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# Was the Little Ice Age the coolest Holocene climatic period in the Italian central Alps?

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#### Abstract

Estimation of the relative intensity of different cold periods occurring during the Late Quaternary are difficult tasks, particularly in non-glaciated mountain landscapes, and where high- to medium-resolution archives for proxy data are lacking. In this paper, we study a Holocene polycyclic soil sequence in the central Alps (Val Cavargna, Northern Italy) to estimate climatic parameters (specifically T) changes in non-glaciated, high altitude environments. We investigate this key site through palaeopedological and micromorphological analyses in order to understand phases of soil development and detect hidden evidence of cold conditions during its formation. Three phases of pedogenesis can be recognized and attributed in time to different periods during the Holocene. Pedogenetic phases were separated by two truncation and deposition episodes related to the reactivation of slope processes under cold conditions at the onset of the Neoglacial and the Iron Age Cold Epoch (IACE) respectively. Micromorphological evidence of frost action on soil can instead relate to pedogenetic processes acting in the Little Ice Age (LIA). The different expression of these three cold periods corresponds to different climatic conditions, pointing to the LIA as a cooler/drier period in comparison to the preceding ones. 

### **Keywords**

Polycyclic palaeosols; Micropedology; Frost pedofeatures; Mid-Late Holocene; Little Ice Age; Southern Alps. 

#### **I. Introduction**

One of the most difficult tasks in paleoclimate studies – before the introduction of instrumental measurements – is the estimation of climate parameters and their variation with time (Edwards et al., 2007a; Bradley, 2015). When records are irregular and limited to shortened time-spans, discontinuous or low in resolution, such as in many continental palaeoenvironmental archives, the reconstruction of climatic conditions and their effects on the landscape becomes much more challenging (Kutzbach, 1976; Federici, 2005; Giraudi et al., 2011; Bradley, 2015; Furlanetto et al., 2018). This is especially true when dealing with the effects of cold periods in middle latitude and Mediterranean mountain ranges, such as the Alps and Apennines of Italy, known as highly dynamic regions (Porter and Orombelli 1985; Baroni and Orombelli 1996; Federici, 2005; Hughes et al., 2011; Kuhlemann et al., 2013; Pelfini et al., 2014; Colucci et al., 2016; Bollati et al., 2018). Where extensive landforms and stratigraphic records of Quaternary glacial advances are not present, evident traces of cold phases are often hard to study. Poorly visible, buried and hidden signs of cold periods – as much as of the subsequent warm phases - are only occasionally embedded and rarely well-preserved in landforms and within palaeosols and sedimentary records (Angelucci et al., 1992; Calderoni et al., 1998; Fischer et al., 2012; Compostella et al., 2012, 2014; Waroszewski et al., 2018). In the latter, evidence of cold phases is often associated with breaks in the sedimentary succession or with an increased frequency of slope processes related to climatic instability (Bertolini et al., 2004; Nicolussi et al., 2005; Magny et al., 2009a; Arnaud et al., 2012; Cremaschi and Nicosia, 2012; Compostella et al., 2014; Pelfini et al, 2014; Mariani et al., 2019). Despite the extensive documentation regarding the Little Ice Age (LIA) traced in paleoclimate studies (Kullman and Öberg, 2009; Arnaud et al., 2012; Nicolussi, 2013; Carturan et al., 2014; Loso et al., 2014), many questions are still open, for example, the influence of climate variations on non-glaciated mountain landscapes during the LIA is poorly known, especially when compared to previous cold intervals such as the Neoglacial, the Lateglacial, and the Last Glacial Maximum (LGM) (e.g., Wanner et al., 2011; Badino et al., 2018; Furlanetto et al., 2018). In the mountain environments of middle latitudes, where glacial and periglacial landforms are undetectable or have been vanished/truncated/erased due to enhanced slope activity (e.g.: Allison, 1996; Giraudi et al., 2011; Compostella et al., 2014; Mariani et al., 2018), paraglacial (Knight and Harrison, 2009), or zoogeomorphological processes (e.g., Butler, 1995, 2012), the effects of cold phases are virtually absent from the scientific record. 

In this paper, we studied a Holocene polycyclic soil sequence formed in the Mid-Late Holocene in the Italian Central Alps (Val Cavargna, CO). Our aim is to find records of Holocene 

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climatic influence on the evolution of surface processes (Nicholson, 1988), and to assess whether soils and paleosols (and their pedofeatures) can record climatic changes in Alpine environments. The studied soil sequence shows clear traces of the presence of cold conditions during its formation, strong enough to promote soil frost and trigger the formation of frost-induced pedofeatures (sensu Van Vliet-Lanoë, 1998; Van Vliet-Lanoë et al., 2018) without the influence of glacial or periglacial processes. No evidence for glacials were found at the study site and in its close vicinity. Using multiple palaeopedological techniques, and in particular micropedology, we were able to characterize different Holocene cold phases affecting soil formation. We also stress the impact as a climatic parameter of different atmospheric temperatures during the cold periods of the last few millennia. We lastly suggest an alternative qualitative approach to interpret past fluctuations of climatic parameters based on their effect on surface processes. 

## II. The study area

The studied soil sequence is located at Alpe Piazza Vacchera (46°06'32"N, 9°08'33"E), in Val Cavargna (San Bartolomeo municipality, Italian Central Alps), at an elevation of 1680 m a.s.l. (Figures 1 and 2). The bedrock of the studied area is part of a portion of the Southalpine basement - the tectono-metamorphic unit of the Dervio-Olgiasca Zone (after Spalla et al., 2002) - and consists mainly of garnet-staurolite-bearing schist and minor gneiss with lenses of amphibolite. Schists are particularly prone to weathering, especially in areas of pervasive jointing due to tectonic deformation. The study site is currently above the treeline and covered by grassland pastures; mean annual rainfall is between 2000-2500 mm/y and mean annual temperature between 3.8 and 10.9°C (Ceriani and Carelli, 2000). Snow accumulation is high, estimated between 1-2 m/y, with a residence time greater than 100 days (Gazzolo and Pinna, 1973). The permanent snow line for the Alps varies from N to S and from W to E according to factors related to latitude, continentality and slope insulation, but it is generally located between 2500-2800 m a.s.l. (Barry, 1992), thus well above the area of study. The area does not contain permafrost: in this portion of the Alps favourable conditions for permafrost are found only above 2200–2300 m a.s.l. (Boeckli et al., 2012), and the first instances of permafrost or related landforms are found in a range of tens of kilometres to the North (Cremonese et al., 2011). During the LGM, valley glaciers did not cover the area but at least a few cirgue or slope glaciers were present in the highest part of the mountain range (Bini et al., 2009). Since then, no traces of further glacial influence are found on the slopes or in the valley below (Bini et al., 2009). Periglacial processes are visible as sparse, possibly inactive solifluction lobes on the surrounding slopes, today highly disturbed by zoogeomorphologically induced game 

trails, causing instability and enhanced gully erosion and transportation of soil material in the 90 vicinity of the studied area (e.g., Butler, 2018; Zerboni and Nicoll, 2018). 91

92 Human activity in Val Cavargna is known since the Mesolithic, with the establishment and abandonment of sporadic settlements in the upper part of the valley. Subsequent occasional 93 occupation of the area with evidence of widespread forest fires took place multiple times from the 94 Neolithic to the Middle Ages (Castelletti et al., 2012a). The systematic exploitation of the area, 95 resulting in an increase in human pressure on the landscape, dates back mainly to post-medieval 96 times (Castelletti and Tremari, 2012). Documented instances of forest clearance in the upper valley 97 appear since the XVI century CE, with a change in land use for charcoal production (Grandi, 2012). 98 99 At this time, large portions of deforested land - between 1400-1800 m a.s.l. - were converted to pasture lands (Castelletti et al., 2012b). Near the studied section, the first establishment of a small 100 <sup>22</sup> 101 cattle farm and trail can be loosely attributed to the same period.

#### **III. Materials and methods** 26 103

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28 104 To investigate the soil in the field we dug a trench along the western slope of Mount Pianchette – 29 105 Pizzo di Gino, in correspondence of a natural filled trench forming a small terrace on a deep-seated 30 31 106 gravitational slope deformation (DSGSD). This landform represents large to extremely large mass 32 <sup>33</sup> 107 movements generally affecting the entire length of high-relief valley flanks, extending up to 200-34 300 m in depth, which can frequently extend beyond the slope ridge (Crosta et al., 2013). Soil 35 108 36 descriptions and horizon designations were carried out according to the guidelines of FAO (2006); 37 109 38 <sub>39</sub> 110 colour definition followed the Munsell Color® (1994) nomenclature. The diagnostic horizons of 40 111 buried palaeosols in the sequence were defined according to the international classification 41 <sup>42</sup> 112 systems (FAO, 2014; Soil Survey Staff, 2014; Zerboni et al., 2011, 2015). Soil samples for chemical-43 <sup>44</sup> 113 physical analyses were collected for each horizon. Particle size distribution was determined using 45 laser diffraction (Malvern Mastersizer MS-2000) after H<sub>2</sub>O<sub>2</sub> and HCl treatments, according to the 46 114 47 procedure described in Crouvi et al. (2008). The total amount of Fe and Al in the samples was 48 115 49 <sub>50</sub> 116 determined by complete dissolution in a mixture of HF, HCl, HNO<sub>3</sub> and HClO<sub>4</sub>, followed by 51 measurement of the solubilised ions using an ICP-ES (Jobin-Yvon JV24). Dithionite- (Mehra and 117 52 <sup>53</sup> 118 Jackson, 1960) and oxalate-extractable (McKeague et al., 1971; Schwertmann, 1973) fractions of Fe 54 55 119 and AI oxyhydroxides, representing a quantification for free and amorphous Fe and AI forms 56 57 120 respectively, were also measured with the same instrument. The Activity Ratio between oxalate-58 and dithionite-extractable iron (Fe(o)/Fe(d)) was also calculated. Analytical data are reported in 59 121 60 122 Table 1 and summarized in Figure 3.

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Thin sections were produced from undisturbed samples taken from relevant soil horizons 123 after impregnation with polyester resin according to the method described in Murphy (1986). 124 Slides were examined with an Olympus BX41 petrographic microscope, under plane-polarized light 125 (PPL), cross-polarized light (XPL), and oblique incident light (OIL). The terminology of Stoops (2003) 126 was used to describe thin sections, whereas micromorphological interpretation was mainly based 127 128 on the concepts reported in Stoops et al. (2018).

