the moraines and recession of Athabasca and Dome Glaciers, Alberta, Canada. Arctic Alpine Res 20(1):40–54

Luckman BH (2000) The Little Ice Age in the Canadian Rockies. Geomorphology 32(3–4):357–384

Magny M, Vannière B, Zanchetta G, Fouache E, Touchais G, Petrika L, Coussot C, Walter-Simonnet A-V, Arnaud F (2009) Possible complexity of the climatic event around 4300–3800 cal. BP in the central and western Mediterranean. Holocene 19:823–833

Mavris C, Plötze M, Mirabella A, Giaccai D, Valboa G, Egli M (2011) Clay mineral evolution along a soil chronosequence in an Alpine proglacial area. Geoderma 165:106–117

Mayewski PA, Rohling EE, Stager JC, Karlen W, Maasch KA, Meeker LD, Meyerson EA, Gasse F, van Krevel S, Holmgren K, Lee-Thorp J, Rosqvist G, Rack F, Staubwasser M, Schneider RR, Steig EJ (2004) Holocene climate variability. Quaternary Res 62:243–255

Mc Carthy DP, Luckman BH (1993) Estimating ecesis for tree-ring dating of moraines—a comparative-study from the Canadian Cordillera. Arct Alp Res 25:63–68

Monegato G, Pini R, Ravazzi C, Reimer P, Wick L (2011) Correlation of Alpine glaciation and global glacioeustatic changes through integrated lake and alluvial stratigraphy in N-Italy. J Quaternary Sci 26(8):791–804

Munsell® (1994) Soil color charts, 1994 rev. Ed. Munsell® Color, New Windsor

Nicolussi K, Patzelt G (2000) Discovery of early-Holocene wood and peat on the forefield of the Pasterze Glacier, Eastern Alps. Austria. Holocene 10(2):191–199

Nicolussi K, Schlüchter C (2012) The 8.2 ka event-Calendar-dated glacier response in the Alps. Geology 40(9):819–822

Nicolussi K, Kauffman M, Patzelt G, van der Plicht J, Thurner A (2005) Holocene tree-line variability in the Kauner valley, central Eastern Alps, indicated by dendrochronological analysis of living trees and subfossil logs. Veg Hist Archaeobot 14:221–234

Omboni G (1861) I ghiacciai antichi ed il terreno erratico di Lombardia. Vallardi, Milan

Orombelli G (2011) Holocene mountain glacier fluctuations: a global overview. Geogr Fis Din Quat 34:17–24

Orombelli G, Pelfini M (1985) Una fase di avanzata glaciale nell'Olocene superiore, precedente alla Piccola Glaciazione, nelle Alpi Centrali. Rend Soc Geol It 8:17–20

Pelfini M (1988) Contributo alla conoscenza delle fluttuazioni oloceniche del Ghiacciaio dei Forni. Natura Bresciana 24:237–257

Pelfini M (1992) Le fluttuazioni glaciali oloceniche nel Gruppo Ortles-Cevedale (settore lombardo). Università degli Studi di Milano. Earth Sc. Dept. PhD thesis IV cycle, 211 p

Pelfini M (1999) Dendrogeomorphological study of glacier fluctuations in the Italian Alps during the Little Ice Age. Ann of Glac 28:123–128

Pelfini M, Carton A, Bozzoni M, Leonelli G, Martinoli M, Santilli M (2009) Enhancement of glacial and periglacial Geomorphosites

based on geomorphological and dendrochronological research. An example from the Trafoi Valley (Ortles—Cevedale Group). Mem Descr Carta Geologica It 87:123–134

Perry CA, Hsu KJ (2000) Geophysical, archaeological, and historical evidence support a solar-output model for climate change. PNAS 97(23):12433–12438

Porter SC, Orombelli G (1985) Glacier contraction during the middle Holocene in the western Italian Alps: evidence and implications. Geology 13(4):296–298

Preusser F, Blei A, Graf HR, Schlüchter C (2007) Luminescence dating of Würmian (Weichselian) proglacial sediments from Switzerland: methodological aspects and stratigraphical conclusions. Boreas 36:130–142

