Changes in high intensity precipitation on the Northern Apennines (Italy) as revealed by multidisciplinary data over the last 9000 years

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Abstract. Several record-breaking precipitation events have stricken the mountainous area of Emilia-Romagna Region (northern Apennines, Italy) over the last years. As consequence, several geomorphological processes, like widespread debris flows along the slopes and hyperconcentrated flood in the stream channels, shallow landslides and overbank flooding affected the territory, causing serious damages to man-made structures. The intensity and wide spatial scale of these phenomena ~~leads~~ led us to investigate their frequency in the past, beyond the instrumental time. A detailed study of ~~these~~ recent ~~deposits compared with~~ fossil peat bog and lake ~~paleo~~ deposits can provide useful insights to support a ~~strong~~ correlations ~~match~~ between precipitation intensity and warm climatic phases in antecedent climatic periods, as expected by the ~~increase~~ increasing air water vapour holding capacity at higher temperatures in the Northern Apennines

Here we present the results of ~~the~~ a field campaign performed in summer 2017 at Lake Moo a 0.15km^2 peat bog located at an altitude of 1130m a.s.l. The chosen area has been affected, during the flooding of the upper Trebbia and Nure valleys 13-14 September 2015, by several high-density flows generated by the stream that ~~flow~~ flows into the plain. Our main assumption is that, in such a small drainage basin (area <2 km^2), with favourable geologic and geomorphic characteristics implying advantageous sediment transfer into lake, high density flood can be triggered only by high intensity precipitation events (HIP) lasting enough time for water to infiltrate and mobilize large quantities of debris.

The sedimentary succession (ca. 13 m-thick) was studied through the ~~extraction~~ drilling of two cores and one trench. The ~~facies/paleoenvironmental interpretation of the~~ sedimentary succession, characterized by clusters of coarse-grained alluvial deposits interbedded with organic-rich silty clays and ~~peaty~~ peat layers, was ~~achieved~~ studied combining sedimentological and pollen data with pedological data and radiocarbon dating (AMS 14C).

Observed depositional cycles were ~~put in relation~~ correlated with other specific paleoclimatic proxies available in literature for the ~~North-~~ northern Apennines area. ~~This comparison illustrates that t~~ The increase of extreme paleo flood, (associated with coarse-grained deposits similar to the ones observed recently) correlates well with warm phases with a maximum activity during the Holocene thermal maximum and from the ~~small ice age~~ Little Ice Age to the present day.

Keywords
extreme precipitation, Holocene flood history, northern Apennines, climate change, water cycle, global warming

1. Introduction

The frequency of high intensity precipitation (HIP), also known as torrential rainstorm for their capacity to generate flash flood of small streams, is a key aspect of the water cycle of Mediterranean climate since a significant amount of annual precipitation is often concentrated in few major events (see for example Frei and Schär 1998 for the Alpine area). Therefore, the knowledge of the expected frequency (and their maximum intensity), in present and future climate, is a very important constraint for planning adequate hydraulic defences and water resources managing. In particular, on the northern Apennines, more than sixty percent of total precipitation of the year is concentrated in days with moderate to high-intensity precipitation (Isotta et al., 2014). Restricting the analysis to the Emilia-Romagna region (Northern-Italy; Fig. 1), over the last years there we have been observed an increase in interannual variability of torrential rainfall, with marked or even exceptional droughts such as those occurring in 2012 and 2017 (Grazzini et al., 2012), followed by years with record rainfall (2014 and 2018). Moreover, between September 2014 and September 2015, the region has been affected by three events of exceptional intensity, estimated to have return period of several centuries (Grazzini et al., 2016).

Under the threat of global warming, a growing number of studies are investigating the link between current temperature rise and precipitation intensity. A consistent increase in long-term trend of extreme daily precipitation has been already detected for the northern extratropics since 1980, although this is largely changing with the area of the globe considered (Lehmann et al . 2015, Papalexiou and Montanari 2019). On the Alpine domain Scherrer et al. (2016) found significant increases in daily extreme precipitation indices over Switzerland (1901-2014). Brugnara and Maugeri (2019), through the analysis of newly digitized data of the last 150 years across the whole Alpine area, found regional differences in the trend of the extremes suggesting that instrumental data are not covering a sufficient period of time to infer reliable changes in extreme events frequency. Although there is a consensus, based on physical arguments, that precipitation intensities are expected to increase with higher temperatures (see the review paper by Westra et al., 2014) limitations in moisture availability can prevent the potential for increased precipitation from being realized (Prein et al. 2017) explaining spatial and seasonal differences observed in the trends.

In this context, the stratigraphic record of current and fossil peat bogs and lakes can provide useful insights to verify/test the hypothesized strong linkage between precipitation intensity and warm phases during the present interglacial (i.e., Holocene). In literature there is ample documentation of the use of these sedimentary archives to reconstruct past flood events chronologies (Ahlborn et al., 2018; Anselmetti et al., 2014; Giguet-Covex et al., 2012; Gilli et al., 2013; Giraudi, 2014; Glur et al., 2013; Longman et al., 2017; Schillereff, 2014; Stoffel et al., 2016; Swierczynski et al., 2017; Wilhelm et al., 2018; Wirth, 2013; Wirth et al., 2013; Zavala and Pan, 2018; Zavala et al., 2006; Zavala et al., 2011), alongside others as tree rings (Ballesteros-Cánovas et al., 2015; Stoffel et al., 2013), speleothems (Regattieri et al., 2014; Zanchetta et al., 2011) and torrential fans and cones (Schneuwly-Bollschweiler et al., 2013).

Contrary to our hypothesis, some studies suggest a synchronization of high frequency of flood events with cooling periods. For example, Glur et al. (2013), presenting results from a multi-archive flood reconstruction based on sediments of ten Alpine lakes, found periods of high frequency of sediment deposition in concomitance with summer cool temperatures. However, those results needs a careful interpretation since lake sediments depositions are influenced by combination of factors which involves precipitation intensity, duration, seasonality, changes in atmospheric-circulation which might overshadow the physically based positive correlation between temperature increase and precipitation intensity (Utsumi et al., 2011; Brönnimann et al., 2018). Those caveats call for an even more multidisciplinary approach integrating paleoclimate (pollen), sedimentary archive information with climatological observations and physical arguments. In this study, we aim to fill this gap, extending and reinforcing observed trends with information from the past, beyond instrumental times, coherently derived from the same region during a specific field campaign.

The study area was chosen because, during the flash-flood of the upper Trebbia and Nure valleys 13-14 September 2015, it has been affected by several high-density floods generated by a small stream that flow into the plain. Our main assumption is that, in such a small drainage basin (area <2 km^2), which has favourable geologic and geomorphic characteristics to achieve substantial sediment transfer into lake (Schillereff, 2014), high magnitude flood events can be reconducted only to HIP, necessary to mobilize large quantities of debris (Milliman and Syvitski, 1992; Mulder and Syvitski, 1995; Mutti et al., 1996). In the Trebbia-Nure case, a detailed analysis of precipitation (Grazzini et al., 2016) over Lake Moo site microbasin showed that the observed debris flow occurred with a peak intensity of 112mm/3h. This is a very high value compared to shallow landslide and debris flow thresholds found find in literature for nearby areas, like the Apuane and Garfagnana regions (Giannecchini et al., 2012), which can be explained by the dense vegetation cover present now in the area. In addition, the absence of surrounding anthropic activities, the vicinity of the lake to the main Apennines crest, very exposed to maritime moist airflow coming from the central Mediterranean Sea, make this site particularly suitable for a detailed reconstruction of HIP events over the Holocene in terms of frequency, sedimentary expression and forcing factors.

Through the analysis of the data acquired in ~~on~~ the field ~~campaign~~, in this paper we want to address the following research questions:

a) Could we consider these recent events unprecedented over longer time-scales?

b) If yes, is the frequency of these events coupled with temperature variations?

The paper is organised as follows. The study area is presented in section 2 with a description of the basin, its morphology and vegetation. In sections 3 source of instrumental data and methods for collecting data in ~~during~~ the field~~s campaign~~ are described. In section 4 stratigraphic results ~~of the field campaign~~ are commented, while in section 5 we develop a full multidisciplinary discussion. ~~Finally, in section 6, conclusions are drawn~~.

2. The study area

2.1. Geographic and climatic context

The Lake Moo plain (44°37'29"N, 9°32'25"E) has a surface area of about 0.15Km^2. It is located near the boundary between Emilia-Romagna and Liguria regions (Piacenza province, Italy), in the upper ~~high~~ valley of the Nure stream at an ~~average~~ altitude of 1130m a.s.l. (Fig. 1). Nowadays, the catchment area of the Lago Moo is characterized by a dense forest cover (total woodland cover of ca. 65.55%; Corticelli et al., 2011), with high vegetational richness and an exceptional concentration of protected mountain species with a high phytogeographical interest. The widespread presence of the *Fagus sylvatica* is locally interrupted by grazing land areas and blueberry moorland with the presence of the rare *Juniperus nana* and *Sorbus chamaemespilus*. Reforestation of *Pinus nigra* is also present (Table 1 and Fig. 1).

