Mass-movement and flood-induced deposits in Lake Ledro, Southern Alps, Italy: Implications for Holocene palaeohydrology and natural hazards.

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Abstract

High-resolution seismic profiles and sediment cores from Lake Ledro combined with soil and river-bed samples from the lake's catchment area are used to assess the recurrence of natural hazards (earthquakes and flood events) in the southern Italian Alps during the Holocene. Two well-developed deltas and a flat central basin are identified on seismic profiles in Lake Ledro. Lake sediments are finely laminated in the basin since 9000 cal. yrs BP and frequently interrupted by two types of sedimentary events: light-coloured massive layers and dark-coloured graded beds. Optical analysis (quantitative organic petrography) of the organic matter present in soils, river beds and lacustrine samples together with lake-sediment bulk density and grain-size analysis illustrate that light-coloured layers consist of a mixture of lacustrine sediments and mainly contain algal particles similar to the ones observed in background sediments. Light-coloured layers thicker than 1.5 cm in the main basin of Lake Ledro are synchronous to numerous coeval mass-wasting deposits remoulding the slopes of the basin. They are interpreted as subaquatic mass movements triggered by historical and pre-historical regional earthquakes dated to AD2005, AD1891, AD1045 and 1260, 2545, 2595, 3350, 3815, 4740, 7190, 9185 and 11495 cal. yrs BP. Dark-coloured SE develop high-amplitude reflections in front of the deltas and in the deep central basin. These beds are mainly made of terrestrial organic matter (soils and ligno-cellulosic debris) and are interpreted as resulting from intense hyperpycnal flood event. Mapping and quantifying the amount of soil material accumulated in the Holocene hyperpycnal flood deposits of the sequence allow to estimate that the equivalent soil thickness eroded over the catchment area reached up to 5 mm during the largest Holocene flood events. Such significant soil erosion is interpreted as resulting from the combination of heavy rainfall and snowmelt. The recurrence of flash-flood events during the Holocene was however not high enough to affect pedogenesis processes and highlight several wet regional periods during the Holocene. The Holocene period is divided into four phases of environmental evolution. Over the first half of the Holocene, a progressive stabilization of the soils present through the catchment of Lake Ledro was associated with a progressive reforestation of the area and only interrupted during the wet 8.2 event when the soil destabilization was particularly important. Lower soil erosion was recorded during the Mid-Holocene climatic optimum (8000-4200 cal. yrs BP) and associated with higher algal production. Between 4200 and 3100 cal. yrs BP, both wetter climate and human activities within the drainage basin drastically increased soil erosion rates. Finally, from 3100 cal. yrs BP to the present-day, data suggest increasing and changing human land-use.

Keywords

Holocene, northern Italy, Lake sediment, organic petrography, seismic profiling, mass-flow deposits, earthquakes, hyperpycnal flood deposits, soil erosion, extreme precipitations

1. Introduction

Climate variability and seismicity represent serious natural concerns to modern societies in the Alps (e.g. Beniston et al., 2007). Actual climate models project that future climate warming in Central Europe will bring more frequent extreme events and especially heavy precipitations and floods (Buma and Dehn, 1998, Christensen and Christensen, 2003, Beniston et al., 2007, Stewart et al., 2011). Flood hazards vary as a function of the hydroclimatic regime, position within the drainage basin and human interaction in the catchment (Wohl, 2000). Changes in the hydrological balance influence therefore the hydrological regime of the slopes and govern the type, rate and occurrence of natural extreme floods (Knox, 2000), associated soil erosion (De Ploey et al., 1995; Cerdà, 1998, Raclot and Albergel, 2006) and can affect human activities and societies especially in mountainous environments (Dearing, 2006a and 2006b).