The age of the polycyclic soil sequence was obtained by dating with radiocarbon (AMS<sup>-14</sup>C) two samples of charcoal. AMS<sup>-14</sup>C dating results were calibrated ( $2\sigma$  range) using the INTCAL13 curve (Reimer et al., 2013).

#### 133 **IV. Results**

Along the slope of Mt. Pianchette and Mt. Pizzo di Gino, inside the morphological trench formed by a detachment niche of a DSGSD, are present a series of shallow depressions filled with 24 135 sediments deposited through colluvial slope processes that were subsequently weathered and 26 136 reorganized into soils. In the uppermost depression, several soil horizons were identified (Table 1), <sub>28</sub> 137 ---30<sup>---</sup>138 consisting of three different soil units on successively deposed parent materials (Figure 2). The 139 uppermost unit corresponds to the extant soil, down to a depth of about 49 cm. It is an organic 33 140 temperate mountain soil differentiated in thicker organic A horizons sometimes alternated with 35 141 thinner levels of rubified soil material containing dark mottles. The same material is also present at the bottom of the unit as a mineral Bw horizon. The boundary between this unit and the 37 142 intermediate one is marked by an erosional surface bearing a residual lens of macroscopic charcoal <sub>39</sub> 143 144 fragments, several centimetres thick, identified as the remains of a fireplace. Dating from two <sup>42</sup> 145 charcoal samples taken from this lens gave a result of 2730±43 (RC-369) and 2683±42 (RC-370) <sup>44</sup> 146 years uncal BP (2926–2756 years cal BP and 2863–2747 years cal BP respectively). The intermediate unit is a buried palaeosol divided into three main horizons: an eluvial 2E horizon occupies the 46 147 47 upper position above a rubified 2Bs horizon; below them is a mineral 2BC horizon with common 48 148 49 50 149 reddish mottles. The lowermost soil unit, starting at a depth of 75 cm, is quite similar to the 51 150 previous one, but pedofeatures are better expressed. A whitish eluvial 3Et horizon, in which are still 52 <sup>53</sup> 151 present reddish mottles comparable to those of the level above it, forms the upper portion of the 54 55 152 unit, followed by a weathered rubified 3Bs horizon. Below the latter, a 3C horizon marks the 56 boundary to the bedrock at about 130 cm below the current surface. Charcoal fragments from the 57 153 58 59 154 3Bs horizon of this unit were dated to 6850±20 years uncal BP (UGAMS-38048, 7721-7621 years 60 155 cal BP).

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Grain size analytical data from a selection of soil samples shows where units differ and 156 157 where instead similarities emerge (Figure 3). The A2 horizon of the top unit differs from the others, 158 showing a bimodal distribution of grain size classes: the main mode is represented by silt, while a secondary mode is shifted towards medium/coarse sand. Its much broader distribution also 159 indicates a poor selection of grains. Horizons from the other two units show very similar categories. 160 10 11 161 In particular, the E horizons share almost the same bell curve weakly skewed to the left and centred 12 13 162 on coarse silt. All B horizons (Bw, 2Bs and 3Bs) also share a similar trend with a mode at the fine 14 sand and a higher skewness towards the finer fractions that are more expressed in the bottom unit. 15 163 16 17 164 Total iron content in the soil sequence amounts to 3-5.5% of the total mass in all soil horizons, with 18 concentrations in the B horizons of the top and bottom units (Figure 3; Table 1). Eluvial horizons 165 19 20 166 show lower concentrations of Fe, with the 3Et horizon being the scarcest in total iron content 21 <sup>22</sup> 167 (3.06%). The intermediate unit is also low in iron content, with only a slight increase of total iron in 23 the 2B horizon. Free iron measured as Fe-dithionite peaks in the Bw and 3B horizons and shows the 24 168 25 lowest concentration at the bottom of the sequence (11.6 g/kg in the 3C horizon); generally, free 26 169 27 iron accounts for 47-71% of total iron content. The Activity Ratio is mostly between 0.35 and 0.5 for <sub>28</sub> 170 29 171 all horizons, with the exception of E horizons where it reaches the lowest values (below 0.3). 30

31 172 The observation of thin sections reveals the general composition and fabric of the soil units 32 <sup>33</sup> 173 (Table 2). The micromass of all investigated horizons shows a dominance of coarse mineral material 34 (mainly micas, then quartz and feldspar) with the fine material either compactly filling the 35 174 36 remaining space in B horizons (Figure 4a), or weakly aggregating in granular peds in E horizons 37 175 38 <sub>39</sub> 176 (Figure 4b). Fine charcoal is always present; coarser fragments can be found in the A1 and 3Et 40 177 horizons as well as in the charcoal-bearing lens at the top of the 2E horizon. The 3Et horizon shows 41 42 178 microlaminated clay coatings (Figure 4c, d) inside a groundmass with marked differences from the 43 <sup>44</sup> 179 B horizons: the fine material bears a greyish colour and no visible aggregation is present. The A1 45 and A2 horizons are locally arranged in a pattern of horizontal planar voids (isoband fabric, sensu 46 180 47 Dumanski and St-Arnaud, 1966), not visible in the deeper parts of the soil sequence (Figure 5a). 48 181 49 <sub>50</sub> 182 This pattern is randomly distributed in the two horizons as large centimetric patches sharing the 51 same features: a net of partially interconnected straight or slightly curved planar voids up to a 183 52 <sup>53</sup> 184 millimetre long and less than 100 µm thick that separate lenses of soil material up to 1 mm thick. 54 55 185 Vesicles are often associated with soil lenses (Figure 5b) and the pattern itself. Clusters of parallel-56 57 186 oriented coarse fragments (Figure 5c) are visible in the Bw horizon. All these features are usually 58 undisturbed by the presence of bioturbation otherwise found in many instances in the soil mass in 59 187 60 188 the form of passage features (Figure 5d).

# 190 V. Discussion

In the following parts we reconstruct the evolution of the investigated soil sequence discussing the main pedogenetic processes involved in its formation. We then highlight the occurrence of pedofeatures in the different soil units that record past temperature shifts in the area.

# 195 **5.1. Soil forming processes and chronology**

The characterization of pedogenesis in the three units shows evidence of similar soil formation processes in different periods of time, thus confirming the existence of a soil polysequence (Cremaschi and Rodolfi, 1991). The very similar grain sizes of the different horizons imply that each soil unit was formed by deposition over the previous surface – exposed by truncation – of the same type of sediments removed from above by short-range (tens to hundreds of metres) slope transportation movements. Each soil unit shares the combined presence of an E/B horizon series, with the E substituted by a moderately depleted A2 horizon in the uppermost unit. The formation of clay and Fe oxyhydroxides in the soil mass is accompanied by their translocation downwards from the eluvial horizons into the lower rubified B horizons, or even below in older soil units, as in the case of the clay coatings that crossed the boundary into the 3Et horizon. Particle translocation is also supported by the shift from the 2Bs to the 3Et horizon, which hints to clay depletion from the second unit and illuviation into the unit below, and by the enrichment in fine material in the 3Bs horizon. The low activity ratio shows a relative depletion in the amorphous iron forms, easier to mobilise, in E horizons. The three units show different degrees of the same pedogenetic processes pedoplasmation, soil formation by weathering and translocation of clay minerals and Fe oxyhydroxides; Duchaufour, 1983), decreasing in strength of expression upwards. In fact, although the bottom unit looks the most developed in a well-defined series of horizons, Fe oxyhydroxides do not change markedly along the units, showing again uniformity in weathering. Pedogenesis is in any case only moderately developed, and the accumulation of Fe in the B horizons appears to be not only a result of in-situ weathering, but also of translocation from the overlying horizons and younger parent materials (Duchaufour, 1977; Cornell and Schwertmann, 2003).

Pedogenesis occurred under warm/temperate climate phases with the presence of continuous vegetation (Duchaufour, 1983) and promoted the accumulation of microlaminated clay coatings by illuviation into the unit below (e.g. Fedoroff, 1997; Compostella et al., 2014). The microstructure of E horizons and the presence of red mottles in B horizons (Table 3) suggest an incipient podsolization process (Duchaufour, 1983; Van Ranst et al., 2018), likely supported by local

conditions of seasonal water saturation (Duchaufour, 1983; Sevink and de Waal, 2010; Vepraskas et 222 al., 2018). The identification of wood species from charcoal fragments found in various soil horizons 223 shows the dominance of silver fir (Abies alba) throughout the soil sequence: reconstructions of the 224 vegetation history of the area point to the presence of an open forest under moderately warm 225 conditions (Castelletti et al., 2012b). At the current surface and towards the top of the intermediate 226 10 11 227 unit, charcoal assemblages suggest a sparsely forested heathland, revealing colder phases of forest 12 retreat or anthropogenic pressure (Castelletti et al., 2012b). 13 228

14 Radiocarbon dating stresses formation of the various soil units within the Holocene, 15 229 16 <sub>17</sub> 230 showing how the soil sequence has in fact experienced more than one warm climate phase. The 18 231 development of the bottom unit, dated to 7721-7621 years cal BP, can be very clearly attributed to 19 20 232 the Early-Middle Holocene (Mayewski et al., 2004; Arnaud et al., 2012; Grosjean et al., 2007), during 21 <sup>22</sup> 233 a warm period preceding the cold event at 4.2 ka cal BP (e.g., Zanchetta et al., 2016), possibly the 23 Atlantic Warm Period (AWP) or the Late Neolithic Thermal Maximum (LNTM). In this longer period 24 234 25 of pedogenesis, potentially lasting a few thousands of years, the soil had the time to develop 26 235 27 <sub>28</sub> 236 pedofeatures under a rapidly warming phase. Afterwards, the warm and stable phase responsible 29 237 for the formation of the intermediate unit should occur after the Middle/Late Holocene transition, 30 31 when several warm fluctuations occurred (Mayewski et al., 2004; Deline and Orombelli, 2005): the 238 32 <sup>33</sup> 239 longest phase takes place during the Bronze Age, loosely between 3800 and 2800 years BP (e.g., 34 Arnaud et al., 2012 and references therein), and can be confirmed by dating from the truncation of 35 240 36 the unit indicated by the residual fireplace (2926–2756 and 2863–2747 years cal BP). It is therefore 37 241 38 <sub>39</sub> 242 possible that this pedogenesis took place in a period not much longer than a thousand years. The 40 243 truncation points to the transition from a warm period to the next cold phase (Plunkett and 41 <sup>42</sup> 244 Swindles, 2008; Magny et al., 2009b; Wanner et a., 2011; Regattieri et al., 2014; Cremaschi et al., 43 <sup>44</sup> 245 2016) corresponding to the Iron Age Cold Epoch (IACE). This cold stage probably witnesses both 45 the truncation of the intermediate unit due to enhanced slope processes and the deposition of the 46 246 47 parent material composing the top one. The last phase of pedogenesis probably started since the 48 247 49 <sub>50</sub> 248 Roman Warm Period (RWP) onwards to present time, covering less than 2000 years of duration in a 51 fluctuating climate. 249 52

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### 55 251 5.2. Are frost-related pedofeatures a proxy for past temperatures?