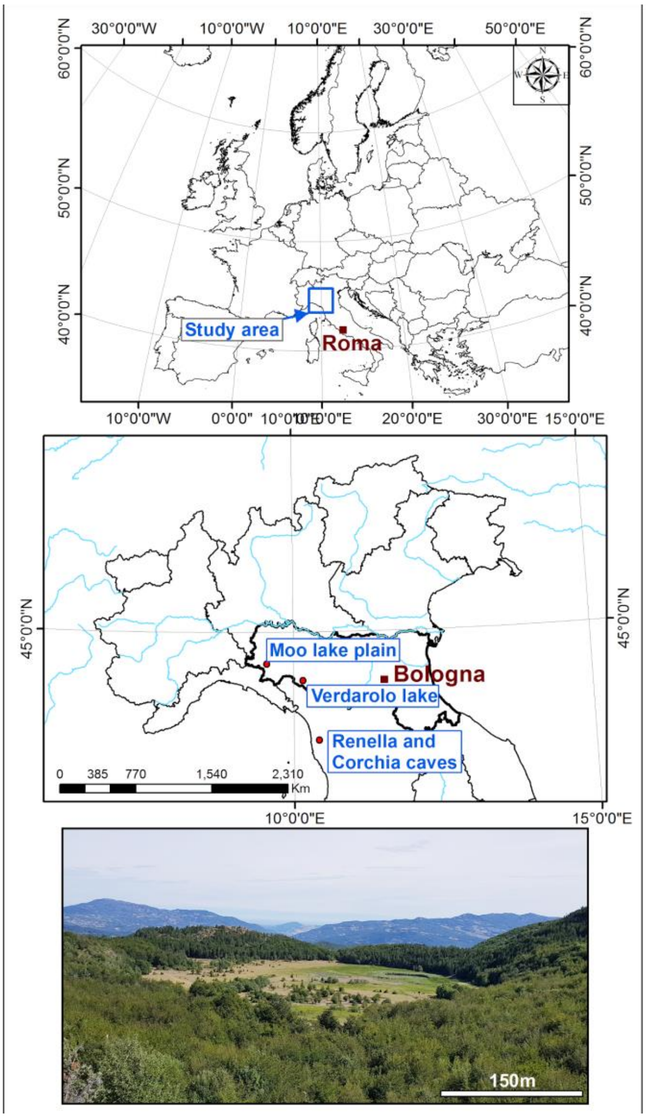

Figure 1. Location and photo of the Lake Moo site

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Tree type specie	Cover area (km^2)	Woodland cover (%)	Forest cover classification in the catchment area of Lago Moo
Fagus sylvatica forest	1.17	63.00	Moderately dense forest
Reforestation of *Pinus nigra* forest	0.02	1.00	Scrub
Mixed wood forest (*Pinus nigra*, *Fagus sylvatica* and *Carpinus* genus)	0.03	1.55	Scrub
Total	1.22	65.55	Moderately dense forest

Table 1 - Actual vegetation cover of Lake Moo area deducted by Corticelli et al., 2011

The climate of the area is characterised by the altitude and the mountain range, with enhanced humidity given the short distance to the Tyrrhenian Sea (Nistor, 2016). The months with the largest amount of precipitation are in the ~~transition seasons~~ (Spring and Autumn~~)~~, with a predominant peak in early autumn (see Fig. 9). HIP conditions are very favourable in Autumn months due to a particular synergy of higher frequency of synoptic disturbances and mesoscale convective systems which could still develop in high thermodynamic unstable environment (Grazzini et al., 2019).

2.2. Geological and geomorphological setting

The study area consists mainly of ~~strongly serpentinized ultramafites~~ serpentinites extensively fractured and representing the accreted fragments of original oceanic crust of the Ligure-Piemontese basin, developed in the Middle to Upper Jurassic, which separated the Europe plate from the Adria plate (Marroni et al., 2010). Due to the compositional heterogeneity of its vertical sequence, the ultramafic medium is made of lithological units, tectonically overlapped. The ultramafites are bordered ~~by deposits which are predominantly characterized~~ by polygenic breccias (Casanova complex, early Campanian ~~age~~, Vescovi, 2002), made of blocks of limestones or marly limestones ~~immersed~~ embedded in a fine-grained matrix or a mineral cement.

The morphology of the area includes flat areas and steep slopes at different altitude that some authors (Elter et al., 1997; Marchetti and Fraccia, 1988; Carton and Panizza, 1988) ~~interpret as originated from the phase of last glacial retreat~~ interpreted as glacial in origin. On these morphological flat areas, marsh deposits have developed originated from the filling of small glacial lakes some of which still exist as the Lago Moo plain and Bino lake. Other authors such as the Geological, Seismic and Soil Service of the Emilia-Romagna Region - Inventory Map of landslides at 1:10000 scale of the Emilia-Romagna Region (available at: http://ambiente.regione.emilia-romagna.it/geologia/temi/ dyseste-hydrogeological/the-paper-inventory-of-landslides, 2019) have interpreted the Moo lake plain as ~~the product of gravitational processes that affect the entire slope area~~ counterslopes of deep-seated gravity failures (available at: http://ambiente.regione.emilia-romagna.it/geologia/temi/ disruption-hydrogeological / the-paper-inventory-of-landslides, 2019). From this point of view, the main factor controlling the morphological evolution of the area of Lake Moo, is the river incision produced by the Nure stream during the Holocene (Gunderson et al., 2014 is incision triggered the development of gravitational phenomena on the slopes. These complex morphological features of the area is also influenced by the presence of lithological elements with a strong mechanical contrast such as ophiolites ~~superimposed on~~ overlying a predominantly clayey substrate (Elter et al., 1997).

3. Data and methods

3.1 Field investigation

The selection of the study site has been obtained following criteria indicated by Gilli et al. (2013) and Schillereff et al. (2014). In this respect, the Lake Moo site presents several advantageous characteristics to the archiving of paleo flood deposits:

- Steep relief (average inclination of 24°) with slopes composed of poligenic and monogetic braccias in clay matrix, highly susceptible to erosion (Monte Ragola Complex, Elter et al., 1997) ~~are present~~;
- No lakes upstream in catchment;
- Small drainage basin area (1.94 km^2);
- One dominant inflow into the lake;
- Absence of regulated flow structures;
- Absence of natural pre-lake sediment storage zones.

The field campaign led to the acquisition of two sedimentary cores (S1 and S2) and one trench, investigating the sedimentary succession capped by the flood deposit formed during the last HIP event (14 September 2015). The location of the cores and trench was planned on the basis of a high-resolution reflection seismic survey (Fig. SUP1 of the supplementary material) and a detailed geomorphological map, both of them originally produced for this purpose (Fig. 2). The former provided information on the lake basin floor morphology and the thickness of the infilling succession.

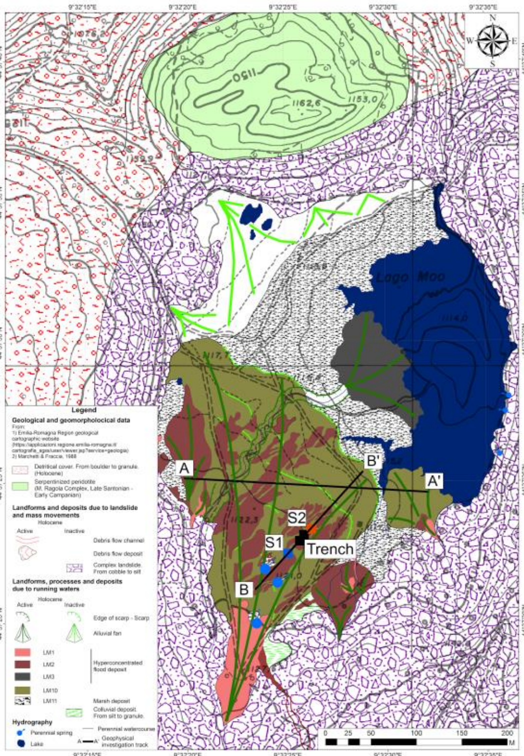

Figure 2. Location of the geognostic investigations, geophysical surveys tracks, and detailed geomorphological mapping of the flood deposit occurs between 13 and 14 September 2015 (upper Trebbia and Nure valleys, province of Piacenza, Italy). *See a larger version of this figure at the end of the manuscript*

The two cores S1 and S2, 14 and 6 meters long respectively, were ~~performed~~ drilled through a continuous ~~perforating~~ drilling system, which guaranteed an undisturbed core stratigraphy and a high recovery percentage (S1 90% and S2 91%). The trench, carried out in between the two cores, reached the depth of 2 meters, the length of 6 meters and the width of 6 meters. The subsurface succession was stratigraphically analysed, and the longest core (S1) was selected as reference and sampled for grain size, radiocarbon and palynological analysis.

3.2 Facies analysis and chronology

A facies characterization of the sedimentary succession has been performed on basis of the observable macroscopic physical characteristics (i.e., grain size, sedimentary structures, Munsell chart colour and types of bounding surfaces), and granulometric data, the latter available for the reference core S1.

Relatively to the different coarse-grained levels recognized, we follow the facies tract concept. A facies tract here means all facies observed within the same deposits relative of the same flood undergoing transformations along its down-slope motion (Lowe, 1982; Mutti, 1992; Mutti et al., 1996). The facies tract approach is important because it allows to recognize the following important information like:

1) the position in the facies tract with respect to the whole fluvial-hyperpycnal system;
2) relative flood event magnitude;
3) expected related facies types in more proximal and distal areas.

The abundance of wood remains and peat levels in the sedimentary cores allowed ^{14}C radiocarbon twelve samples that were analysed at the CEDAD Laboratory of the University of Salento (Province of Puglia, Italy). The data are collected in Table TS2 of the supplementary material. The ^{14}C ages were converted into calendar years using the OxCal version 3.10 software (Reimer et al., 2013).

3.3 Temperature reconstruction and modern climatological dataset

Central to our analysis is the availability of a reliable temperature reconstruction for the chronological period explored through the coring. In this respect the chironomid analysis of the nearby Lake Verdarolo conducted by Samartin et al. (2017), represent a unique opportunity. Lake Verdarolo site is located at 1390m a.s.l., 270m higher and 54km south from Lake Moo (Fig. 1), in a very similar climatic context. They reconstructed the mean July air temperature using a chironomid-based inferenced model developed from a combination of data of over 200 lakes from Norway and Swiss Alps (Heiri et al., 2011). This represent the first vegetation independent holocenic temperature reconstruction of the Northern Apennine.

Modern temperature and precipitation time series (1961-2018) of Lago Verdarolo and Lake Moo are derived from the gridded high-resolution dataset of Emilia-Romagna (Eraclito4), described in Antolini et al. (2016). Trend estimation and Mann Kendall significance trend test are computed with the pyMannKendall package (Hussain et al., 2019).

3.4 Pollen analysis

Palynological analyses were carried out on 14 samples collected from core S1 to refine facies characterization of fine-grained deposits and obtain vegetation-derived paleoclimate data (Fig. 3). After the radiocarbon dating, a further choice was made using only 11 samples falling into two stratigraphic intervals of our interest: the first one (I_1), covering 10.77m to 9.33m depth and with temporal resolution 7300 - 9600 cal yr BP centred on the Holocene Thermal Maximum (HTM), the second one (I_2) from 5.48m to 4.55 depth and corresponding to the exit of HTM (3900 - 5500 cal yr BP). In these two stratigraphic intervals, the mean sampling resolution is 28cm. The choice of these two periods ensure a significant thermal/climatic separation and at the same time the samples were taken from predominantly lacustrine fine layers where the stratigraphic series shows characteristics of continuity of sedimentation.