The Southern Alps in Italy are sensitive to natural hazards such as earthquakes and flash-floods (Tropeano and Turconi, 2004; Barredo, 2007; Marchi et al., 2010; Luterbach et al, 2012). Former studies suggested that precipitation regimes in this part of the Alps may have been affected by Atlantic influences at millennial and multi-centennial time scales (Magny et al., 2009, 2012). Over the last decade, different authors have also shown that lake sediments represent valuable archives to reconstruct past river discharges (Chapron et al., 2005, Bøe et al., 2006, Debret et al., 2010, Stewart et al., 2011; Wirth et al., 2011; Gilli et al 2013) and past seismic events (Chapron et al., 1999, Schnellmann et al., 2002; Fanetti et al, 2008; Lauterbach et al, 2012).

In this paper, drainage basin descriptions of slope and soils are combined with seismic profiles and sedimentological analysis of lacustrine cores retrieved from peri-Alpine Lake Ledro, Italy. On the basis of the Holocene chronology and floods frequency reconstructions presented in Vannière et al. (this issue) established on sediment cores, our results propose a new organic geochemistry approach to distinguish the sources of exceptional deposits attributed to natural hazards such as earthquakes or flash-floods. This allows the reconstruction of past regional seismicity and wet regional periods during the Holocene.

2. Study area

The drainage basin of Lake Ledro covers 111 km², culminates at 2254 m above sea level (m a.s.l.) and is today influenced by a subcontinental climate characterized by mean total annual precipitations of 900 mm, mean annual temperature of 8°C and significant snowfalls in winter above 1500 m a.s.l. (Beug, 1964). Recent river corrections have been installed in the Massangla River (west of Lake Ledro) and the Pur River (south of Lake Ledro) in order to reduce the effects of flood events. Indeed, these two temporary torrential tributaries of Lake Ledro and their drainage network develop canyons or gullying on steep slopes, transport decimetric blocks and export the fine fraction to the lacustrine basin (Figure 1). Lake Ledro (45°52'N/10°45'E) is a small basin (3.7 km², 2.6 km long, 1.3 km wide, 46 m deep) of glacial origin dammed by a frontal moraine along its eastern side at 653 m a.s.l., where the Ponale River forms the outlet of the lake draining into Lake Garda located at 65 m a.s.l.. Since AD1929, the level of Lake Ledro has been regulated for hydroelectricity production between lakes Ledro and Garda.

The bedrock of the drainage basin of Lake Ledro is composed of Mesozoic rocks with Triassic dolomite and Jurassic and Cretaceous limestones. The steep slopes (>30%, 50 km², yellow areas in Figure 1B) are formed by Quaternary glacial and fluvial deposits (Bollettinari et al., 2005) and are covered by forest and open landscape (> 2000 m a.s.l.). In contrast, two flat valleys (0-5%, hatched red areas in Figure 1B) correspond to the paleolake Ledro maximal extension after glacier retreat and to the present-day alluvial plains of the Massangla and Pur rivers. These alluvial plains and the lake shorelines are associated with agricultural areas and human settlements since at least the Bronze Age, corresponding at Lake Ledro to a period of development of lake-dwelling which declined around 3100 cal. yrs BP (Magny et al., 2009). In addition, this part of the Southern Alps was affected by five strong regional earthquakes over the last millennia (Guidoboni et al., 2007, Figure 1A, Table 1).

3. Methods

The sedimentary infill of the lake was imaged in fall 2007 by high-resolution seismic profiling (Figure 2A). A 3.5 kHz pinger system navigated with a GPS was employed from an inflatable boat. A dense grid of profiles enable us to establish the seismic stratigraphy of the lacustrine infill and allowed the determination of two coring sites: LL082 (14.6 m core length) in the central deepest basin (water depth: 46 m) and LL081 (9.9 m core length) in the eastern part of the central basin (water depth: 45 m) (Figure 2C). These two cores were retrieved in areas lacking massive reworked material (Figure 2) using the UWITEC piston corer from a platform. Continuous composite sections were defined using two parallel cores at each site. The stratigraphic correlation between the two coring sites is supported by the identification of characteristic lithological layers and the seismic stratigraphy. Initial core analysis of LL082 and LL081 included gamma-ray attenuation density measured with a GEOTEK multi-sensor core logger (sampling interval: 0.5 cm), macroscopic core description and digital photographs. Punctual laser diffraction grain-size measurements were performed using a Malvern Mastersizer 2000 on several Sedimentary Event (SE) samples. Age-depth models of lacustrine cores are based on gamma-spectroscopic radionuclide measurements (^{137}Cs, ^{210}Pb) on core LL082 and 19 AMS radiocarbon dates (6 on LL082 and 13 on LL081, Figure 3A) that are reported in Table 2 and discussed in Vannière et al. (this issue).