The typical pedofeatures found at the top unit (A1-A2 horizons) relate to specific climate 57 252 58 59 253 conditions and can be safely attributed to a post-RWP cold phase on the basis of the above-60 254 mentioned chronological framework. The LIA is most likely the coldest climatic phase in that time Page 9 of 55

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interval (Wanner et al., 2011; Furlanetto et al., 2018). The pattern of microscopic horizontal planar voids separating the matrix into homogeneous lenses of soil material indicates the action of frost on soil horizons (Dumanski and St-Arnaud, 1966). Vesicles are also related to the entrapment of air bubbles in the soil mass during the freezing process (Table 3). As suggested by Van Vliet-Lanoë (1987, 1998) and Van Vliet-Lanoë et al. (2018), this regular pattern is connected to the presence of intermittent or seasonal frost episodes localised at the soil surface when the penetration of the freezing front is not very deep. This is expected for temperate environments, considering that very low air temperatures are needed to freeze the open ground below the first centimetres (Henry, 2007). Deformation of the soil mass is only limited to sporadic preferential orientations of coarse fragments, also indicating weak freezing conditions (Van Vliet-Lanoë et al., 1984). Nevertheless, the durability of these features to later pedo/bio-turbation (Van Vliet-Lanoë et al., 1984) indicates a certain level of stability compatible with repeated freeze-thaw cycles during an extended period.

The weak expression of the above described frost-related pedofeatures suggests the occurrence in the past of periglacial processes unrelated to permafrost (Van Vliet-Lanoë, 1998), the presence of which would have forced much stronger cryoturbation and very different features in the soil and is linked to more rigid conditions, possibly unmet here since the LGM. In fact, considering the stability through time of frost-related pedofeatures (Van Vliet-Lanoë et al., 1984), their absence in the two buried soil units suggests that frost acted in the area only during the most recent cold phase corresponding to the LIA, after the accumulation of the parent material of the uppermost soil unit. Since most of the pedogenetic factors identified by Jenny (1941) and the related soil-forming processes do not show dramatic changes over time, as seen above, this occurrence is probably more related to fluctuations in the climate. A climatic trend toward cooler conditions seems also confirmed by the general decrease in expression of pedogenetic processes from the bottom to the top of the pedosequence. This trend has been recently suggested from multi-proxy models of insolation at middle latitudes on alpine scale (Mauri et al., 2015). The supposed duration for each phase of soil formation, probably lasting several millennia to centuries, also needs to be taken into consideration. It is clear how time alone is not able to explain the differences in pedogenesis. In fact, both factors contributed in synergy to the development of soil formation processes (Boardman, 1985; Birkeland, 1999). We believe that in this case, while no simple comparison can be done between climate and time, the former seems to play the main role. The rapid succession of environmental changes in the Holocene represents the limiting factor in 58 59 286 the development of pedogenesis. Time in this case cannot be the primary factor driving the 60

expression of pedogenesis, since the different units are formed too suddenly because of the 287 288 continuous climate shifts.

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289 Considering the strong similarities in soil formation conditions between the three units, the effect of different cold periods on each is very noticeable. The abrupt truncation of the bottom unit 290 could possibly correspond to the initial part of the Neoglacial period, often associated with a sharp 291 10 11 292 increase in denudation processes (Arnaud et al., 2012). Denudation is in turn related to vegetation 12 loss events often indirectly caused by the passage to cold and unstable climate phases (Bertolini et 13 293 14 al., 2004; Nicolussi et al., 2005; Magny et al., 2009a; Compostella et al., 2014). Slope instability 15 294 16 <sub>17</sub> 295 events responsible for the deposition of the two upper units are also a typical result of denudation 18 296 processes, where erosion and deposition often occur consecutively on the same topographic 19 20 297 surface (Giraudi et al., 2011; Compostella et al., 2014). The same appears to happen for the 21 <sup>22</sup> 298 truncation of the second unit dated to the IACE (Magny et al., 2009b). For sake of clarity we need to 23 consider that the anthropogenic contribution to the deposition and development of these units is 24 299 25 not to be underestimated. Multiple fire events very likely connected to forest clearance practices 26 300 27 <sub>28</sub> 301 started in the area since the Mesolithic (Castelletti et al., 2012b). Fire events greatly enhanced the 29 302 effect of washout and solifluction on the slopes, mobilising the colluvial material that forms the two 30 31 303 upper soil units. Human contribution to slope instability is in this case guite important, enhancing 32 33 304 ongoing processes in synergy with the effect of climate variations. Later, also the 34 zoogeomorphological effect due to the introduction of herding may have contributed to accelerate 35 305 36 ongoing denudation and rill erosion. 37 306

38 <sub>39</sub> 307 The different setting of the uppermost unit, where frost features represent the effect of cold 40 308 conditions in place of truncations, can be ultimately regarded as a distinct process attributed 41 <sup>42</sup> 309 specifically to the LIA. Neoglacial cold events appear to have mainly impacted the soil through 43 <sup>44</sup> 310 slope instability and processes of removal/addition of material, but no features directly related to 45 freezing and ice formation are found at the top of the buried units. In this regard, while it is true 46 311 47 that no actual surface A horizon is currently present on both units, it must be noted that the new 48 312 49 <sub>50</sub> 313 surfaces produced by truncation were probably exposed to the weather for a non-insignificant 51 314 length of time. On the intermediate unit this was enough to allow the establishment of a fireplace 52 <sup>53</sup> 315 on top of the former topographic surface - or at least not far from it – which does not exhibit any 54 55 316 visible frost feature. On the contrary, anthropogenic features as fireplaces are able to record frost-56 related pedofeatures (Cremaschi et al., 2015). The LIA has instead triggered in the soil a variety of 57 317 58 stable features related to intermittent freezing cycles. Such clear difference might suggest that 59 318 60 319 other climate dynamics were in place during the cold phases preceding the LIA (for instance, the Page 11 of 55

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IACE). In this perspective, it might be plausible to characterise the LIA as a colder or drier period 320 than the previous ones: lower temperatures in comparison with the other Holocene cold periods 321 322 would have allowed more widespread episodes of seasonal frost. Holocene temperature anomalies reconstructed in the Southern Alps by Furlanetto et al. (2018) support this hypothesis suggesting a 323 moderate shift towards lower temperatures in the LIA compared to other Holocene climatic phases. 324 325 Moreover, a recent assessment of post-LGM permafrost distribution in the Mediterranean region 13 326 suggests a widespread occurrence of soil frost in the LIA (Oliva et al., 2018). Similarly, a lessened amount of precipitation would have reduced the snow cover, well below the current thickness and 15 327 <sub>17</sub> 328 down to only a few tens of centimetres (Zhang, 2005), weakening the thermal isolation of the soil below and allowing frost to take hold (Edwards et al., 2007b and references therein). A consequent 329 330 shift downwards of the freezing front would plausibly have left more visible and stable features in <sup>22</sup> 331 the soils, while in less rigid and wetter phases they would only have suffered the consequences of more snow thawing upslope, especially a higher water discharge rate and in turn the activation of 24 332 slope movements. The relationship between precipitation and slope processes is well studied in the 26 333 <sub>28</sub> 334 Alps: today, where climate conditions are more severe lower rainfall thresholds are needed to 335 trigger slope movements (Guzzetti et al., 2007). Considering the enhanced possibility of slope instability in cold environments, the absence of truncations in the upper soil unit confirms stable 336 <sup>33</sup> 337 slope conditions and further supports a possible dry phase. While it is very difficult to assess past precipitation amount, reconstructed temperatures from proxy data in the Alps seem to favour this 35 338 idea (for comparison, see Badino et al., 2018; Furlanetto et al., 2018). Similar conditions have also 37 339 <sub>39</sub> 340 been very recently postulated for the Northern Apennines (Regattieri et al., 2014; Mariani et al., 41 341 2019). The occurrence of other evidence confirming the climatic conditions in Mediterranean <sup>42</sup> 342 mountain ranges during the LIA confirms that soils and pedofeatures can reflect regional climatic 43 <sup>44</sup> 343 conditions and they are not only triggered by local conditions and surface processes. The effect of 45 forest clearance must be taken into account when discussing temperature in the topsoil. In fact, the 46 344 47 presence of a forest cover greatly mitigates the effect of air temperature on the soil, with the 48 345 49 50 346 canopy protecting the lower air strata and producing a warmer microclimate that reaches 51 347 temperatures below zero with more difficulty (Körner. 2003). On the other hand, the canopy effect 52 <sup>53</sup> 348 also prevents part of the snow accumulation, reducing its isolating power. In this area, the 54 55 349 continuous presence since the Mesolithic of clearance events by fire and the more recent 56 establishment of pasturelands (Castelletti et al., 2012b) probably prevented for long periods of time 57 350 58 59 351 the reestablishment of a closed forest, leaving more open vegetation in which both these effects 60 352 were probably greatly reduced.

#### **VI.** Conclusions

This study reconstructs climatic fluctuations throughout the Holocene on the basis of a soil polysequence the pedogenetic processes that occurred in a high mountain range. Our study shows new evidence regarding the importance of the LIA in the Alps as one of the main cold intervals after the LGM. While it is difficult to make assumptions based on indirect archives, it is plausible to infer, based on the evidence found in this study, that during the LIA the intensity of frost action 13 359 might have been stronger compared to other Holocene cold episodes. An increase in ice formation 15 360 <sub>17</sub> 361 could in turn be related to the occurrence of drier/colder conditions weakening snow deposition on the soil surface and favouring overall freezing conditions.