Identification of the pollen grains was performed at 1000 light microscope magnification and based on the atlases and a vast amount of specific morpho-palynological bibliography stored at the CAA Laboratory (S. Giovanni in Persiceto, Italy). Names of the families, genus and species of plants conform to the classifications of Italian Flora proposal by Pignatti (2017-2019) and European Flora (Tutin et al., 1964-1993). The pollen terminology is based on Berglund and Ralska-Jasiewiczowa (1986), Faegri and Iversen (1989) and Moore et al. (1991) with slight modifications that tend to simplify nomenclature of plants. The term “taxa” is used in a broad sense to indicate both the systematic categories and the pollen morphological types (Beug 2004). Identified pollen groups (between 300 and 400 pollen grains) have been expressed as percentages of the total (usually between 300 and 400 pollen grains). Pollen percentages are computed on the basis of the total pollen sum. All samples are characterized by fairly high concentration, ranging from 1,072 -30,659 p/g, and good conservation status. The discreet pollen biodiversity (60 pollen types: 22 woody, 32 herbaceous and 6 Monolophyta) found, suggests that flood deposits formed in a rich vegetal environment, with high floristic biodiversity. Pollen groups are defined on the basis of common biological characteristics of the plants, useful to reconstruct vegetation dynamics due to climate fluctuations. In particular groups composition are described in Fig. 10.

4. Results

4.1 Stratigraphical data and their geological context

4.1.1 Sedimentary facies

The stratigraphic distribution in the core profiles and the synthetically description facies are shown in Fig. 3. Thirteen different facies types have been identified and named from LM1 to LM13:

- LM1 to LM2 Clast-supported deposit with thickness ranging from 5 to 15 cm. Extremely coarse (LM1) to medium pebbles (LM2) with abundant coarse to fine grained sand sandstone matrix, showing a low degree of sorting. Polygenic clasts have low sphericity and very angular shape. Occasional fragments of wood;
- LM3 Massive matrix-supported deposit composed of medium pebbles to granules with very fine sand to silt matrix. Polygenic clasts have low sphericity and subangular shape. Sharp basal and top contacts with evidence of occasionally erosion along the basal one. Presence of fragments of wood;
- LM4 to LM6 General clast-supported, poorly sorted deposit with thickness ranging from 10 to 30 cm. Polygenic clasts, massive or crudely graded angular\subangular medium pebbles to very fine granules. Crudely horizontal laminae at the top. Sharp basal and top contacts with evidence of occasionally erosion along the basal one. Occasional fragments of wood at the base of the layers;
- LM7 to LM9 Massive or crudely graded, poorly sorted very coarse to fine sands 5-20 cm thick. The top part of the detrital layer consists of the finest particles with planar lamination. Sharp basal and top contacts. Occasional fragments of wood at the top of the layers;
- LM10 Sandy loam to clayey loam. Presence of polygenic fine to medium pebbles aligned with low sphericity and very angular shape. Dark greyish brown colour (10YR 4/2 or 10YR 3/2). Sharp basal and top contacts;
- LM11 Peat layer and organic rich clay layers. Fine to medium pebbles aligned with low sphericity and very angular shape. Dark colour (10YR 3/1);
- LM12 Massive clayey silts with rare organic matter. Occasional polygenic clasts (fine pebbles) have low sphericity and very angular shape. Sharp basal and top boundaries. Dark greenish grey colour (5G 4\1);
- LM13 Loam to silty clay texture, strong coarse angular blocky, dark olive grey dry colour (5Y3/2) with yellowish brown redox concentrations (10YR5/6), no carbonate, field pH 5.5.

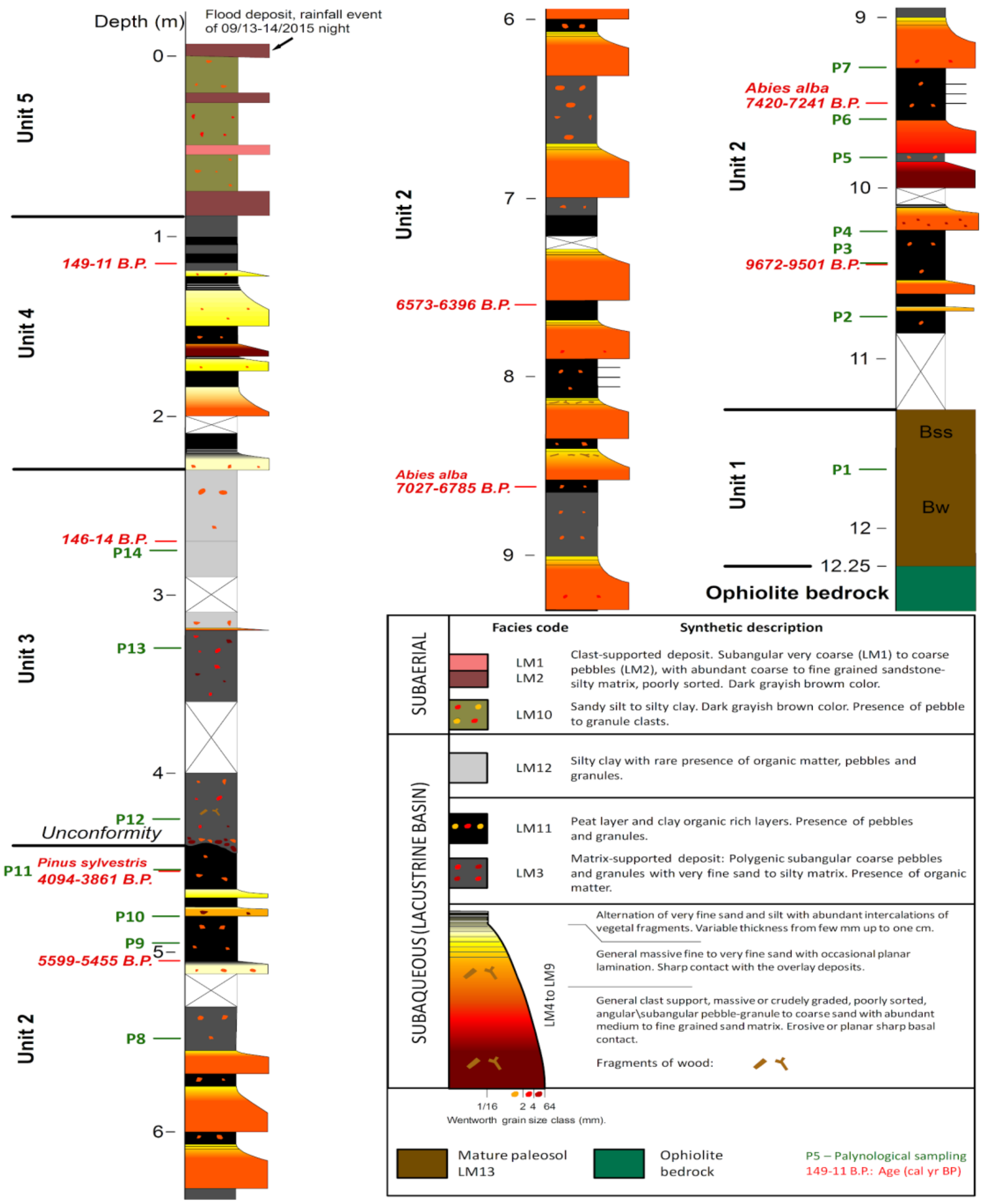

Figure 3. Sediment core description (see legend) and radiocarbon dates. *See a larger version of this figure at the end of the manuscript*

Relatively to the Lake Moo site, the different coarse-grained facies from LM1 to LM9 have been interpreted as the extreme flood events triggered only by high-intensity convective rainfall events in the catchment area that flow into the Lake Moo as hyperpycnal flow. Our main assumption is that, with favourable sediment transfer into lake and small catchment area (<2km^2), high density flood can be triggered only by HIP due to erosion of material from the drainage system network (Milliman and Syvitski, 1992; Mulder and Syvitski, 1995; Mutti et al., 1996). The facies from LM1 to LM9 were grouped according to the genetic approach and therefore on the basis of facies tract concept as described in Fig. 4 (Lowe, 1982; Mutti, 1992; Mutti et al., 1996).

Fine-grained facies, from LM10 to LM13, are subdivided into two groups. In the first group belong the facies LM11 and LM12, expression of environment shore zone and subaqueous lacustrine deposits respectively. The second group includes the facies LM10 and LM13, expression of subaerial deposits.

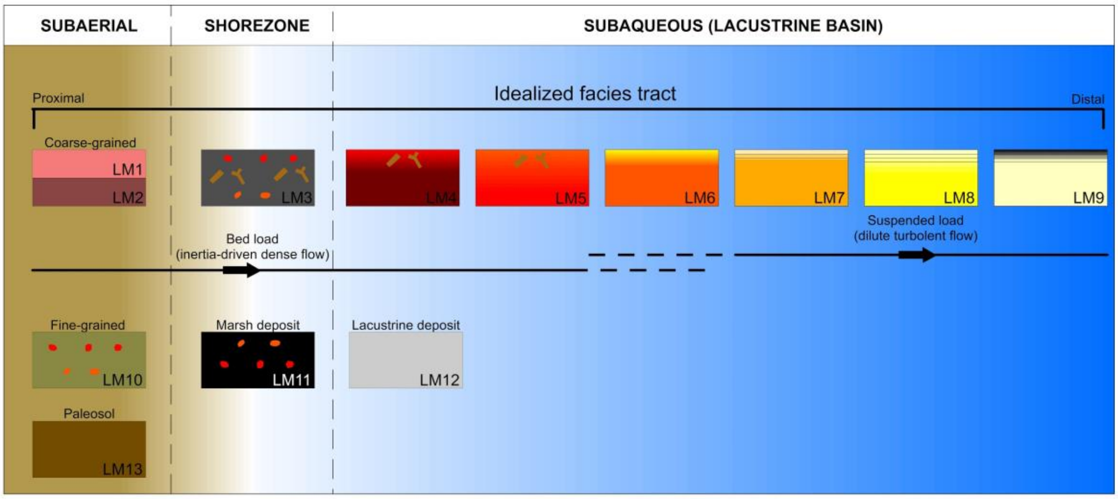

Figure 4. Idealized genetic facies tract interpretation of clastic deposits associated with S1 core.