In July 2011, 11 complete pedological profiles and 6 (dry) river beds were sampled within the watershed (coloured circles in Figure 1B). They were selected at different altitudes and under various vegetation covers in order to be representative of (i) high-altitude thin soils composed of lithic and rendzic Leptosols (62% of the catchment area), (ii) well-developed soils composed of Cambisols (21% of the catchment area) and (iii) alluvial soils divided into colluvic Regosols and Fluvisols (17% of the catchment area).

Organic geochemistry of lake sediments and catchment area samples was measured by Rock-Eval pyrolysis (RE) and quantitative organic petrography (QOP). RE is used to characterize the organic content of natural samples by thermal cracking (Espitalié et al., 1985, Behar et al., 2001). RE parameters as the Total Organic Carbon (TOC, %), the S2 (expressed in mgHC) and the thermal maturity (Tpeak, °C) measurements can be used to characterize soil organic matter (Di Giovanni et al., 1998, Sebag et al. 2005, Copard et al., 2006) and to discriminate between an aquatic or terrestrial origin of the organic matter into lacustrine environments (Talbot and Livingstone, 1989; Simonneau et al., 2013). S2 represents the total amount of hydrocarbon that escapes from the sample during the thermal cracking (Ariztegui et al., 2001). The regression lines (slopes) of the diagram S2 *versus* TOC determine constant values of the Hydrogen Index (HI, expressed in mgHC.g^{-1}TOC) since HI=(S2*100)/TOC (Behar et al., 2001). In this diagram, the matrix effect, essentially due to clay particles which can retain the hydrocarbon produced from the cracking of the organic matter (Ariztegui et al., 2001), can be shown by the positive x intercept of the regression lines with the TOC axis. Classically, two particular slopes, corresponding to HI equals to 750 and 300 mgHC.g^{-1}TOC, respectively, are represented in the S2 *versus* TOC diagrams in order to identify the chemical quality or the origin of the organic compounds (Ariztegui et al., 2001). Values of HI inferior to 300 mgHC.g^{-1}TOC can point towards organic matter oxidation in the sediment or a contribution of terrestrial material (Ramanampisoa and Disnar, 1994; Disnar et al., 2003; Calvert, 2004; Jacob et al., 2004; Simonneau et al., 2013). Inversely, HI values superior to 300 mgHC.g^{-1}TOC suggest well preserved organic matter in the sediment or higher contributions of lacustrine algal particles the specific pole of which is represented by HI values superior to 750 mgHC.g^{-1}TOC (Talbot and Livingstone, 1989). The Tpeak reflects the maximal temperature reached during the S2.

QOP developed by Graz et al. (2010) is based on the optical identification and quantification of the organic fraction after elimination of carbonate and silicate phases by hydrochloric and hydrofluoric attacks. Components are characterized by their optical properties (colour and reflectance), their forms (amorphous or figurative) and their origins (algal, phytoclastic or fossil) (Combaz, 1964; Tyson, 1995; Di Giovanni et al., 2000, Sebag et al., 2006; Simonneau et al., 2013). Excluding the standard, which was deliberately added into preparations, three main types of organic particles have been used in this study: red or grey amorphous particles (rAP and gAP, respectively) and ligno-cellulosic fragments (LCF), whose significations are given from analyses results (see below section 4.3.).