While soil archives are considered a low-mid resolution resource in palaeoclimatic studies <sup>22</sup> 364 (Yaalon, 1990), in this case the reconstruction of pedogenesis was the only reliable tool for recording cold intervals that occurred after the LGM in a non-glaciated area and their influence on 24 365 surface processes. The study of soils and specifically micromorphology discloses important 26 366 <sub>28</sub> 367 information on past climate, where evidence of processes triggered by specific climatic and environmental conditions (in this case atmospheric temperature) can be observed and put inside their proper placement in time (sensu Cremaschi et al., 2018). In environments where human <sup>33</sup> 370 actions started tuning surface processes earlier than expected in the Mid-Late Holocene, as suggested by recent studies (ArchaeoGLOBE Project, 2019), soil evidence also helps in 35 371 disentangling natural and anthropogenic factors shaping the landscape in human-settled contexts. 37 372 <sub>39</sub> 373 The absence of deposits and landforms allowing the formation and conservation of soils and palaeosols would indeed render many of such reconstructions quite arduous, if not implausible.

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### 623 Captions

3 624 Figure 1. (A) Hillshade of the central sector of Southern Alps indicating the location of the study 4 5 area (the inset indicates its position in northern Italy). (B) Satellite view of the study area (source: 625 6 Google Earth<sup>™</sup>); the star indicates the position of the soil profile. 626 8

9 Figure 2. (A) General view of the study area during the opening of the test trench. In the 627 10 11 foreground the high portion of the DSGSD is visible to the right; the DSGSD is broken 628 12 13 629 downslope to the left by a morphological trench associated with a counterscarp. In the 14 background the peak of Mt. Pizzo di Gino and its southern slope are visible to the left. (B) 15 630 16 <sub>17</sub> 631 Picture of the investigated polycyclic soil sequence indicating the position of soil horizons and 18 samples for analyses (squares: blocks for thin sections; triangles: samples for chemical-physical 632 19 20 633 analyses; dots: samples for radiocarbon dating). 21

### <sup>22</sup> 634 Figure 3. Results of chemical-physical analyses: on the left, curves of grain size distribution (after 23 H<sub>2</sub>O<sub>2</sub> and HCl treatments); on the right, chemical determinations of Fe content. Key: Fe(o): 24 635 25 amorphous iron; Fe(d): free iron; Fe(t): total iron. 26 636

27 <sub>28</sub> 637 Figure 4. Micromorphological features of the investigated soil horizons: a) well developed yellowish 29 ---30<sup>638</sup> fabric devoid of iso-oriented features in the intermediate unit (2Bs horizon; 2x, PPL); b) depleted 31 639 soil mass in the lower unit (3Et horizon; 2x, PPL); c) microlaminated clay coatings in the eluvial 32 <sup>33</sup> 640 horizon of the lower unit (3Et horizon; 10x, PPL); d) same as c), in XPL. 34

35 641 Figure 5. Frost related features of the investigated soil horizons: a) horizontal planar voids in the 36 upper unit (A2 horizon; 4x, PPL); b) groups of circular vesicles in the upper unit (A2 horizon; 10x, 37 642 38 <sub>39</sub> 643 PPL); c) horizontal iso-oriented mica fragments in the fabric of the upper unit (Bw horizon, 10x; 41 644 XPL); d) passage features produced by beetle larvae around undisturbed planar voids (A2 <sup>42</sup> 645 horizon; 4x, PPL). 43

Table 1. Field and chemical properties of the described soil sequence. 46 647

47 Table 2. Micromorphological descriptions of soil thin sections. G: gravel size; VCS: very coarse sand 48 648 49 <sub>50</sub> 649 size; CS: coarse sand size; MS: medium sand size; FS: fine sand size; VFS: very fine sand size; S: 51 silt size. Abundance: very dominant - >70%; dominant - 50-70%; frequent - 30-50%; common -650 52 <sup>53</sup> 651 15-30%; few -5-15%; very few -<5%; weak.: weakly; mod.: moderately; str.: strongly. 54

55 652 Table 3. Summary of microscopic properties of investigated soil horizons (full micromorphological 56 data are in Supplementary Materials). Frost related pedofeatures in *italics*. 57 653

58 59 60

<sup>44</sup> 646 45









420x292mm (300 x 300 DPI)



420x292mm (300 x 300 DPI)

2	Horizon	Texture	Colour	Mottles	Fe(o) (g/kg)	Fe(d) (g/kg)	Fe(t) (g/kg)
3	0	Silty loam	10YR 3/2		9.67	23.14	43.03
4	A1	silty loam	10YR 3/2	10 YR 6/6	11.18	24.20	39.17
5	A2	silty clay	10YR 2/1		12.06	25.05	35.51
6 7	Bw	silty loam	10YR 6/8		15.86	38.02	55.66
/ Q	2E	silty clay	10YR 5/4		8.16	28.26	44.88
9	2Bs	silty sand	10YR 5/6		7.36	22.00	47.02
10	2BC	silty sand	10YR 6/4		4.90	21.47	40.06
11				10YR 6/8,			
12	3Et	silty clay	10YR 6/1	5Y 5/8	3.44	17.55	30.61
13	3Bs	silty clay	10YR 5/8		11.53	32.37	52.27
14 15	3C	silty sand	10YR 4/2		5.00	11.59	43.30

Horizon	Microstructure	Aggregates	Porosity
A1 A2	Crumb Granular	Dominant weak. separated crumbs, FS to VFS; dominant weak. separated granular peds inside crumbs. SS Dominant weak. separated granular peds, SS	Common complex packing voids, MS to SS; very few linear planes locally horizontally oriented, MS to SS; very fee channels, VCS to CS; very few vughs, M to FS: : verv few vesicles. FS to VFS Very few complex packing voids, FS to VFS; few linear planes horizontally oriented, MS to VFS; few channels, CS FS; very few vughs, MS to FS; very few vesicles, FS to VFS
Bw	Channel	Dominant weak. separated granular peds, SS	Common channels, CS to FS; few vugh MS to FS
2E	Channel	No visible aggregates	Few channels, CS to FS; very few vughs MS to FS
Fireplace	Channel	Few weak. separated granular peds, SS	Common channels, CS to FS; few vugh MS to FS
3Et	Complex, vughy/spongy	No visible aggregates	Very few channels, CS to FS; few vughs CS to FS
3Bs	Channel	Frequent weak. separated granular peds. SS	Few channels, CS to MS; few vughs, M to FS; very few complex packing voids,

Mineral fragments	Organic material	c/f limit, ratio	c/f related distribut
Common weak. weathered micas, CS to VFS,	Very few charcoal	10 µm,	Single
well sorted on FS; few weak. weathered FS	fragments, GS to MS; very	60/40	spaced
quartz and feldspar, MS to VFS; very few mod.	few plant remains (roots),		porphyr
weathered rock fragments, GS to CS	GS to CS		
Few weak. weathered micas locally sub-	Very few charcoal	10 µm,	Double
horizontally oriented, FS to VFS; very few	fragments, CS to FS; very	40/60	spaced
weak. weathered FS quartz and feldspar, FS to	few plant remains (roots),		porphyr
VFS; very few mod. weathered rock	VCS to CS		,
fragments, GS to CS (GS concentration on the			
unner houndary with Δ2)			
Common weak. weathered micas locally sub-	Very few charcoal	10 µm,	Close
horizontally oriented, MS to VFS; few weak.	fragments, CS to FS; very	75/25	porphyr
weathered FS quartz and feldspar, MS to FS;	few plant remains (roots),		
very few mod. weathered rock fragments,	CS to MS		
VCS to CS			
Common weak. weathered micas, MS to VFS;	Very few charcoal	10 µm,	Close
very few weak. weathered FS quartz and	fragments, CS to FS; very	75/25	porphyr
feldspar, MS to FS; very few mod. weathered	few plant remains (roots),		
rock fragments, VCS to CS	CS to MS		
Common weak. weathered micas, MS to VFS;	Frequent charcoal	10 µm,	Close
few weak. weathered FS quartz and feldspar,	fragments, GS to MS; very	75/25	porphyr
MS to FS; very few mod. weathered rock	few plant remains (roots),		
fragments, VCS to CS	CS to MS		
Frequent weak. weathered micas, MS to VFS;	Very few charcoal	10 µm,	Close
few weak. weathered FS guartz and feldspar,	fragments, VCS to MS	80/20	porphyr
CS to FS; few mod. weathered rock fragments.			,
GS to CS			
Common mod. weathered micas, CS to VFS;	Very few charcoal	10 µm,	Single
few weak. weathered FS quartz and feldspar,	fragments, MS to FS	40/60	spaced
MS to VFS; few mod. weathered rock			porphyr
fragments, GS to CS			-

FS material	b-fabric	Pedofeatures
Brown (darker	Undifferentiated.	Very few subangular alteromorphic Fe-Mn
with depth)	dark brown	nodules with sharp boundary, CS to FS; very fe
dotted		rounded typic Fe-Mn nodules with clear
		boundary, FS to SS; very few dense incomplete
		matrix infillings (passage features). GS to VCS
Dark brown	Undifferentiated,	Very few subangular alteromorphic Fe-Mn
dotted	dark brown	nodules with sharp boundary, CS to FS; very fe
		rounded typic Fe-Mn nodules with clear
		boundary, FS to SS; very few dense incomplete
		matrix infillings (passage features), GS to CS
Yellowish	Stipple speckled,	Very few subangular alteromorphic Fe-Mn
brown speckled	brown	nodules with sharp boundary, VCS to FS; very
·		rounded typic Fe-Mn nodules with clear
		boundary, MS to SS; very few dense incomplet
		matrix infillings (nassage features). GS to CS
Grayish brown	Stipple speckled,	Very few subangular alteromorphic Fe-Mn
speckled	grayish brown	nodules with sharp boundary, VCS to FS; very
		rounded typic Fe-Mn nodules with clear
		boundary, MS to SS; very few dense incomplet
Yellowish	Stipple speckled,	matrix infillings (passage features). GS to CS Very few subangular alteromorphic Fe-Mn
brown speckled	brown	nodules with sharp boundary, VCS to FS; very
·		rounded typic Fe-Mn nodules with clear
		boundary, MS to SS; very few dense incomplet
		matrix infillings (nassage features). GS to CS
Gray speckled	Crystallitic, gray	Very few subangular alteromorphic Fe-Mn
		nodules with sharp boundary, VCS to FS; very
		microlaminated typic-crescent dusty clay coat
		VFS to SS; very few fabric hypocoatings
		(compaction) around channels
Reddish brown	Stipple speckled,	Very few subangular alteromorphic Fe-Mn
speckled	reddish brown	nodules with sharp boundary, VCS to MS; very
		few rounded typic Fe-Mn nodules with clear
		boundary. MS to VFS