4.1.2 Stratigraphic units

The sedimentary succession of the reference core S1 is subdivided into five informal units, described below from the bottom to the top (Fig. 3):

Unit 1: This unit, 95 cm-thick, is represented only by the LM13 facies. Two levels can be distinguished: from 11.30 m to 11.60 m core depth is present a slickensides horizon (Bss), while from 11.60 m to 12.00 m core depth is present a weathered horizon (Bw). This unit is interpreted as a mature paleo soil, likely developed on a colluvium forming the base of a structural depression;

Unit 2: This unit is 6.9 m thick and ranging from 11.30 m to 4.4 m core depth, and is characterized by the presence of several layers of coarse sediments (LM3) separated by deposits with a predominantly fine composition (LM11). The thickness of coarse layers, belonging to facies LM4-LM6 ranges from 10 cm to 30 cm. To the top of the succession and if age dating is reliable, the unit is closed by an unconformity surface recording a important time gap. The same surface is the base of a lacustrine transgression which make up the unit 3;

Unit 3: This unit is thick 2.1 m and ranging from 4.4 m to 2.3 m of depth. Sharp basal and top boundaries. The basal portion of this unit (from 4.4 m to 3.2 m of depth) present matrix-supported deposit with several fragments of wood which we attribute to the shore zone environment. Only this portion of core show a characteristic mottledling-like appearance. From the 3.2 m of depth follows a lacustrine deposit that closed the unit. This unit is characterized by a period of apparent inactivity of the fluvial system, until its reactivation documented in the uppermost part of the core (unit 4 and 5).

Unit 4: This unit is thick 1.4m and ranging from 2.3m to 0.9m of depth and registers the return of several coarse-grained levels which are in general less thick and less coarse than those present in unit 2. These levels are prevalent separated by marsh deposits. Sharp basal and top unit contacts.

Unit 5: This unit is thick 0.9m, ranging from 0.9m of depth to land surface and records the disappearance of lake deposits replaced by fluvial ones through an erosional contact. The flood deposits produced by the rainfall event of September 13th and 14th 2015 closes the sequence (Fig. 5).

Figure 5. Though the exposure is quite small, these graded pebble-sand couplets could be interpreted as a sheet-flood deposit (Unit 5).

As a whole, we interpret the local lacustrine succession (units 1, 2, 3 and 4) is like to the infill of a structural depression produced by gravitational block sliding that was induced by post-glacial fluvial incision (Gunderson et al., 2014).

4.2 Age-depth model

The age model for the S1 core is based on eight ^{14}C dates (Fig. 6). Coarse levels are removed from the sediment record when constructing the age-depth model because represent instantaneous deposits. The 27 deposits interpreted as instantaneous events representing a total of 374.5 cm were removed, the remaining were used to build an event-free sedimentary record.

Four radiocarbon dates were rejected: one (LTL18275Abis code) because it was not possible to date the sample for poor presence of organic matter, the others (LTL18275A, LTL18575A and LTL18272A codes) because it was not possible to identify a calibrate age.

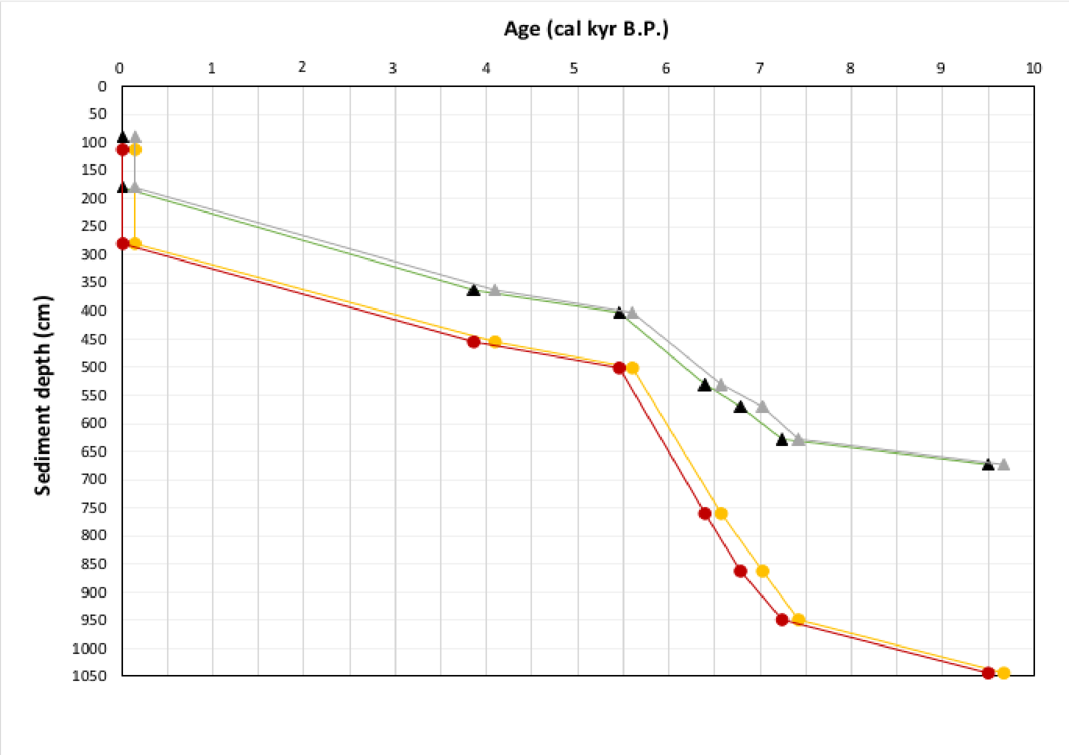

Figure 6. Age-depth model obtained from radiocarbon dates. Black and grey line represents the two-sigma probability envelope depth without coarse grained events. Red and orange line represents the two-sigma probability envelope depth with coarse grained events.

5. Discussion

Figure 7 shows the stratigraphic succession of the S1 core compared with the most relevant climate proxy available from literature for the area of interest. These includes: reconstructed mean July air temperature from Lago Verdarolo (from Samartin et al., 2017), $\delta^{18}O$ speleothem records and reconstructed precipitation trends (mean anomaly time series) from Renella cave (data modified from Combourieu et al., 2013; Regattieri et al., 2014; Zanchetta et al., 2011; Zhornyak et al., 2011), distribution of the higher lake levels event reconstructed in Jura and Pre Alpine mountains (modified from Magny, 2004), and June (red) - December (blue) insolation values records reported for 45° Nord

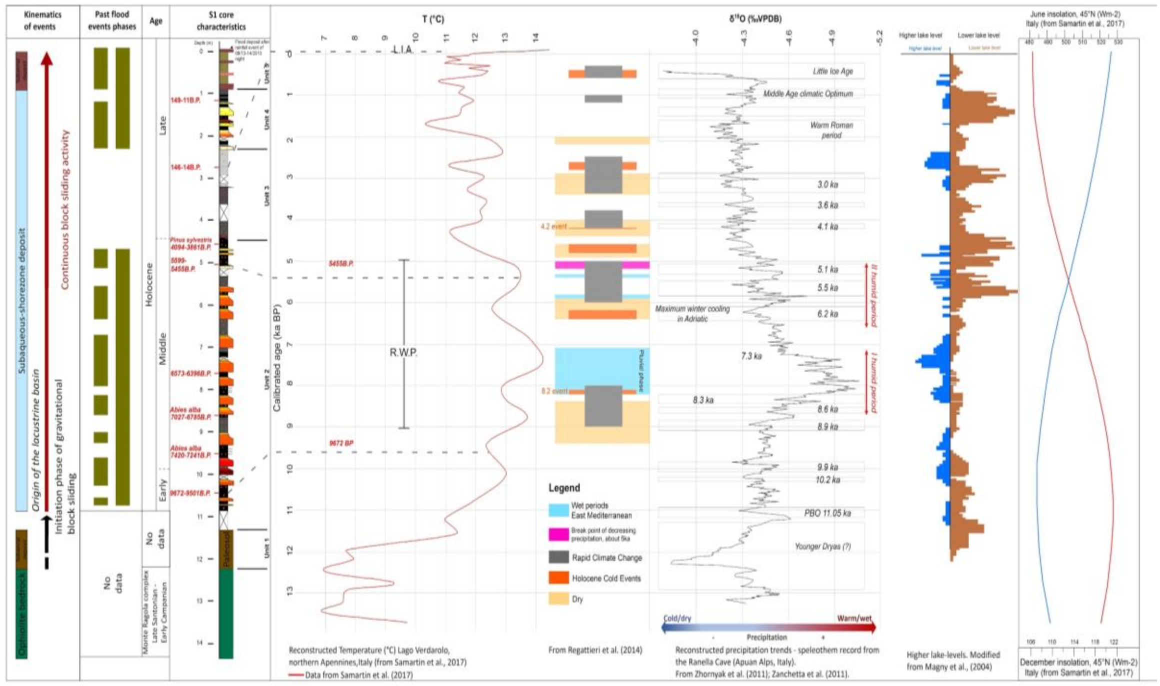

Figure 7. The stratigraphic succession of the S1 core compared with the most relevant climate proxy available from literature for the area of interest. *See a larger version of this figure at the end of the manuscript*

The lake Moo stratigraphic sequence (Fig. 3) is showing the presence of several coarse grained layers separated by deposit with a predominantly fine composition. These coarse levels are particularly developed within unit 2 (between 5 and 10.5m in depth) and correspond chronologically to range of the HTM of the Verdarolo curve and with the wet/high intensity phase reported at the nearby Renella and Corchia Cave (Fig. 7, Unit 2). Zhornyak et al. (2011) attributed this high fluvial activity, which reached levels of the caves flooded only during extreme events, to an increase of strong convective events like the one that affected the region in 1996. Other authors confirm, through model simulations, higher precipitation accumulations during HTM over the Mediterranean area, especially at end of summer/autumn seasons. This has been linked with a greater expansion of the African Monsoon which contributed to enrich of water vapour air masses extracted from north-Africa by mid-latitude synoptic disturbances (Skinner and Poulsen, 2016 and Tinner et al., 2013 in their Climatic simulations section, Fig. 4). With the end of the HTM a drastic decrease of the coarse deposit levels is observed which we are assuming attributed to a decrease in frequency of HIP. In particular, the transition between unit 2 and 3 is marked by an important unconformity contact. This unconformity is followed by deposits of shorezone environment and subsequently at the top of unit 3 by lacustrine deposits. The top of the unit 3 sequence has a calibrated age that is approximately 146-14 BP and is characterized by a period of apparent inactivity of the fluvial system, until its reactivation documented in the units 4 and 5 due to hypothesized new increase of HIP in recent times. The uppermost part of the unit 4 has an age of about 149-11BP. Finally, the disappearance of lake deposits replaced by fluvial ones through an erosional contact is marked by unit 5.