4. Results

4.1 Seismic basin analysis

The bathymetric map of Lake Ledro (Figure 2B) has been calculated interpolating the seismic data (Figure 2A) and highlights the occurrence of steep slopes surrounding a relatively wide and flat central basin. The morphology of the glacial or bedrock substrate is seismically imaged in many areas and suggests that the sediment infill reaches a thickness of more than 40 m in the central basin (Figure 2C). Downlapping geometries just basinward from the western and southern areas lacking seismic penetration indicate prograding beds from the Massangla and Pur river deltas, respectively (Figure 2C). In the deepest part of the basin, sediments are thickest, well stratified and characterized by high-amplitude reflections, which have a spacing that becomes thinner towards the eastern edge of the basin (Figure 2C). Some reflections (such as J, Figure 2) delimited by deltas and bedrock on the northern coast are defined by forming the top of transparent thin units whose extensions are limited by onlap configurations toward the eastern edge of the central basin (Figure 2D).

Many transparent to chaotic lens-shaped bodies of various sizes are also present and coeval within the lacustrine basin. Events 4 and 11 (Figure 2) are for instance described by nine and ten coeval independent bodies, which are interpreted to be the result of mass-wasting processes along the subaquatic slopes (e.g. Schnellmann et al., 2002). The thicker lens-shaped bodies (event 11) turn into a thin layer bearing few discontinuous reflections in the deepest part of the lake. The reflections connecting the tops of all coeval mass-wasting deposits are picked as seismic-stratigraphic horizons for each event, respectively (Figure 2). They represent isochrones and coincide with the thickest SE (i.e. Sedimentary Events) recognized in LL082 and LL081 (SE 1, 4, 5, 6, 9, 11, 12, 13 and 14, Table 3, Figures 2 and 3a). The event horizon can be traced throughout the lake basin, except in windows of no acoustic penetration. They also allow seismic-to-core correlations between the two coring sites (Figure 2D).

4.2 Physical properties of lacustrine sediment and sedimentary events

Cores LL081 and LL082 are mainly composed of Holocene sedimentary sequences reaching 6.9 m and 11.70 m length, respectively (Figure 3a). Before 9000 cal. yrs BP and back to 13330 cal. yrs BP (i.e. below 620 and 1020 cm core depth) in cores LL081 and LL082, respectively, the background sediment is not laminated and is only interrupted by few SE. After 9000 cal. yrs BP, the succession becomes finely laminated in the background sediment. Based on thin sections on selected part of core LL082, core scanner XRF analysis and high-resolution digital photographs (Wirth, 2012; Vannière et al., this issue), laminated background sedimentation is made of a succession of millimetric to inframillimetric couplets of discrete white calcite layers (WL, Figure 3b) and brown organic layers (BL, Figure 3b) typical of calcite varves (Lotter and Lemcke, 1999; Brauer et al., 2008; Czymzik et al., 2010) reflecting the succession of summer (WL) and winter (BL) seasons. Grey clayey iron rich layer are, in addition, frequently occurring at different positions within the vaved sequence (Wirth, 2012) and are interpreted as thin detrital layers (i.e. small-scale flood deposit, c.f. Czymzik et al., 2010). During the Holocene laminated background sedimentation, the occurrence of SE (i.e. Sedimentary Events) increases (Figure 3a) in both cores, interrupting the annual succession. SE are characterized by specific colour, bulk density and grain-size (Figures 3a and 4), clearly contrasting with the background sedimentation. SE represent a cumulative length of almost 5 and 2.5 m length of the Holocene sequence in LL082 and LL081, respectively. Two kinds of SE are easily identified from the Holocene background sediment based on their thickness (centimetric to pluricentimetric layers), colour (dark or light-coloured), texture (graded or massive) and density data. As discussed in Vannière et al., (this issue), the identification of these two types of SE at both coring sites highlights a good core-to-core correlation between LL081 and LL082 and suggests that these SE usually affect a major part of the deep basin since only few layers are only documented in LL082, as for example the light-coloured deposit 1 (Figure 3a). Because all these SE are generally characterized by higher densities than the background sediment, their frequent occurrence in the basin fill can explain the relative high-amplitude reflections identified with a high-frequency on seismic data in the entire deep basin. For analytical reasons, only SE thicker than 1 cm could be sampled, and are considered in the following sections. It means that we are here not discussing thin events (below 1 cm) and flood frequency, which are included in the study of Vannière et al. (this issue).