I	Horizon	Microstr	Aggregates	Porosity
_	1	Country	Dominant	Complex packing voids linear planes
A	41	Crumb	granular	
		Cronular	granular	Channels, linear planes legelly
Д	42	Granular	Dominant	Channels, linear planes locally
			granular	horizontally oriented, vesicles
R	314/	Channel	Dominant	Channels yughs
	JVV	Channel	granular	Channels, vugis
			granular	
2	2E	Channel	None	Channels, vughs
F	ireplace	Channel	Few	Channels, vughs
			granular	
3	BEt	Vughy/s	None	Channels, vughs
		pongy		
3	Bs	Channel	Frequent	Channels, vughs, complex packing
			granular	voids

Mineral fragments	Charcoal fragments	c/f ratio	c/f related distribution	Fine material
Common micas, few quartz and feldspar, very few rock fragments	Very few	60/40	Single spaced porphyric	Brown
Few micas horizontally oriented, very few quartz and feldspar, very few rock fragments	Very few	40/60	Double spaced porphyric	Dark brown
Common micas horizontally oriented, few quartz and feldspar, very few rock fragments	Very few	75/25	Close porphyric	Yellowish brown
Common micas, very few quartz and feldspar, very few rock fragments	Very few	75/25	Close porphyric	Grayish brown
Common micas, few quartz and feldspar, very few rock fragments	Frequent	75/25	Close porphyric	Yellowish brown
Frequent micas, few quartz and feldspar, few rock fragments	Very few	80/20	Close porphyric	Gray
Common micas, few quartz and feldspar, few rock fragments	Very few	40/60	Single spaced porphyric	Reddish brown

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b-fabric

Undifferentiated

Undifferentiated

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#### 10 1 Was the Little Ice Age the coolest Holocene climatic period in the Italian central Alps?

#### 3 Abstract

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Estimations of the relative intensity of different cold periods occurring during of the Late 4 5 Quaternary are difficult tasks, particularly in non-glaciated mountain landscapes, and where high-6 to medium-resolution archives for proxy data are lacking. In this paper, we study a Holocene 7 polycyclic soil sequence in the central Alps (Val Cavargna, Northern Italy)explore an alternative tool 8 - soil micropedology - to estimate climatic parameters (specifically T) changes in non-glaciated, 9 high altitude environments. A Holocene polycyclic soil sequence in the central Alps (Val Cavargna, 22 10 Northern Italy) Wwe investigate this key site was investigated through palaeopedological and 11 micromorphological analyses in order to understand phases of soil development its formation and 24 25 <sup>12</sup> detect hidden evidence of cold conditions during its formation. Three phases of pedogenesis could 26 13 can be recognized and attributed in time to different periods during of the Holocene. Pedogenetic 14 phases were separated by two truncation and deposition episodess related to the reactivation of 28 29 <sup>15</sup> slope processes under cold conditions at the onset of the Neoglacial and the Iron Age Cold Epoch 30 16 (IACE) respectively. Robust Micromorphological evidences stress evidence of of frost action on soil 31 32 <sup>17</sup> revealed by micropedology could can instead relate to pedogenetic processes acting in the Little Ice Age (LIA). The different expression of these three cold periods corresponds to different climatic 33 18 34 <sub>19</sub> conditions, pointing to the LIA as a cooler/drier period in comparison to the preceding ones. 35 36 <sup>20</sup>

#### 37 21 Keywords

38 22 Polycyclic palaeosols; Micropedology; Frost pedofeatures; Mid-Late Holocene; Little Ice Age; 39<sup>--</sup> 40<sup>23</sup> Southern Alps.

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### I. Introduction

One of the most difficult tasks in paleoclimate past climate studies - before the introduction of 28 instrumental measurements - is the estimation\_- even relative, of climate parameters and their 14 <sup>29</sup> variation with across time (Edwards et al., 2007a; Bradley, 2015). When records are irregular and 15 <sub>30</sub> limited to shortened time-spans, discontinuous or low in resolution, such as in many continental . 3 17 <sup>31</sup> palaeoenvironmental archives, the reconstruction of climatic conditions and their effects on the 18 32 landscape becomes much more challenging (Kutzbach, 1976; Federici, 2005; Giraudi et al., 2011; 19<sub>33</sub> Bradley, 2015; Furlanetto et al., 2018). This is especially true when dealing with the effects of cold \_0 21 <sup>34</sup> periods in middle latitude and Mediterranean mountain ranges, such as the Alps and Apennines of 22 35 Italy, known as highly dynamic regions (Porter and Orombelli 1985; Baroni and Orombelli 1996; 23 <sub>36</sub> Federici, 2005; Hughes et al., 2011; Kuhlemann et al., 2013; Pelfini et al., 2014; Colucci et al., 2016; 24 25 <sup>37</sup> Bollati et al., 2018). Where extensive landforms and stratigraphic records of Quaternary glacial 26 38 advances are not present, evident traces of cold phases are often hard to study. Poorly visible, 27 <sub>39</sub> 28 buried and hidden signs of cold periods - as much as of the subsequent warm phases - are only 29 <sup>40</sup> occasionally embedded and rarely well-preserved in landforms and within (palaeo)soilssols and 30 41 sedimentary records (Angelucci et al., 1992; Calderoni et al., 1998; Fischer et al., 2012; Compostella 31 32 <sup>42</sup> et al., 2012, 2014; Waroszewski et al., 2018). In the latter, evidence of cold phases is often 33 43 associated with breaks in the sedimentary succession or with an increased frequency of slope 34 44 processes related to climatic instability (Bertolini et al., 2004; Nicolussi et al., 2005; Magny et al., 35 36 <sup>45</sup> 2009a; Arnaud et al., 2012; Cremaschi and Nicosia, 2012; Compostella et al., 2014; Pelfini et al, 2014; 37 46 Mariani et al., 2019). Despite the extensive documentation regarding on the Little Ice Age (LIA) 38 <sub>47</sub> traced in paleoclimate studies (Kullman and Öberg, 2009; Arnaud et al., 2012; Nicolussi, 2013; 39 40 <sup>48</sup> Carturan et al., 2014; Loso et al., 2014), many questions are still open, for example its role and 41 49 importance inside the wider frame of the Holocene is less understood. For instance, LIA's the 42 <sub>50</sub> influence of climate variations on non-glaciated mountain landscapes during the LIA is poorly 44<sup>51</sup> known, especially when compared to previous older cold intervals such as the Neoglacial, the 45 52 Lateglacial, and the Last Glacial Maximum (LGM) (e.g., Wanner et al., 2011; Badino et al., 2018; 46 <sub>53</sub> Furlanetto et al., 2018). In the mountain environments of middle latitudes, where glacial and 48 <sup>54</sup> periglacial landforms are undetectable or have been vanished/truncated/\_erased due to enhanced 49 55 slope\_activity (e.g.: Allison, 1996; Giraudi et al., 2011; Compostella et al., 2014; Mariani et al., 2018), 51 56 paraglacial (Knight and Harrison, 2009), or zoogeomorphological processes (e.g., Butler, 1995, 2012), the effects of cold phases are virtually absent from the scientific record.

10 <sup>58</sup> In this paper, we studied consider a Holocene polycyclic soil sequence formed in the Mid-11 59 Late Holocene in the Italian Central Alps (Val Cavargna, CO). Our aim is to find records ways to 60 detect hidden evidence of Holocene climatic influence on the evolution of surface processes 14 <sup>61</sup> (Nicholson, 1988), and to assess whether soils and paleosoils (and their pedofeatures) can really 62 record climatic changes in Alpine environments. The studied considered soil sequence shows clear 17<sup>63</sup> traces of the presence of cold conditions during its formation, strong enough to promote soil frost 18 64 and trigger the formation of frost-induced pedofeatures (sensu Van Vliet-Lanoë, 1998; Van Vliet-19<sub>65</sub> Lanoë et al., 2018) without the influence of glacial or periglacial processes. No evidence for glacials 21 <sup>66</sup> landforms, were found at the study site and in its close not present in the vicinity.\_\_\_of the study 22 67 site. Using multiple palaeopedological techniques, and in particular micropedology, we were are 68 able to characterize different Holocene cold phases eriods affecting acting on the soil formation. -≄ 25 <sup>69</sup> We also stress also suggest interpretations on the relative intensity the impact as a climatic 26 70 parameter of ofdifferent atmospheric temperatures- during the cold periods of the last few 71 millennia.and its impact as a climatic parameter during the last few millennia. We lastly suggest 29 <sup>72</sup> offer an alternative qualitative approach to interpret past fluctuations of climatic parameters based 30 73 on their effect on surface processes. 31 32 <sup>74</sup>

### II. The study area

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34 <sub>76</sub> The studied soil sequence is located at Alpe Piazza Vacchera (46°06'32"N, 9°08'33"E), in Val 35 36 <sup>77</sup> Cavargna (San Bartolomeo municipality, Italian Central Alps), at an elevation of 1680 m a.s.l. 37 78 (Figures 1 and 2). The bedrock of the studied area is part of belongs to a portion of the Southalpine 38 <sub>79</sub> basement - the tectono-metamorphic unit of the Dervio-Olgiasca Zone (after Spalla et al., 2002) -39 40 <sup>80</sup> and consists mainly of garnet-staurolite-bearing schist and minor gneiss with lenses of 41 81 amphibolite. Schists are particularly prone to weathering, especially in areas of pervasive jointing 42 <sub>82</sub> due to tectonic deformation. The study site is currently above the treeline and covered by .5 44 <sup>83</sup> grassland pastures; mean annual rainfall is between 2000-2500 mm/y and mean annual 45 84 temperature between 3.8 and 10.9°C (Ceriani and Carelli, 2000). Snow accumulation is high, 46 <sub>85</sub> estimated between 1-2 m/y, with a residence time higher\_greater\_than 100 days (Gazzolo and 48 <sup>86</sup> Pinna, 1973). The permanent snow line for the Alps varies from N to S and from W to E according 49 87 to factors related to latitude, continentality and slope insulation, but it is generally located between 88 2500-2800 m a.s.l. (Barry, 1992), thus well above the area of study. The area is with no-does not contain unaffected by the presence of permafrost: in this portion of the Alps favourable conditions 52 <sup>89</sup> 53 <sub>90</sub> for permafrost isare found only formation can only be met above 2200-2300 m a.s.l. (Boeckli et al.,

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10 91 2012), and the first instances of permafrost or related landforms are found in a range of tens? of 11 92 many-kilometres to the North (Cremonese et al., 2011). During the LGM, valley glaciers did not 93 cover the area but at least a few cirque or slope glaciers were present in the highest part of the 14 <sup>94</sup> mountainous range region (Bini et al., 2009). Since then, no traces of further glacial influence are 15 <sub>95</sub> found on the slopes or in the valley below (Bini et al., 2009). Periglacial processes are visible as 16 17 <sup>96</sup> sparse, possibly inactive solifluction lobes on the surrounding slopes, today highly disturbed by 18 97 zoogeomorphologically induced game trails, causing and related instability, and causing 19 <sub>98</sub> enhanced gully erosion and transportation of soil material in the vicinity of the studied area (e.g., 21 <sup>99</sup> Butler, 2018; Zerboni and Nicoll, 2018).