From this first qualitative comparison we can affirm that there is a positive correlation (at the millennial scale) between temperatures and precipitation peak deducted from nearby speleothem records and the level of alpine lakes. This confirms findings from other authors (for example Marcott et al. 2013, Giguet-Covex et al., 2012), which are associating greater warmth (in the northern hemisphere) with periods of more intense precipitation.

Instrumental data, available since the second half of the last century from the Eraclito ER dataset, has been added to the Verdarolo curve to allow a comparison between geological time and recent instrumental data. The overlap with the latest part of Verdarolo reconstructed curve suggests a good accuracy of the reconstruction technique in this region (Fig. 8). The recent temperature increase is striking if compared with the previous period, and the current July temperature is comparable with the maximum temperature reached at HTM over this area. The actual trend of July temperature, estimated over the period 1961-2018, is +4.3°C in 100 years. This value is highly statistically significant, with a p-value=0.0004 (see section 3.3 for a description of the method and significance). The recent trend is more than double of the maximum temperature gradient found in the Verdarolo curve, +2°C/100y, ~~found, for a short period of time,~~ at end of the Little Ice Age 1850-1900. While the maximum positive temperature gradient found at the end of Younger Dryas age is about +1°C/100y. Is therefore clear that summer (July) temperature is increasing very rapidly, with an unprecedented rate in the whole Holocene. Such a large difference in increase rate can hardly be explained by the lower frequency sampling of the Verdarolo reconstructed curve although uncertainty in comparison instrumental data with reconstructed temperature data has been discussed before (Marcott et al. 2013).

This rise of temperature is associated also with a comparable unprecedented intensification of fluvial deposition, testified in the core, by the deposition of units 4 and 5, which marks the transition (in a short time) from marshy to fluvial sheet-flood deposits (Fig. 5). In fact, the recent sedimentation rate (computed from the core S1) is 1.27m/100y since 1850, that is 10 times higher than HTM (0.124 m/100y from 5455-9672 BP). In particular, whether the lower or upper end of the 2 sigma confidence level associated with the dating at 280cm depth (146-14 B.P.) is considered, the frequency of the coarse grained deposits (Unit 4 and 5 in figure kk), triggered hence by HIP, varies from a minimum of 5 events every 100 years to a maximum of 12 events every 100 years, respectively. This observation reinforces the trend of increasing precipitation intensity (both as daily maximum and as monthly cumulative values) that is already emerging in the autumn months from the instrumental data as shown in Fig. 9.

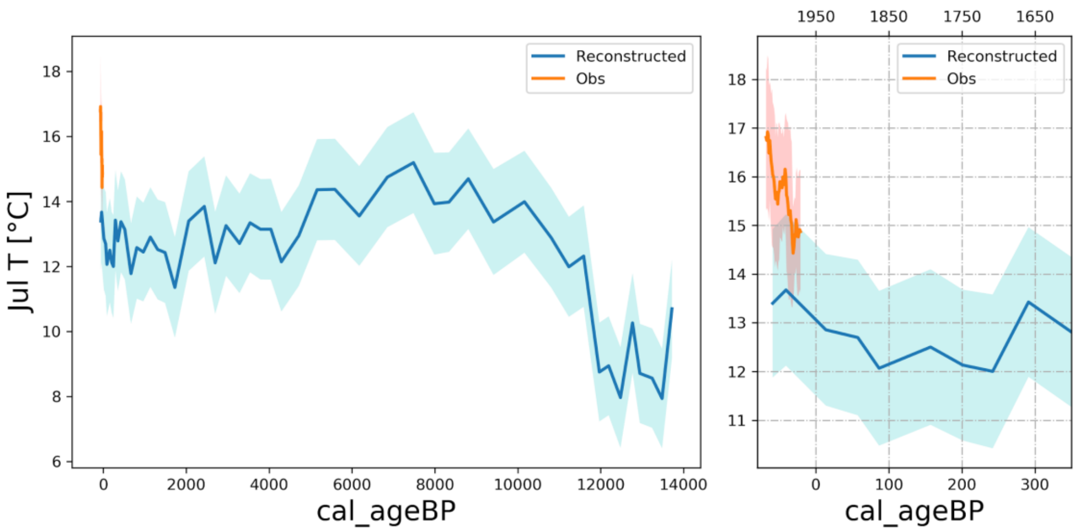

Figure 8. Comparison of current data and reconstructed July mean temperature at Lake Verdarolo site. The blue line is the reconstructed temperature and the shaded area is the sample-specific estimated standard error associated with the temperature reconstruction based on chironomid assemblage from Samartin et al. (2017). The orange line represent the July mean temperature (1961-2018) retrieved for the grid cell of Lago Verdarolo from Emilia-Romagna climate reanalysis ERACLITO (11 years running average). The shaded orange area is +/- one standard deviation. On the left the full available period while on the right a zoom on the most recent period from 1600 AD up to now.

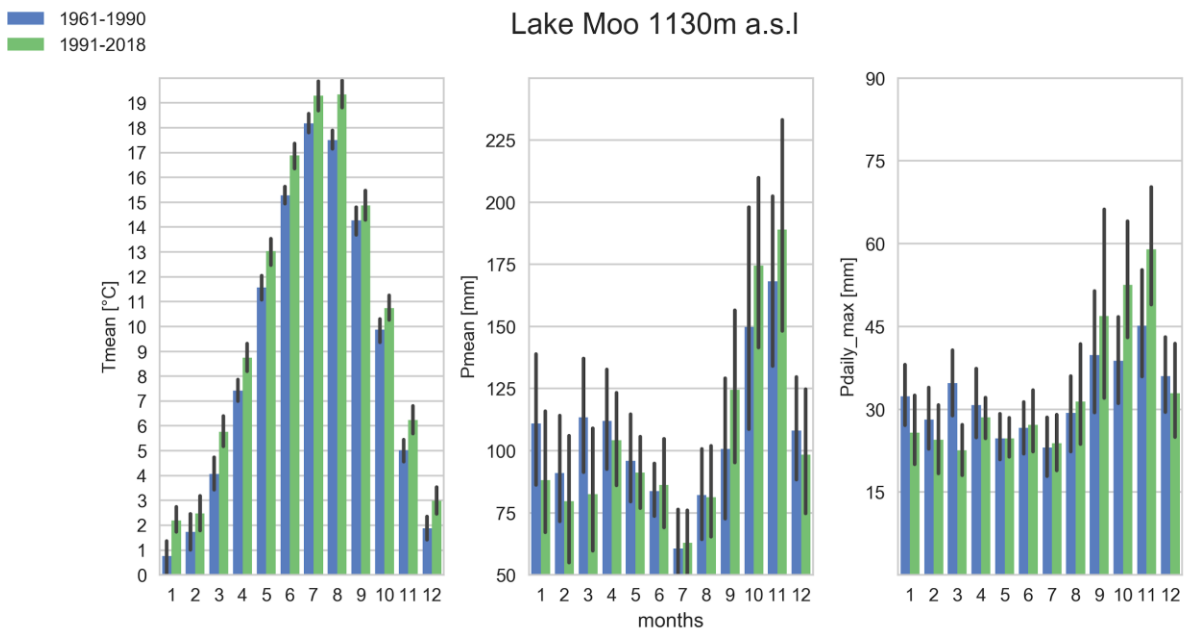

Figure 9. Monthly mean, 2m temperature (a), accumulated precipitation (b), maximum daily precipitation (c), for 1961-1990 (blue) and 1991-2018 (green) computed over Lake Moo site grid cell of Eraclito reanalysis (grid cell 258, Ferriere Municipality). Confidence intervals at 95% significance (black vertical segments) are computed with a bootstrapping method (1000 iterations) as part of the Seaborn python library.

5.1 Detailed comparison on two key intervals of the Holocene

In this section, we introduce the pollen data to fully exploit the multidisciplinary approach. As discussed in section 3.4, we focus on two specific intervals, I_1 and I_2, synthesizing all available data for these periods in Fig. 10. The difference in mean temperature between I_1 and I_2, obtained averaging the corresponding samples in the reconstructed temperature curve from Verdarolo site, is +1.3°C while the maximum difference reach +3.1°C.

The main considerations arising from this comparison are the following:

- I_1) the arboreal component is always higher than the herbaceous one, with an average value of 80.1%. The presence of conifers with a prevalence of pines and silver fir is significant compared to deciduous hardwoods. Conifers reach a maximum of 95% in P4 sample. The peak occurs during a relative cooling, just before the 8.2 literature event, in accordance with the bibliography (Allen et al., 2007; Kofler et al., 2005; Matero et al., 2017; Tinner and Lotter, 2001). Subsequently, samples P5 and P6 (HTM) show a decrease in the presence of conifers, respectively 64% and 45%, with a corresponding increase in deciduous species, from 1.5% in P4 to 20% in P5 and P6. This occur in response to warme[illegible]ditions and pluvial phase, as indicated by Regatieri et al., 2014; Zhornyak et al., 2011; Zanchetta et al., 2011. It should also be noted the absence of species typical of umid stand environment (hygro+hydro in Fig.10), which suggests a high stationing of the lake-level. This confirms higher rainfall accumulation in the period, in accordance with lake-level evidence from Jura Mountains and the central-northern Italy Magny et al. (2004, 2009, 2012). In P7 sample, we observe a new increase in conifers (75%) and a consequent reduction in deciduous trees (10%). These results, combined with the stratigraphic interpretation of the S1 core, suggest that pluvial phase, in this period, had been characterized by a high component of HIP. This can be deduced from the characteristics of the basin and the presence of an extensive vegetation cover which implies the need of even more intense rainfall to able to trigger high flood activity (as recorded in this interval) in a dense vegetated area, with forest coverage that ranges from 65 to 97%. thickness of coarse grained layers range from 30 and 13 cm with pebble-sands, crudely graded characterised by basal and top sharp contact. These coarse grained deposits are expressing of proximal facies (LM4 to LM6, in Fig. 10).