Dark-coloured SE (labelled by letters) are graded beds and are characterized by a sharp increase of density at their base progressively decreasing towards the top (Figures 3b and 4a). Some organic debris were identified within these dark-coloured SE and sampled for radiocarbon dating (cf. Vannière et al, this issue). Mean grain size in most of these dark-coloured SE highlights the development of inverse (coarsening upward) and normal (fining upward) grading (from 44 to 64 and then 4 µm, and from 31 to 39 and then 2 µm, in events D and I respectively; Figure 4a). Some dark-coloured SE are however only characterized by normal grading (e.g. from 35 to 6 µm in event G, Figure 4a). In addition, all dark-coloured SE are not well sorted (sorting values > 2), but sorting is always increasing at the top of the deposits and associated with the formation of a thin clay cap (Figure 4a). Dark-coloured SE thicker than 1 cm are relatively frequent (73 events during the Holocene), have a wide range of thicknesses (from 1 to 38 cm) and have mean grain-size < 30 µm (Figure 4a) in average.

Light-coloured SE (labelled by numbers) thicker than 1.5 cm are comparatively less frequent (13 events during the Holocene), less variable in thicknesses (ranging from 1.5 to 13 cm) and slightly thicker on average (5.25 cm). They are in addition much more massive both in terms of mean grain size and density (Figures 3c and 4b). These light-coloured SE are also made of smaller particles (mean grain-size < 25 µm, Figure 4b).

4.3 Soil and lacustrine sediments organic characterisation

Soils in the drainage basin vary strongly according to elevation. High-altitude thin soils are present above 1100 m a.s.l. They are not much developed as they show no accumulation or eluviation layers, are rich in calcareous gravels and do not exceed 30 cm in thickness. They form on the calcareous bedrock and are composed of two main silty or sandy layers associated with various amounts of calcareous gravels ranging from 0 to 15%. Well-developed soils are found between 800 and 1100 m a.s.l. They are located in forested areas, do not exceed 70 cm in thickness and form over fissured limestone bearing up to 80% of gravels. Finally, alluvial soils are found in the alluvial plain of the flat valleys. They are characterized by a silty texture and can reach 80 cm in thickness.

The S2 (i.e. the amount of hydrocarbon that escapes from the sample during the thermal cracking) *versus* TOC (i.e. Total organic Carbon) diagram of soil and river-bed samples show that for various TOC content (ranging from 0.09 to 29.4%) all samples are systematically near or below the line representing HI (i.e. Hydrogen Index, see section 3) equals to 300 mgHC.g^{-1}TOC (Figure 5A). In agreement with Sebag et al (2005), S2 curves from soil samples can be linked to the vegetation cover: in superficial layers from grassland soils within the drainage basin of Lake Ledro, the chart S2 *versus* temperature shows a unimodal symmetric curve with Tpeak around 462°C, whereas in superficial layers from forested soils, the chart shows a bimodal dissymmetric curve with Tpeaks around 378 and 455°C (Figure 5B).

QOP highlights that watershed samples are composed of two major groups of organic particles: (1) non-pollen microfossil particles, consisting of colloidal red amorphous particles defined by diffuse external limits and without internal structures (rAP, Figure 5C), cuticles and ligno-cellulosic fragments (LCF, Figure 5C) and opaque particles without high reflectance; and (2) pollen microfossil particles composed of spores and pollens. The rAP and the LCF identified in this study are similar to those described by Di Giovanni et al. (1998), Graz et al. (2010) or Simonneau et al. (2013) and associated with soil particles (rAP) and upper vegetation debris (LCF) coming both from the watershed. Variations in the values of the rAP/LCF ratio can be used to disentangle the impact of land-use and climate during the Holocene on the vegetal cover, soil erosion and sediment load of rivers in Alpine environments (c.f. Noël et al., 2001; Arnaud et al., 2005; Dearing, 2006a, 2006b, Jacob et al., 2009, Simonneau et al., 2013).