22100 Human frequentation activity in Val Cavargna is known since the Mesolithic, with the 23<mark>1</mark>01 establishment and abandonment of sporadic settlements in the upper part of the valley. 24 25<sup>102</sup> Subsequent occasional occupation of the area with evidence of widespread forest fires took place 26103 multiple times from the Neolithic to the Middle Ages (Castelletti et al., 2012a). The systematic 27<sub>104</sub> 28 exploitation of the area, resulting in an increase in human pressure on the landscape, dates back 29<sup>105</sup> mainly to post-medieval times (Castelletti and Tremari, 2012). Documented instances of forest 30106 clearance in the upper valley appear since the XVI century CE, with a change in land use for 31 32<sup>107</sup> charcoal production (Grandi, 2012). At this time, large portions of deforested land - between 1400-33108 1800 m a.s.l. - were converted to pasture lands (Castelletti et al., 2012b). Near the studied section, 34109 the first establishment of a small cattle farm and trail can be loosely attributed to the same period. 35 36<sup>110</sup>

#### 37111 **III. Materials and methods**

38<sub>112</sub> To investigate the soil in the field we dug a trench along the western slope of Mount Pianchette -39 40<sup>113</sup> Pizzo di Gino, in correspondence of a natural filled trench forming a small terrace on a deep-seated **41**114 gravitational slope deformation (DSGSD). This landform represents large to extremely large mass 42<sub>115</sub> movements generally affecting the entire length of high-relief valley flanks, extending up to 200-43<sup>115</sup> 44<sup>116</sup> 300 m in depth, which can frequently extend beyond the slope ridge (Crosta et al., 2013). Soil 45117 descriptions and horizon designations were carried out according to the guidelines of FAO (2006); 46<sub>118</sub> 47 colour definition followed the Munsell Color® (1994) nomenclature. The diagnostic horizons of 48<sup>119</sup> buried palaeosols in the sequence were defined according to the international classification 49120 systems (FAO, 2014; Soil Survey Staff, 2014; Zerboni et al., 2011, 2015). Soil samples for chemical-50 51<sup>121</sup> physical analyses were collected for each horizon. Particle size distribution was determined using 52<sup>122</sup> laser diffraction (Malvern Mastersizer MS-2000) after H<sub>2</sub>O<sub>2</sub> and HCl treatments, according to the 53<sub>123</sub> procedure described in Crouvi et al. (2008). The total amount of Fe and Al in the samples was 54

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determined by complete dissolution in a mixture of HF, HCl, HNO<sub>3</sub> and HClO<sub>4</sub>, followed by measurement of the solubilised ions using an ICP-ES (Jobin-Yvon JV24). Dithionite- (Mehra and Jackson, 1960) and oxalate-extractable (McKeague et al., 1971; Schwertmann, 1973) fractions of Fe and Al oxyhydroxides, representing a quantification for free and amorphous Fe and Al forms respectively, were also measured with the same instrument. The Activity Ratio between oxalateand dithionite-extractable iron (Fe(o)/Fe(d)) was also calculated. Analytical data are reported in Table 1 and summarized in Figure 3.

19<br/>20<br/>21Thin sections were produced from undisturbed samples taken from relevant soil horizons<br/>after impregnation with polyester resin according to the method described in Murphy (1986).22.133Slides were examined with an Olympus BX41 petrographic microscope, under plane-polarized light<br/>(PPL), cross-polarized light (XPL), and oblique incident light (OIL). The terminology of Stoops (2003)<br/>was used to describe thin sections, whereas micromorphological interpretation was mainly based<br/>on the concepts reported in Stoops et al. (2018).

### IV. Results

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34142 Along the slope of Mt. Pianchette and Mt. Pizzo di Gino, inside the morphological trench formed 35 36<sup>143</sup> by a detachment niche of a DSGSD, are present a series of shallow depressions allowed several 37144 events of accumulation of poorly sorted sediments after colluvial phenomena and slope processes, 38<sub>145</sub> later weathered into soils.filled with sediments deposited through colluvial slope processes that 39 40<sup>146</sup> were subsequently weathered and reorganized into soils. In the uppermost depression, several soil **41**147 horizons were identified (Table 1), consisting of three different soil units on successively deposed 42<sub>148</sub> parent materials (Figure 2). The uppermost unit corresponds to the extant soil, down to a depth of 43 44<sup>149</sup> about 49 cm. It is an organic temperate mountain soil differentiated in thicker organic A horizons **45**150 sometimes alternated with thinner levels of rubified soil material containing dark mottles. The same 46<sub>151</sub> 47 material is also present at the bottom of the unit as a mineral Bw horizon. The passage-boundary between this unit and the intermediate one is marked by an erosional surface bearing a residual 48<sup>152</sup> **49**153 lens of macroscopic charcoal fragments, several centimetres thick, identified as the remains of a 50 51<sup>154</sup> fireplace. Dating from two charcoal samples taken from this lens gave a result of 2730±43 (RC-369) 52<sup>155</sup> and 2683±42 (RC-370) years uncal BP (2926-2756 years cal BP and 2863-2747 years cal BP 53<sub>156</sub> respectively). The intermediate unit is a buried palaeosol divided into three main horizons: an

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10<sup>157</sup> eluvial 2E horizon occupies the upper position above a rubified 2Bs horizon; below them is found a 111158 mineral 2BC horizon with common reddish mottles. The lowermost soil unit, starting at a depth of 12 159 13 75 cm, is quite similar to the previous one, but pedofeatures are better expressed. A whitish eluvial 14160 3Et horizon, in which are still present reddish mottles comparable to those of the level above it, 15<sub>161</sub> forms the upper portion of the unit, followed by a weathered rubified 3Bs horizon. Below the latter, 16 17<sup>162</sup> a 3C horizon marks the passage\_boundary to the bedrock at about 130 cm below the current 1**8**163 surface. Charcoal fragments from the 3Bs horizon of this unit were dated to 6850±20 years uncal 19<sub>164</sub> BP (UGAMS-38048, 7721-7621 years cal BP).

20 21<sup>165</sup> Grain size analytical data from a selection of soil samples shows where units differ and 22166 where instead similarities emerge (Figure 3). The A2 horizon of the top unit differs stands out from 23<mark>|</mark> 23<sub>167</sub> the others, showing a bimodal distribution of grain size classes: the main mode is represented by 24 25<sup>168</sup> silt, while a secondary mode is instead shifted towards medium/coarse sand. Its much broader 26169 selection distribution also indicates a poor selection of grains. Horizons from the other two units 27<sub>170</sub> 28 show instead very similar categories. In particular, the E horizons share almost the same bell curve 29<sup>171</sup> weakly skewed to the left and centred on coarse silt. All B horizons (Bw, 2Bs and 3Bs) also share a 30172 similar trend with a better selected mode at into the fine sand and a higher skewness towards the 31 32<sup>173</sup> finer fractions that are more expressed in the bottom unit. Total iron content in the soil sequence 33174 amounts to 3-5.5% of the total mass in all soil horizons, with concentrations in the B horizons of 34175 the top and bottom units (Figure 3; Table 1). Eluvial horizons show lower concentrations of Fe, with 35 36<sup>176</sup> the 3Et horizon being the scarcest in total iron content (3.06%). The intermediate unit is also low in 37177 iron content, with only a slight increase of total iron in the 2B horizon. Free iron measured as Fe-38<sub>178</sub> dithionite peaks in the Bw and 3B horizons and shows the lowest concentration at the bottom of 39 40<sup>179</sup> the sequence (11.6 g/kg in the 3C horizon); generally, free iron accounts for 47-71% of total iron **41**180 content. The Activity Ratio is mostly between 0.35 and 0.5 for all horizons, with the exception of E 42<sub>181</sub> horizons where it reaches the lowest values (below 0.3). 43 44<sup>182</sup>

The observation of thin sections reveals the general composition and fabric of the soil units 45183 (Table 2). The micromass of all investigated horizons shows a dominance of coarse mineral material 46<sub>184</sub> 47 (mainly micas, then quartz and feldspar) with the fine material either compactly filling the 48<sup>185</sup> remaining space in B horizons (Figure 4a), or weakly aggregating in granular peds in E horizons 49186 (Figure 4b). Fine charcoal is always present; coarser fragments can be found in the A1 and 3Et 50 51<sup>187</sup> horizons as well as in the charcoal-bearing lens at the top of the 2E horizon. The 3Et horizon shows 52<sup>188</sup> microlaminated clay coatings (Figure 4c, d) inside a groundmass with marked differences from the 53<sub>189</sub> B horizons: the fine material bears a greyish colour and no visible aggregation is present. The A1

10<sup>190</sup> and A2 horizons are locally arranged in a pattern of horizontal planar voids (isoband fabric, sensu 11191 Dumanski and St-Arnaud, 1966), not visible in the deeper parts of the soil sequence (Figure 5a). 12 13<sup>192</sup> This pattern is randomly distributed in the two horizons as large centimetric patches sharing the 14193 same features: a net of partially interconnected straight or slightly curved planar voids up to a 15<sub>194</sub> millimetre long and less than 100 µm thick that separate lenses of soil material up to 1 mm thick. 16 17<sup>195</sup> Vesicles are often associated to-with soil lenses (Figure 5b) and the pattern itself. Clusters of **18**196 parallel-oriented coarse fragments (Figure 5c) are visible in the Bw horizon. All these features are 19197 usually undisturbed by the presence of bioturbation otherwise found in many instances in the soil 21<sup>198</sup> mass in the form of passage features (Figure 5d).