Ravazzi C, Aceti A (2004) The timberline and treeline ecocline altitude during the Holocene Climatic Optimum in the Alps and the Apennines. In: Antonioli F., Vai GB (eds) Lithopaleoenvironmental maps of Italy during the last two climatic extreemes. Explanatory notes, Florence: 32nd International Geological Congress:21–22

Ravazzi C, Badino F, Marsetti D, Patera G, Reimer PJ (2012) Glacial to paraglacial history and forest recovery in the Oglio glacier system (Italian Alps) between 26 and 15 ka cal BP. Quat Sci Rev 58:146–161

Reimer PJ, Bard E, Bayliss A, Beck JW, Blackwell PG, Bronk Ramsey C, Buck CE, Cheng H, Edwards RL, Friedrich M, Grootes PM, Guilderson TP, Haflidason H, Hajdas I, Hatté C, Heaton TJ, Hogg AG, Hughen KA, Kaiser KF, Kromer B, Manning SW, Niu M, Reimer RW, Richards DA, Scott EM, Southon JR, Turney CSM, van der Plicht J (2013) IntCal13 and MARINE13 radiocarbon age calibration curves 0-50000 years calBP. Radiocarbon 55(4):1869–1887

Rinn F (2005) TSAPWin—Time Series Analysis and Presentation for Dendrochronology and Related Applications, Version 0.53, User Reference. Heidelberg, 91 pp

Roethlisberger F, Schneebeli W (1979) Genesis of lateral moraine complexes, demonstrated by fossil soils and trunks; indicators of post glacial climatic fluctuations. In: Schlüchter C (ed) Moraines and Varves. Balkema, Rotterdam, pp 387–419

Sandweiss DH, Maasch KA, Anderson DG (1999) Transitions in the mid-Holocene. Science 283:499

Schweingruber FH (1996) Tree rings and environment. Dendroecology, Verlag Paul Haupt, Bern/Stuttgart, p 609

Shroder JF (1980) Dendrogeomorphology; review and new dating techniques of tree-ring dating. Progr Phys Geogr 4:161–188

Starnberger R, Rodnight H, Spötl C (2011) Chronology of the Last Glacial Maximum in the Salzach Paleoglacier Area (Eastern Alps). J Quat Sci 26(5):502–510

Stokes MA, Smiley TL (1968) An Introduction to Tree-Ring Dating. University of Chicago Press, Chicago, p 73

Stoppani A (1865) I dintorni di Santa Caterina ossia le serate dello zio. Legros Felice, Milan

Stoppani A (1875) Il Bel Paese. Conversazioni sulle bellezze naturali. La Geologia e la Geografia fisica d'Italia. Ed. Agnelli, Turin, 662 pp

Stuiver M, Reimer PJ (1993) Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon 35:215–230

Stuiver M, Reimer PJ, Reimer RW (2014) CALIB Rev 7.0.2 [WWW program and documentation]

Tinner W (2007) Treeline studies. In: Scott EA (ed) Encyclopedia of Quaternary Science, Elsevier, pp 2374–2384

Trachsel M, Kamenik C, Grosjean M, McCarroll D, Moberg A, Brázdil R, Büntgen U, Dobrovolný P, Esper J, Frank DC, Friedrich M, Glaser R, Larocque-Tobler I, Nicolussi K, Riemann D (2012) Multi-archive summer temperature reconstruction for the European Alps, AD 1053–1996. Quat Sci Rev 46:66–79

Rend. Fis. Acc. Lincei (2014) 25:427–437

437

Walker MJC, Berkelhammer M, Björck S, Cwynar LC, Fisher DA, Long AJ, Lowe JJ, Newnham RM, Rasmussen SO, Weiss H (2012) Formal subdivision of the Holocene Series/Epoch: a Discussion Paper by a Working Group of INTIMATE (Integration of ice-core, marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). J Quat Sci 27(7):649–659

Walkley A, Black IA (1934) An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. Soil Sci 37:29–38

Zhu HF, Xu P, Shao XM, Luo HJ (2013) Little Ice Age glacier fluctuations reconstructed for the southeastern Tibetan Plateau using tree rings. Quat Int 283:134–138