Holocene lacustrine samples from core LL082 (Figure 3a) were taken from the SE and the background sediment. SE (Figure 6A) are always defined by HI values lower than to 300 mgHC.g^{-1}TOC and thus systematically lower than background sediment samples (for the same TOC) whose HI values are higher than 300 mgHC.g^{-1}TOC (Figure 6A). Regression lines are calculated for background sediment and SE samples and show that light-coloured SE are not identified by a specific domain but are located between the two others. The matrix effect is equal for background sediment and dark-coloured SE samples, representing 0.3% of TOC. QOP performed on the same set of lacustrine samples only differs from the watershed samples by the presence of grey amorphous particles (gAP, Figure 5C). However, the proportion of rAP, gAP and LCF is different between background-sediment and SE since background-sediment samples and light-coloured SE are mainly composed of gAP (in mean, gAP=65%, rAP=13% and LCF=22%), whereas dark-coloured SE are essentially composed of rAP (in mean, rAP=59%, gAP=12% and LCF=29%, Figure 6B). Only two dark-coloured SE samples are dominated by gAP and correspond to samples rich in clays at the top of the deposit (clay cap; Figures 4a and 6B, red squares).

5. Discussion

5.1 Origins of sedimentary events

As shown in Figures 5 and 6, the organic fraction of background sediments in Lake Ledro is composed of LCF, rAP and gAP, while soils and river-bed samples are only composed of rAP and LCF. The gAP are only found in background lacustrine sediment samples and typically resulting from lacustrine algal productivity (Sifeddine et al., 1996; Di Giovanni et al., 1998).

This optical organic identification is also in agreement with RE results since (i) all HI values below 300 mgHC.g^{-1}TOC are measured in soils and river-bed samples and characteristic of a terrestrial pole (Simonneau et al., 2013) and (ii) intermediate HI values of background lacustrine sediment samples are lying between the algal pole (750 mgHC.g^{-1}TOC, Talbot and Livingstone, 1989) and the terrestrial one (300 mgHC.g^{-1}TOC).

<u>Light-coloured SE and earthquakes.</u>

Light-coloured SE are mainly composed of gAP similar to the ones observed throughout the background sediment and previously identified as resulting of algal growth in the lake waters. This therefore suggests a common origin between the two sedimentary facies. Besides, HI values (<300 mgHC.g^{-1}TOC) do not correspond here with higher terrestrial inputs but specify that the organic matter in these light-coloured SE is more degraded than in the background sediments. This oxidation suggests that light-coloured SE consist of redeposited background lacustrine sediment that became mobilized and oxidized in the water column. This interpretation is in agreement with the seismic data indicating that these light-coloured SE are restricted to the central basin of the lake. Moreover, some light-coloured SE are contemporaneous to several subaquatic mass-wasting events affecting the steep slopes of the lake (Figures 2 and 7d and 7e). The constant mean grain-size and the stable values of sorting in these light-coloured SE (Figure 4b) are in addition typical of mass-flow deposits (Mulder and Cochonat, 1996). The latter are therefore interpreted as distal mass-flow deposits. Event 1, only identified in core LL082 (Figure 3a), is composed of tilted finely laminated sediments. This event 1 is too thin (12 cm thick) to be clearly identified on seismic data, but appears contemporaneous to hummocky morphologies identified on the eastern and northern parts of the basin (Figure 2).

As discussed in Vannière et al (this issue), radionuclide measurements in core LL082 revealed that event 1 consists of a superposition of two equal recent sedimentary sequences. All together these characteristics of event 1 are typical from the initial stage of a thin slide deposit in the central basin favoured by a limited displacement of recent sediments along several slopes of the lake basin (i.e. creeping phenomena developing hummocky morphologies). This event 1 is dated to AD2005±3 and therefore consistent with the Salo earthquake in AD2004, the epicentre of which being located at only 35 km SW from Lake Ledro (Figure 1, Tables 1 and 3). This earthquake could therefore be the trigger event for the development of creeping along the slopes and the formation the slide event 1 in the central basin.