### V. Discussion

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23<sub>200</sub> 24 25<sup>201</sup> In the following parts we reconstruct the evolution of the investigated soil sequence discussing the 26202 main pedogenetic processes involved in its formation. We then highlight the occurrence of 27<sub>203</sub> 28 pedofeatures in the different soil units that record allow the reconstruction of past temperature 29<sup>204</sup> shifts in the area.

### 31 32<sup>206</sup> 5.1. Soil forming processes and chronology

33207 The characterization of pedogenesis in the three units shows evidence of similar soil formation 34208 processes in different periods of time, thus confirming the existence of a soil polysequence 35 36<sup>209</sup> (Cremaschi and Rodolfi, 1991). The very similar grain sizes of the different horizons imply that each 37210 soil unit was formed by deposition over the previous surface - exposed by truncation - of the same 38211 type of sediments removed from above by short-range (tens to hundreds of metres) slope 39 40<sup>2</sup>12 41213 transportation? movements. Each soil unit shares the combined presence of an E/B horizon series, with the E substituted by a moderately depleted A2 horizon in the uppermost unit. The formation 42<sub>214</sub> of clay and Fe oxyhydroxides in the soil mass is accompanied by their translocation downwards 43<sup>215</sup> 44<sup>215</sup> from the eluvial horizons into the lower rubified B horizons, or even below in older soil units, as in 45216 the case of the clay coatings found inside that crossed the boundary into the 3Et horizon. Particle 46<sub>217</sub> translocation is also supported by the highlighted by the shift from the 2Bs to the 3Et horizon, 48<sup>218</sup> which hints to clay depletion from the second unit and illuviation into the unit one below. -. An and **49**219 by the enrichment in fine material is also clearly visible in the 3Bs horizon. The low activity ratio also 50 51 51 weakly shows highlights this trend showing a relative depletion in the amorphous iron forms, easier to mobilise, in E horizons. The three units show different degrees of the same pedogenetic 52221 53222 processes (pedoplasmation, soil formation by weathering and translocation of clay minerals and Fe 54

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oxyhydroxides; Duchaufour, 1983), decreasing in strength of expression upwards. In fact, although the bottom unit looks the most developed in a well-defined series of horizons, Fe oxyhydroxides do not change sensibly markedly along the units, showing again uniformity in weathering.
Pedogenesis is in any case only moderately developed, and the accumulation of Fe in the B horizons appears to be not only a result of in-situ weathering-alone, but also of translocation from the overlying horizons and younger parent materials (Duchaufour, 1977; Cornell and Schwertmann, 2003).

19230 Pedogenesis occurred under warm/temperate climate phases with the presence of 20 21<sup>231</sup> continuous vegetation (Duchaufour, 1983) that and promoted the accumulation of microlaminated 22232 clay coatings by illuviation into the unit below (e.g. Fedoroff, 1997; Compostella et al., 2014). The 23<sub>233</sub> 24 25<sup>234</sup> microstructure of E horizons and the presence of red mottles in B horizons (Table 3) suggest an incipient podsolization process (Duchaufour, 1983; Van Ranst et al., 2018), likely supported helped 26235 by local conditions of seasonally -periodical water saturation (Duchaufour, 1983; Sevink and de 27<sub>236</sub> 28 Waal, 2010; Vepraskas et al., 2018). The identification of wood species from charcoal fragments 29<sup>2</sup>87 found in various soil horizons shows the dominance of silver fir (Abies alba) open forest throughout 30<mark>2</mark>38 the soil sequence; reconstructions of the vegetation history of the area point to the presence of an 31 32<sup>239</sup> 32 open forest indicating under moderately warm conditions (Castelletti et al., 2012b). At the current 33240 surface and towards the top of the intermediate unit, charcoal assemblages suggest a sparsely 34241 forested heathland, revealing colder phases of forest retreat or anthropogenic pressure (Castelletti 35 36<sup>242</sup> et al., 2012b).

37243 38<sub>244</sub> Radiocarbon dating stresses helps in placing the formation of the various soil units within the Holocene, showing how the soil sequence has in fact experienced more than one warm climate 39 40<sup>245</sup> phase. The development of the bottom unit, dated to 7721-7621 years cal BP, can be very clearly **41**246 attributed to the Early-Middle Holocene (Mayewski et al., 2004; Arnaud et al., 2012; Grosjean et al., 42<sub>247</sub> 2007), during a warm period preceding the cold event at 4.2 ka cal BP (e.g., Zanchetta et al., 2016), 43 44<sup>248</sup> possibly the Atlantic Warm Period (AWP) or the Late Neolithic Thermal Maximum (LNTM). In this 45249 longer period of pedogenesis, potentially lasting a few thousands of years, the soil had the time to 46<sub>250</sub> 47 develop pedofeatures under a rapidly warming phaseclimate. Afterwards, the warm and stable phase responsible for the formation of the intermediate unit should occur after the Middle/Late 48251 49252 Holocene transition, when several warm fluctuations occurred (Mayewski et al., 2004; Deline and 50 253 51 Orombelli, 2005): the longest phase takes place during the Bronze Age, loosely between 3800 and 2800 years BP (e.g., Arnaud et al., 2012 and references therein), and can be confirmed by dating 52254 53,55 from the truncation of the unit indicated by the residual fireplace (2926-2756 and 2863-2747 years

10<sup>256</sup> cal BP). It is therefore possible that this pedogenesis took place in a period not much longer than a 11257 thousand years. The truncation points to the transition passage from a warm period to the next 12 258 13 cold phase (Plunkett and Swindles, 2008; Magny et al., 2009b; Wanner et a., 2011; Regattieri et al., 14259 2014; Cremaschi et al., 2016) corresponding to the Iron Age Cold Epoch (IACE). This cold stage 15<sub>260</sub> probably witnesses both the truncation of the intermediate unit due to enhanced slope processes 16 17<sup>261</sup> and the deposition of the parent material composing the top one. The last phase of pedogenesis 18262 probably started since the Roman Warm Period (RWP) onwards to present time, covering less than 19263 2000 years of duration in a fluctuating climate. 20 21<sup>264</sup>

# 22265 5.2. Are frost-related pedofeatures a proxy for past temperatures?

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23<sub>266</sub> The typical pedofeatures found at in the top unit (A1-A2 horizons) relate to specific climate 24 25<sup>267</sup> conditions and can be safely attributed to a post-RWP cold of phase on the basis of the above-26268 mentioned chronological framework. The LIA is most likely the coolest coldest climatic phase in 27<sub>269</sub> 28 that time interval (Wanner et al., 2011; Furlanetto et al., 2018). The pattern of microscopic 28 29<sup>2</sup>70 horizontal planar voids separating the matrix into?? Dividing homogeneous lenses of soil material 30271 indicates the action of frost on soil horizons (Dumanski and St-Arnaud, 1966). Vesicles are also 31 32<sup>272</sup> related to the entrapment of air bubbles in the soil mass during the freezing process (Table 3). As 33273 suggested by Van Vliet-Lanoë (1987, 1998) and Van Vliet-Lanoë et al. (2018), this regular pattern is 34274 connected to the presence of intermittent or seasonal frost episodes localised at the soil surface 35 36<sup>275</sup> when the penetration of the freezing front is not very deep. This is expected for temperate 37276 environments, considering that very low air temperatures are needed to freeze the open ground 38277 below the first centimetres (Henry, 2007). Deformation of the soil mass is only limited to sporadic 39 40<sup>278</sup> preferential orientations of coarse fragments, also indicating weak freezing conditions (Van Vliet-41279 Lanoë et al., 1984). Nevertheless, the durability of these features to later pedo/bio-turbation (Van 42<sub>280</sub> Vliet-Lanoë et al., 1984) indicates a certain level of stability compatible with repeated freeze-thaw 43 44<sup>281</sup> cycles during an extended period.

The weak expression of the above described frost-related pedofeatures suggests the occurrence in the past of periglacial processes unrelated to permafrost (Van Vliet-Lanoë, 1998), the presence of which would have forced much stronger cryoturbation and very different features in the soil and is linked to more rigid conditions, possibly unmet here since the LGM. In fact, considering the stability through time of frost-related pedofeatures (Van Vliet-Lanoë et al., 1984), their absence in the two buried soil units suggests that frost acted in the area only in recent timesduring the most recent cold phase corresponding to the LIA, after the accumulation of the

10<sup>289</sup> parent material of the uppermost soil unit. Since most of the pedogenetic factors identified by 11290 Jenny (1941) and the related soil-forming processes do not show dramatic changes over time, as 12 291 13 seen above, this occurrence is probably more related to fluctuations modifications in the climate. A 14292 climatic trend toward cooler conditions seems also confirmed by the general decrease in 15293 expression of pedogenetic processes from the bottom to the top of the pedosequence. This trend 16 17<sup>94</sup> has been recently suggested from multi-proxy models of insolation at middle latitudes on alpine 18295 scale (Mauri et al., 2015). The supposed duration for each phase of soil formation, probably lasting 19<sub>296</sub> 20 several millennia to centuries, also needs to be taken into consideration. It is clear how time alone 21<sup>297</sup> is not able to explain the differences in pedogenesis. In fact, both factors contributed in synergy to 22298 the development of soil formation processes (Jenny, 1941Boardman, 1985; Birkeland, 1999). We 23<sub>299</sub> believe that in this case, while no simple comparison can be done between climate and time, the 24 25<sup>300</sup> former seems to play the main role. The rapid succession of environmental changes in the 26801 environmental conditions during the Holocene represents the limiting factor in the development of 27<sub>302</sub> 28 pedogenesis, while In fact, the amount of time, though necessary for soil formation, is more 29<sup>303</sup> relevant as the duration of the climate phases than as a factor itself. Time in this case cannot be the 30304 primary factor driving the expression of pedogenesis, since the different units are formed too 31 32<sup>305</sup> suddenly because of the continuous climate shifts.