- I_2 instead is characterized by LM7 to LM8 distal facies from hyperpycnal flows, as a result of a low flood activity. The ~~thickness~~ layers do not exceed 5 cm and they are medium-fine sands. From a bibliographic point of view, this time interval is characterized by a cooling trend and dry conditions over the Mediterranean region occurred approximately between 4.2 - 3.9 ka BP (Regatieri et al., 2014; Zhornyak et al., 2011; Zanchetta et al., 2011, 2016), recently confirmed by a review paper of Bini et al. (2019). Further supporting these evidences low pluvial activity, pollen samples highlight a significant reduction of forest, whose coverage falls to a minimum of 30% (in P10 sample), in favour of a growth of grassland area (with maximum extension of 31% in P10) and hygro+hydro species (13.2%).

The increase of hygrophilous species, which double their presence, supports the hypothesis of reduction of the lake level, due to colonization of swampy areas which were forming as the lake level drop. Although the conditions in I_2 interval are favourable for the activation of hyperconcentrated flows (due to the lower vegetation cover), the low flood activity observed suggests a low frequency of HIP events.

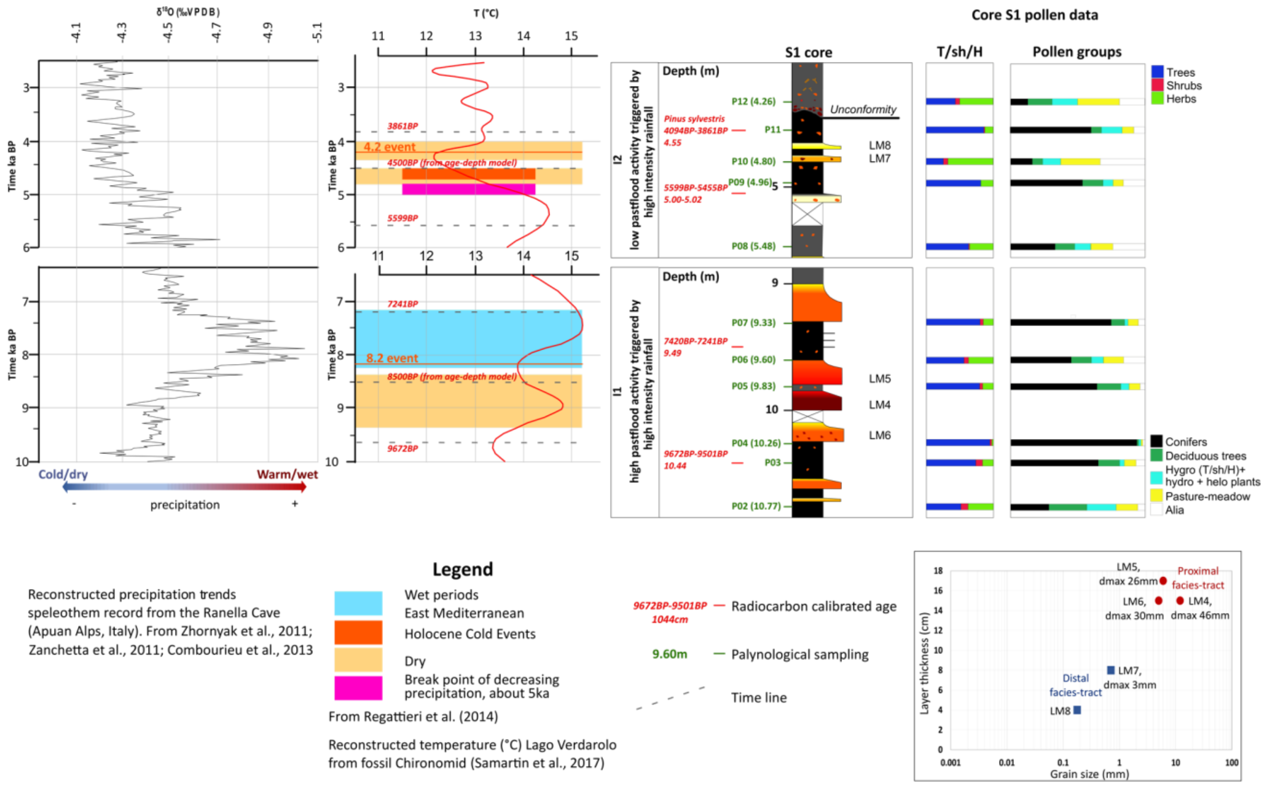

Figura 10. The stratigraphic intervals I_1 and I_2 from S1 core compared with the original pollinic data and the relevant climate proxy available from literature for the area of interest. *See a larger version of this figure at the end of the manuscript*

6. Conclusions

Placing present climate conditions into a geological perspective time, beyond instrumental record, is important for understanding changes in the hydrological cycle induced by anthropogenic climate warming, complementing projections of model climate simulations. Physical reasons and regional climate reconstructions are consistently pointing to an increase of precipitation intensity when water vapour is not limited (Prein et al., 2017). In the last decade record-breaking rainfall events have occurred frequently around the world, this trend is emerging with different strength in different area, and often, on the short timescale of the instrumental series, doesn't allow yet to draw firm conclusion. Therefore, in the attempt to consolidate confidence about extreme precipitation trend, we extended our analysis, passing from the instrumental time scale to the geological time. This choice implies a strong multidisciplinary approach which includes, in addition to climate and meteorological data, proxy and competences coming from geological, geomorphological, stratigraphical, paleobotanical area. We acquired original data during a field survey the months of June and July 2017.

Here we can summarize the principal results:

1) The matching of instrumental temperature data and the paleoenvironmental data allow us to affirm that recent temperature trends (over the period 1961-2018), and in particular those of the summer months (July), are in absolute terms the highest ever recorded in the Northern Apennines with an estimated gradient of +4.3°C/100y (highly statistically significant), which is four time higher than the maximum recorded at the exit of last ice age (Younger Dryas).

2) The recent sedimentation rate (1.27m/100y since 1850) is 10 times higher than that observed during the HTM (0.124 m/100y from 5455-9672 BP) and therefore higher the previous warmer period. The observed sedimentation increase, and higher frequency of high flow discharge has to be linked to an increase of HIP over the Lake Moo basin since we could not attribute it to other changes in physiographic and vegetation factors. The ~~afforestation~~ forested area for example, during HTM and in current time persisted on high percentage, a factor which should be detrimental for the mobilization of debris.

3) HIP increase in response to higher temperature is already detectable in observation series, especially in seasons when moisture availability is not limited, like in Autumn (Brönnimann et al., 2018; Prein et al., 2017). We found evidences that this occurred also in the past, especially during HTM testified by higher deposition of large size sediment in to the lake. A comparison with the past help understanding future projections on the area, although we are aware that past evolution cannot be taken as an analogous for future due to the different forcing and consequent response of climate system (D'Agostino et al. 2019). As temperature will continue to increase on the Mediterranean area precipitation intensity would keep increasing over the Northern Apennines. We hypothesize that precipitation intensity increase will be evident in months with cooler and moist air masses, like in Autumn as it already emerging (see Fig.9), but gradually extending towards Winter. In summer, increasing conditions of moisture limitations will induce a decrease in frequency and intensity of precipitation (Dobrinski et al. 2016a and 2016b)

4) The concept of facies tract (Lowe, 1982; Mutti et al., 1996; Zavala and Pan, 2018) applied here, may represent an important approach for activity flood reconstruction dynamics and may be applied to other peat-bog deposits to further strengthen and regionalize the signal.

Lake Moo site, in the Northern Apennine, was chosen for its strategic geographical position with respect to the dominant atmospheric flow associated with heavy precipitation events. In addition to this, the site has the right geological, geomorphological, vegetation characteristics, basin size (< 2 km^2), to achieve a strong and clear response between high intensity precipitation and debris flow triggering. For these reasons, Lake Moo basin represents an ideal study area which deserves further investigation on the relation between past climatic conditions and the dynamics of past flood.

Data availability: Original data concerning pollen and radiometric data are available on the open data repository of ARPAE Emilia-Romagna (*https://arpaeprv.datamb.it/dataset/lake-moo*)

Author contribution: SS and FG developed the idea and the research activity planning and execution. SN, MA, MTDN have taken care of the administrative aspects. All authors, except for SN and MTDN, have contributed to field activity. Granulometric analysis has been conducted by AC. Pollen analysis have been conducted by VR, SM and MM. SS and FG prepared the manuscript with contributions from all co-authors. FG management and coordination.

Competing interests: The authors declare that they have no conflict of interest.

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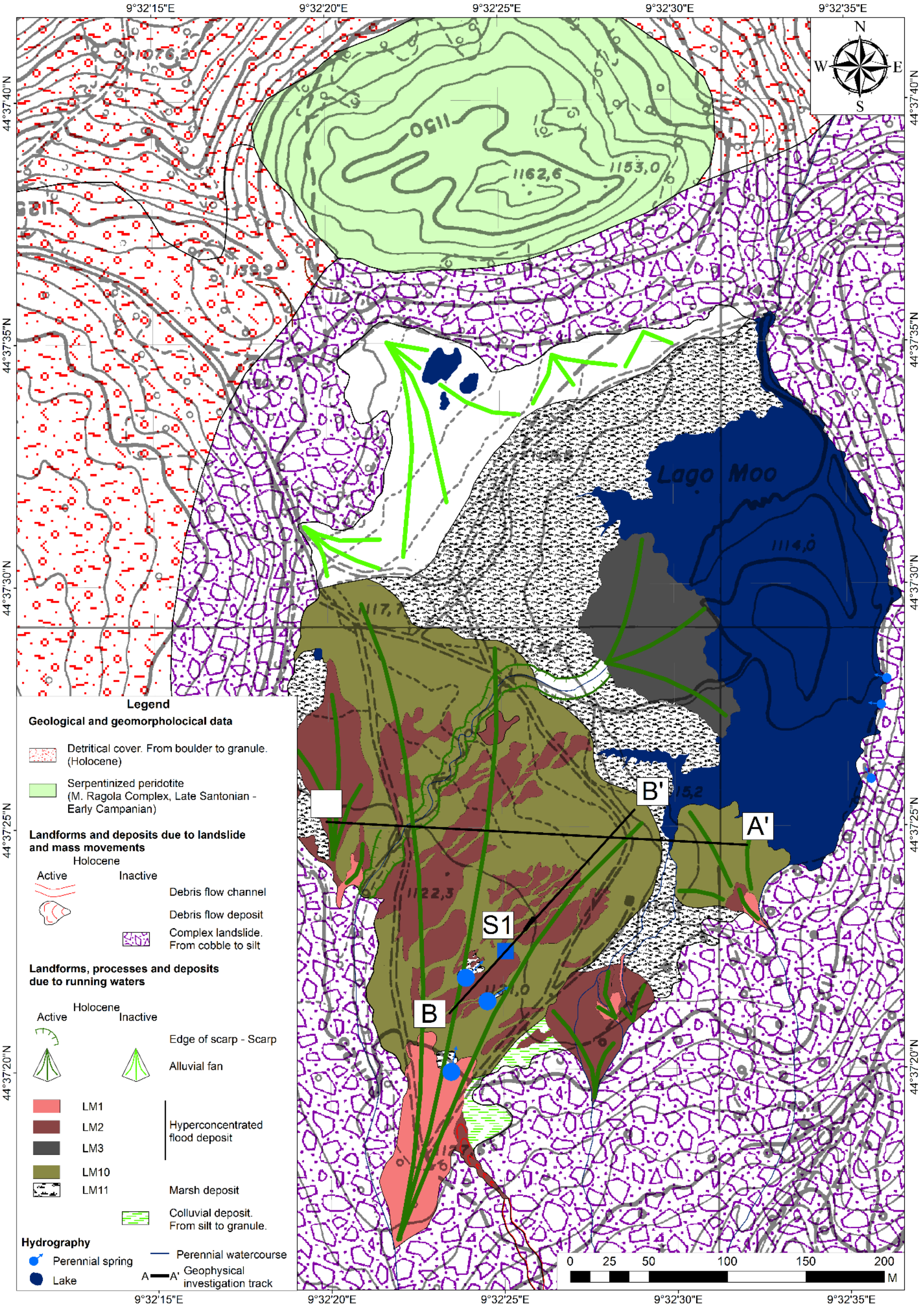
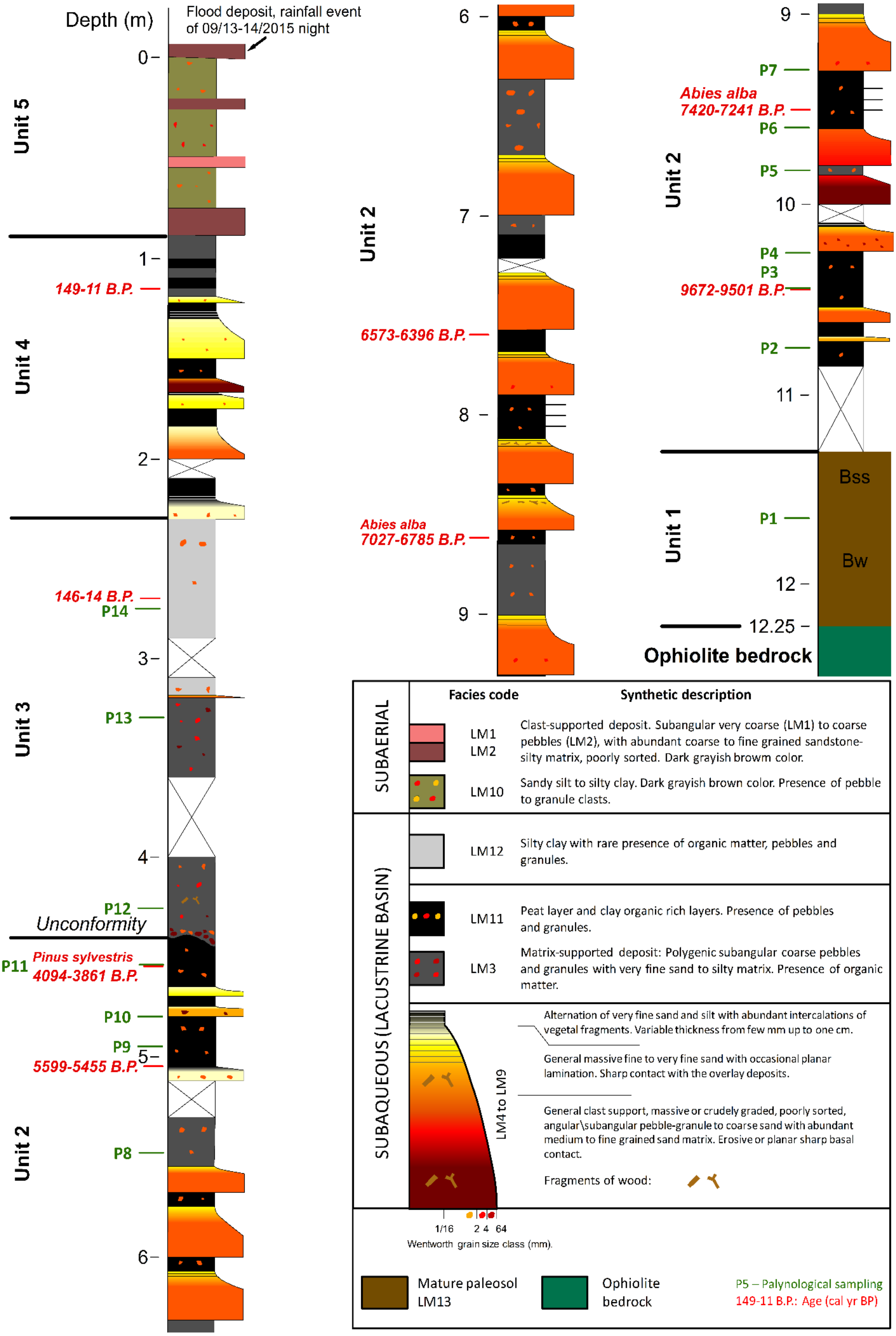


9°32'15"E
9°32'20"E
9°32'25"E
9°32'30"E
9°32'35"E
44°37'40"N
44°37'35"N
44°37'30"N
44°37'25"N
44°37'20"N
N
S
W
E
Lago Moo
1150
1162,6
1153,0
1114,0
1122,3
B'
A'
S1
B
Legend
Geological and geomorphological data
Detritical cover. From boulder to granule. (Holocene)
Serpentinized peridotite (M. Ragola Complex, Late Santonian - Early Campanian)
Landforms and deposits due to landslide and mass movements
Holocene
Active
Inactive
Debris flow channel
Debris flow deposit
Complex landslide. From cobble to silt
Landforms, processes and deposits due to running waters
Holocene
Active
Inactive
Edge of scarp - Scarp
Alluvial fan
LM1
LM2
LM3
Hyperconcentrated flood deposit
LM10
LM11
Marsh deposit
Colluvial deposit. From silt to granule.
Hydrography
Perennial spring
Lake
Perennial watercourse
A A' Geophysical investigation track
0 25 50 100 150 200 M