33806 Considering the strong similarities in soil formation conditions between the three units, the 34307 effect of different cold periods on each is very noticeable. The abrupt truncation of the bottom unit 35 36<sup>308</sup> could possibly correspond to the initial part of the Neoglacial period, often associated with a sharp 37309 increase in denudation processes (Arnaud et al., 2012). Denudation is in turn related to vegetation 38<sub>310</sub> loss events often indirectly caused by the passage to cold and unstable climate phases (Bertolini et 39 40<sup>311</sup> al., 2004; Nicolussi et al., 2005; Magny et al., 2009a; Compostella et al., 2014). Slope instability 41312 events responsible for the deposition of the two upper units are also a typical result of denudation 42<sub>313</sub> processes, where erosion and deposition often occur consecutively on the same topographic 43 د<del>،</del> 44<sup>314</sup> surface (Giraudi et al., 2011; Compostella et al., 2014). The same appears to happen for the 45815 truncation of the second unit dated to the IACE (Magny et al., 2009b). For sake of clarity we need to 46<sub>316</sub> consider that the anthropogenic contribution to the deposition and development of these units is 47 not to be underestimated. Multiple fire events very likely connected to forest clearance practices 48<sup>317</sup> 49318 started in the area since the Mesolithic (Castelletti et al., 2012b). Fire events greatly enhanced the 50 319 51 effect of washout and solifluction on the slopes, mobilising the colluvial material that forms the two upper soil units. Human contribution to slope instability is in this case quite important, enhancing 52820 53321 ongoing processes in synergy with the effect of climate variations. Later, also the

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zoogeomorphological effect due to the introduction of herding may have contributed to accelerateongoing denudation and rill erosion.

The different setting of the uppermost unit, where frost features represent the effect of cold conditions in place of truncations, can be ultimately regarded as a distinct process attributed specifically to the LIA. Neoglacial cold events appear to have mainly impacted the soil through slope instability and processes of removal/addition of material, but no features directly related to freezing and ice formation are found on the surfaceat the top of the buried units. In this regard, while it is true that no actual surface A horizon is currently present on both units, it must be noted that the new surfaces produced by truncation were probably exposed to the weather for a noninsignificant length of time. On the intermediate unit this was enough to allow the establishment of a fireplace on top of the former topographic surface - or at least not far from it - which does not exhibit any visible frost feature. On the contrary, anthropogenic features as fireplaces are able to record frost-related pedofeatures (Cremaschi et al., 2015). The LIA has instead triggered in the soil a variety of stable features related to intermittent freezing cycles. Such clear difference might suggest that other climate dynamics were in place during the cold phases preceding the LIA (for instance, the IACE). In this perspective, it might be plausible to characterise the LIA as a colder or drier period than the previous ones: lower temperatures in comparison with the other Holocene cold periods would have allowed more widespread episodes of seasonal frost. Holocene temperature anomalies reconstructed in the Southern Alps by Furlanetto et al. (2018) support this hypothesis suggesting a moderate shift towards lower temperatures in the LIA compared to other Holocene climatic phases. Moreover, a recent assessment of post-LGM permafrost distribution in the Mediterranean region suggests a widespread occurrence of soil frost in the LIA (Oliva et al., 2018). Similarly, a lessened amount of precipitation would have reduced sensibly the snow cover, well below the current thickness and down to only a few tens of centimetres (Zhang, 2005), weakening the thermal isolation of the soil below and allowing frost to take hold (Edwards et al., 2007b and references therein). A consequent shift downwards of the freezing front would plausibly have left more visible and stable features in the soils, while in less rigid and wetter phases they would only have suffered the consequences of more snow thawing upslope, especially a higher water discharge rate and in turn the activation of slope movements. The relationship between precipitations and slope processes is well studied in the Alps: today, where climate conditions are more severe lower rainfall thresholds are needed to trigger slope movements (Guzzetti et al., 2007). Considering the enhanced possibility of slope instability in cold environments, the absence of truncations in the upper soil unit confirms stable slope conditions and further supports a possible

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10<sup>355</sup> dry phase. While it is very difficult to assess past precipitation amount?-rates, reconstructed 11356 temperatures from proxy data in the Alps seem to favour this idea (for comparison, see Badino et 12 357 13 al., 2018; Furlanetto et al., 2018). Similar conditions have also been very recently postulated for the 14<sup>858</sup> Northern Apennines (Regattieri et al., 2014; Mariani et al., 2019). The occurrence of other evidence 15<sub>359</sub> confirming the climatic conditions in Mediterranean mountain ranges during the LIA confirms that 16 17<sup>360</sup> soils and pedofeatures can reflect regional climatic conditions and they are not only triggered by 18861 local conditions and surface processes. The effect of forest clearance must be taken into account 19<sub>362</sub> when discussing temperature in the topsoil. In fact, the presence of a forest cover greatly mitigates 20 21<sup>363</sup> the effect of air temperature on the soil, with the canopy protecting the lower air strata and 22364 producing a warmer microclimate that reaches temperatures below zero with more difficulty 23<sub>365</sub> 24 25<sup>366</sup> (Körner. 2003). On the other hand, the canopy effect also prevents part of the snow accumulation, reducing its isolating power. In this area, the continuous presence since the Mesolithic of clearance 26867 events by fire and the more recent establishment of pasturelands (Castelletti et al., 2012b) probably 27<sub>368</sub> 28 29<sup>369</sup> prevented for long periods of time the reestablishment of a closed forest, leaving more open vegetations in which both these effects were probably greatly reduced. 30<sub>370</sub>

### **VI. Conclusions**

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3372 This study reconstructs climatic fluctuations throughout the Holocene on the basis of a soil 34373 polysequence the pedogenetic processes that occurred in a high mountain range throughout the 35 36<sup>374</sup> Holocene. Moreover, we believe oOur study shows highlights it brings new evidence regarding on 37875 the importance of the LIA in the Alps as one of the main cold intervals after the LGM. While it is 38<sub>376</sub> difficult to make assumptions based on indirect archives, it is plausible to infer, based on the 39 40<sup>377</sup> evidence found in this study, that during the LIA the intensity of frost action might have been 41378 stronger compared to other Holocene cold episodes. An increase in ice formation could in turn be 42<sub>379</sub> related to the occurrence of drier/colder conditions weakening snow deposition on the soil surface 43 44<sup>380</sup> and favouring overall freezing conditions.

45381 While soil archives are considered a low-mid resolution resource in palaeoclimatic studies 46<sub>382</sub> (Yaalon, 1990), in this case the reconstruction of pedogenesis was the only reliable tool for recording cold intervals that occurred after the LGM in a non-glaciated area and their influence on 48<sup>383</sup> **49**384 surface processes. The study of soils and specifically micromorphology discloses important 50 51<sup>385</sup> information on past climate, especially under the microscope, where evidence traces of processes triggered by specific climatic and environmental conditions (in this case atmospheric temperature) 52<sup>886</sup> can be observed and put inside their proper placement in time (sensu Cremaschi et al., 2018). In

10<sup>388</sup> environments where human actions started tuning surface processes earlier than expected in the Mid-Late Holocene, as suggested by recent studies (ArchaeoGLOBE Project, 2019), soil evidence <sup>390</sup> 13 also helps in disentangling natural and anthropogenic factors shaping the landscape in human-settled contexts. The absence of such specific deposits and landforms allowing the formation and 15<sub>392</sub> conservation of soils and palaeosols would indeed render many of such reconstructions quite 17<sup>393</sup> arduous, if not implausible.- Finally, recent studies suggested that human actions started tuning surface processes earlier than expected in the Mid-Late Holocene (ArchaeoGLOBE Project, 2019); in 19<sub>395</sub> 20 this case, the study of soil also helps detangling natural and anthropogenic factors shaping the landscape in human-settled contexts. 21<sup>396</sup> or peer perieview 

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Captions
 Figure 1. (A) Hillshade of the central sector of Southern Alps indicating the location of the study area (the inset indicates its position in northern Italy). (B) Satellite view of the study area (source: Google Earth<sup>™</sup>); the star indicates the position of the soil profile.

Figure 2. (A) General view of the study area during the opening of the test trench. In the foreground the high portion of the DSGSD is visible to the right; the DSGSD is broken downslope to the left by a morphological trench associated with a counterscarp. In the background the peak of Mt. Pizzo di Gino and its southern slope are visible to the left. (B) Picture of the investigated polycyclic soil sequence indicating the position of soil horizons and samples for analyses (squares: blocks for thin sections; triangles: samples for chemical-physical analyses; dots: samples for radiocarbon dating).

Figure 3. Results of chemical-physical analyses: on the left, curves of grain size distribution (after  $H_2O_2$  and HCl treatments); on the right, chemical determinations of Fe content. Key: Fe(o): amorphous iron; Fe(d): free iron; Fe(t): total iron.

Figure 4. Micromorphological features of the investigated soil horizons: a) well developed yellowish
fabric devoid of iso-oriented features in the intermediate unit (2Bs horizon; 2x, PPL); b) depleted
soil mass in the lower unit (3Et horizon; 2x, PPL); c) microlaminated clay coatings in the eluvial
horizon of the lower unit (3Et horizon; 10x, PPL); d) same as c), in XPL.

Figure 5. Frost related features of the investigated soil horizons: a) horizontal planar voids in the upper unit (A2 horizon; 4x, PPL); b) groups of circular vesicles around horizontal planar voids in the upper unit (A2 horizon; 10x, PPL); c) horizontal iso-oriented mica fragments in the fabric of the upper unit (Bw horizon, 10x; XPL); d) passage features produced by <u>earthworms beetle</u> <u>larvae (possibly *Enchytraeidae*: Kooistra and Pulleman, 2018) around undisturbed planar voids (A2 horizon; 4x, PPL).</u>

Table 1. Field and chemical properties of the described soil sequence.

Table 2. Micromorphological descriptions of soil thin sections. G: gravel size; VCS: very coarse sand size; CS: coarse sand size; MS: medium sand size; FS: fine sand size; VFS: very fine sand size; S: silt size. Abundance: very dominant – >70%; dominant – 50–70%; frequent – 30–50%; common – 15–30%; few – 5–15%; very few – <5%; weak.: weakly; mod.: moderately; str.: strongly.</li>

Table 3. Summary of microscopic properties of investigated soil horizons (full micromorphological
 data are in Supplementary Materials). Frost related pedofeatures in *italics*.