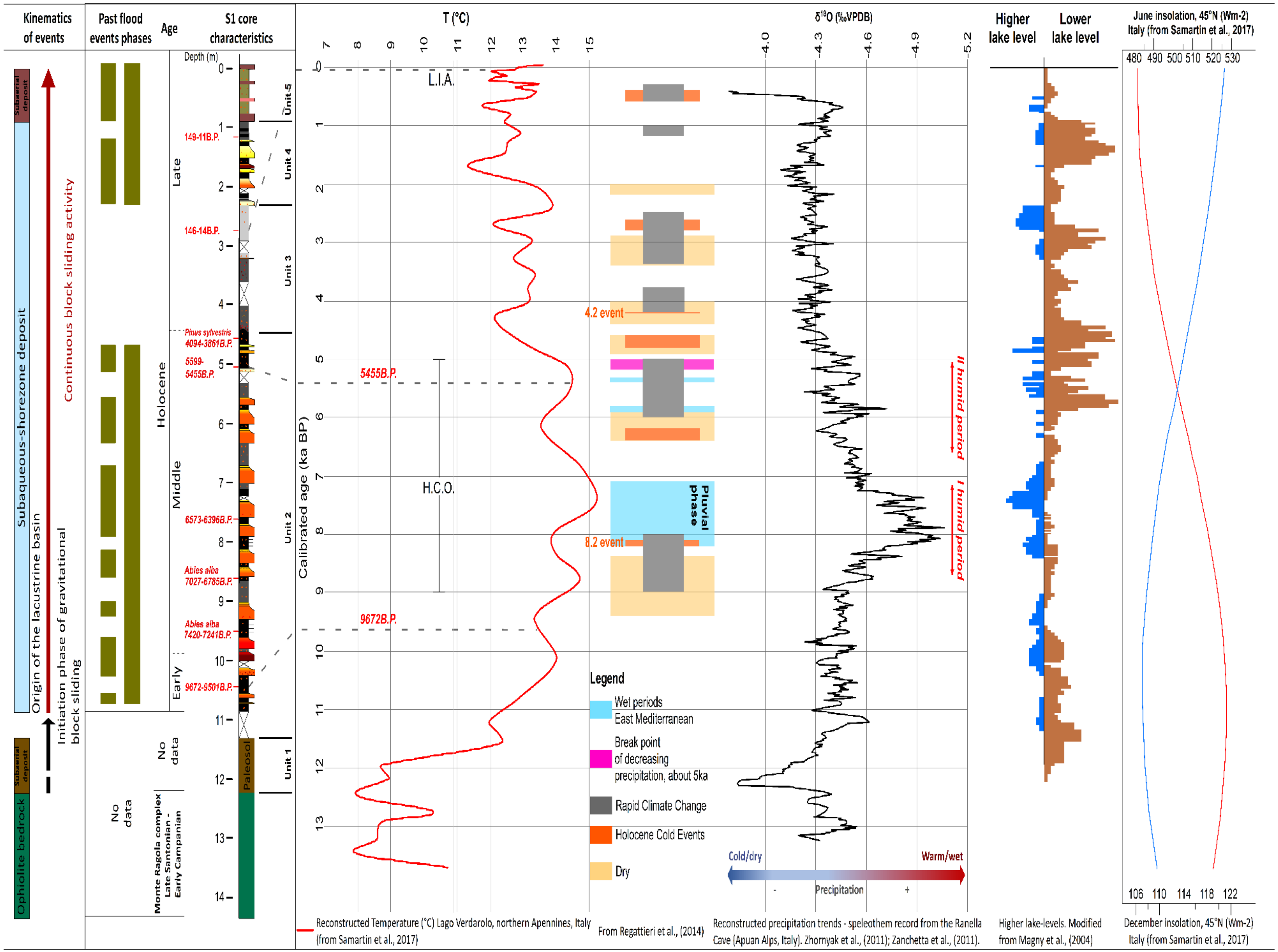
Figure 2



Depth (m)
Flood deposit, rainfall event of 09/13-14/2015 night
Unit 5
Unit 4
Unit 3
Unit 2
Unit 1
149-11 B.P.
146-14 B.P.
P14
P13
P12
Unconformity
P11
Pinus sylvestris 4094-3861 B.P.
P10
P9
5599-5455 B.P.
P8
6573-6396 B.P.
Abies alba 7027-6785 B.P.
P7
Abies alba 7420-7241 B.P.
P6
P5
P4
P3
9672-9501 B.P.
P2
P1
Bss
Bw
12.25
Ophiolite bedrock
SUBAERIAL
SUBAQUEOUS (LACUSTRINE BASIN)
Facies code
Synthetic description
LM1
LM2
Clast-supported deposit. Subangular very coarse (LM1) to coarse pebbles (LM2), with abundant coarse to fine grained sandstone-silty matrix, poorly sorted. Dark grayish browm color.
LM10
Sandy silt to silty clay. Dark grayish brown color. Presence of pebble to granule clasts.
LM12
Silty clay with rare presence of organic matter, pebbles and granules.
LM11
Peat layer and clay organic rich layers. Presence of pebbles and granules.
LM3
Matrix-supported deposit: Polygenic subangular coarse pebbles and granules with very fine sand to silty matrix. Presence of organic matter.
LM4 to LM9
Alternation of very fine sand and silt with abundant intercalations of vegetal fragments. Variable thickness from few mm up to one cm.
General massive fine to very fine sand with occasional planar lamination. Sharp contact with the overlay deposits.
General clast support, massive or crudely graded, poorly sorted, angular\subangular pebble-granule to coarse sand with abundant medium to fine grained sand matrix. Erosive or planar sharp basal contact.
Fragments of wood:
1/16
2 4 64
Wentworth grain size class (mm).
Mature paleosol LM13
Ophiolite bedrock
P5 – Palynological sampling
149-11 B.P.: Age (cal yr BP)

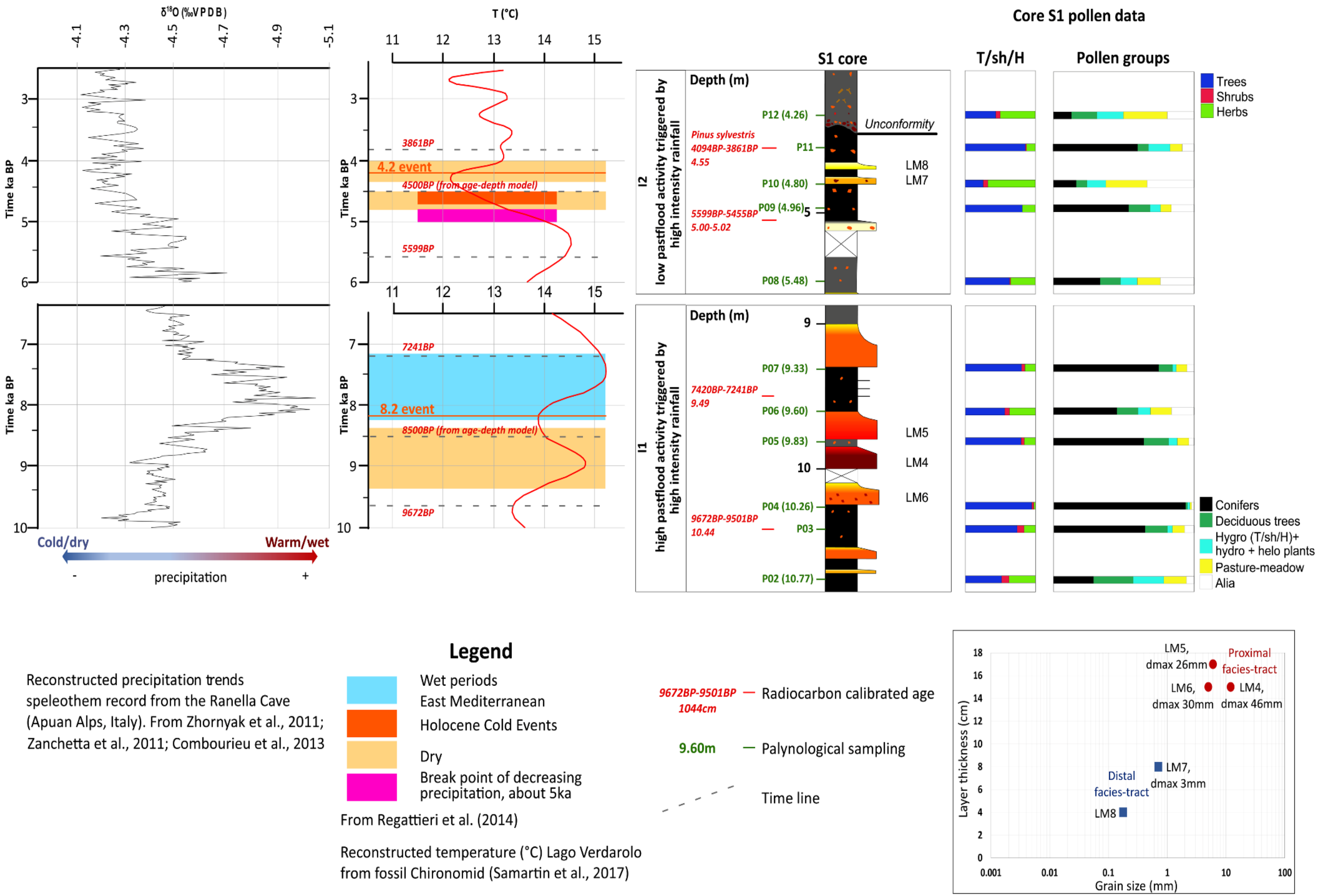
Figure 3

740



Kinematics of events
Past flood events phases
Age
S1 core characteristics
Depth (m)
Subaerial deposit
Subaqueous-shorezone deposit
Origin of the lacustrine basin
Continuous block sliding activity
Initiation phase of gravitational block sliding
Ophiolite bedrock
Late
Middle
Early
Holocene
No data
Monte Ragola complex Late Santonian - Early Campanian
Unit 5
Unit 4
Unit 3
Unit 2
Unit 1
Paleosol
149-11B.P.
146-14B.P.
Pinus sylvestris 4094-3861B.P.
5593-5455B.P.
6573-6396B.P.
Abies alba 7027-6785B.P.
Abies alba 7420-7241B.P.
9672-9501B.P.
T (°C)
Calibrated age (ka BP)
L.I.A.
H.C.O.
5455B.P.
9672B.P.
4.2 event
8.2 event
Pluvial phase
Legend
Wet periods East Mediterranean
Break point of decreasing precipitation, about 5ka
Rapid Climate Change
Holocene Cold Events
Dry
δ18O (‰VPDB)
II humid period
I humid period
Cold/dry
Warm/wet
Precipitation
Higher lake level
Lower lake level
June insolation, 45°N (Wm-2) Italy (from Samartin et al., 2017)
December insolation, 45°N (Wm-2) Italy (from Samartin et al., 2017)
Reconstructed Temperature (°C) Lago Verdarolo, northern Apennines, Italy (from Samartin et al., 2017)
From Regattieri et al., (2014)
Reconstructed precipitation trends - speleothem record from the Ranella Cave (Apuan Alps, Italy). Zhornyak et al., (2011); Zanchetta et al., (2011).
Higher lake-levels. Modified from Magny et al., (2004)

Figure 10


δ18O (‰VPDB)
-4.1
-4.3
-4.5
-4.7
-4.9
-5.1
Time ka BP
Cold/dry
Warm/wet
precipitation
-
+
T (°C)
4.2 event
3861BP
4500BP (from age-depth model)
5599BP
7241BP
8.2 event
8500BP (from age-depth model)
9672BP
S1 core
Depth (m)
low pastflood activity triggered by high intensity rainfall
I2
high pastflood activity triggered by high intensity rainfall
I1
P12 (4.26)
Unconformity
Pinus sylvestris
4094BP-3861BP
4.55
P11
LM8
LM7
P10 (4.80)
5599BP-5455BP
5.00-5.02
P09 (4.96)
P08 (5.48)
P07 (9.33)
7420BP-7241BP
9.49
P06 (9.60)
LM5
P05 (9.83)
LM4
LM6
P04 (10.26)
9672BP-9501BP
10.44
P03
P02 (10.77)
Core S1 pollen data
T/sh/H
Pollen groups
Trees
Shrubs
Herbs
Conifers
Deciduous trees
Hygro (T/sh/H)+ hydro + helo plants
Pasture-meadow
Alia
Legend
Reconstructed precipitation trends speleothem record from the Ranella Cave (Apuan Alps, Italy). From Zhornyak et al., 2011; Zanchetta et al., 2011; Combourieu et al., 2013
Wet periods
East Mediterranean
Holocene Cold Events
Dry
Break point of decreasing precipitation, about 5ka
From Regattieri et al. (2014)
Reconstructed temperature (°C) Lago Verdarolo from fossil Chironomid (Samartin et al., 2017)
9672BP-9501BP
1044cm
Radiocarbon calibrated age
9.60m
Palynological sampling
Time line
LM5, dmax 26mm
Proximal facies-tract
LM6, dmax 30mm
LM4, dmax 46mm
LM7, dmax 3mm
Distal facies-tract
LM8
Layer thickness (cm)
Grain size (mm)