The next two older mass-flow deposits, reaching at least 1.5 cm in thickness in the sediment cores (Figure 8a, events 2 and 3), are dated to AD1870±40 and AD1860±40 and are synchronous, within the dating error of the sediment core, with two historic earthquakes from AD1901 and AD1891, respectively (Figure 1, Tables 1 and 3). Light-coloured SE 4 (Figure 4b) is dated to 905±130 cal. yrs BP (AD1045±130) and associated with numerous coeval mass movements along the basin slopes (Figure 7d, Table 3) which are the typical signature of large earthquakes in lakes (Schnellmann et al., 2002, Lauterbach et al., 2012). Lake Ledro is located only 50 km NE from Verona (Figure 1A) where a catastrophic seismic event occurred in AD1117 (Table 1, Guidoboni and Comastri, 2005), and it is nearby the Adige valley affected by an earthquake in AD1046 (Figure 1A, Table 1, Guidoboni et al., 2007). Event 4 could therefore be likely the consequence of one of these two regional historical earthquakes. In core LL082, pre-historical mass-flow deposits thicker than 1.5 cm are dated to 1255±115, 2545±105, 2595±100, 3350±80, 3815±85, 4740±155, 7190±130, 9185±85 and 11495±340 cal. yrs BP, respectively (Table 3, Figure 8a). Some of them are, within the age-depth model errors, synchronous with pre-historical earthquakes recorded in nearby Lake Iseo (2430±105, 2545±105, 2595±100 and 4745±155 cal. yrs BP, Figures 1A and 8a, Lauterbach et al., 2012) and suggest that they were triggered by large regional earthquakes (Table 3). The others light-coloured mass-flow deposits in Lake Ledro are supposed to correspond to previously undocumented local earthquakes around 3350±80; 3815±85; 7190±130; 9185±85 and 11495±340 cal. yrs BP (Table 3). Event 11, dated between 5800 and 5980 cal. yrs BP, has probably a seismic origin since this event is associated with the largest coeval mass-movements (Figures 2c and 7e) that occurred in Lake Ledro during the Holocene (Table 3). Among the 14 seismic events recorded in Lake Ledro during the Holocene (Figure 8a, Table 3), ten events occurred during the last 5000 years, i.e. during a period characterised by higher lake levels, based on a series of littoral cores (Magny et al., 2012) (Figures 2B and 8b). These higher levels may have therefore favoured slope instabilities and increased the sensitivity of Lake Ledro to regional seismo-tectonic activity. Otherwise, this could also result from a higher seismicity over the last 5000 years.

Dark-coloured SE and flood deposits.

Dark-coloured SE in Lake Ledro present the same organic signature as that of the watershed samples since they are essentially composed of terrestrial components similar to the ones identified throughout the drainage basin (rAP and LCF, Figure 5B) and characterized by HI values clearly below 300 mgHC.g^{-1}TOC. In addition, laser grain-size and bulk-density measurements in these beds clearly indicate that most of their bases are successively inversely and normally graded. This is the typical signature of hyperpycnal flood deposits in a subaquatic basin (Mulder and Alexander, 2001; Mulder et al., 2003; Mulder and Chapron, 2011; St-Onge et al, 2012), where the coarsening-upward and the fining-upward sequences are correlated to the rising and the falling limb of a flood hydrograph, respectively. The very thin basal unit of event J (Fig. 4a), compared to the thick upper unit, implies therefore an asymmetric flood hydrograph, which is typical of hyperpycnites and corresponds to the succession of the waxing and waning flows (St-Onge et al., 2004; Mulder and Chapron, 2011). Because the preservation of the waxing unit of a hyperpycnite at a given location in a basin is typically linked to (i) the flood hydrograph, (ii) the peak intensity of the flood event and (iii) the proximity of the tributary (Mulder et al. 2003), dark-coloured SE characterized only by a fining upward sequence (such as event G) at coring sites LL081 and/or LL082 in Lake Ledro can be related to exceptional flood events whose peak intensities were high enough to erode the waxing unit. In addition, the significant occurrence of algal particles in the clay caps of dark-coloured SE is interpreted as resulting from the remobilization in the water column of lacustrine sediments at the lake floor during the development of the hyperpycnal current (Chapron et al, 2007). These clay caps would therefore essentially result from the settling of fine-grained particles suspended near the lake floor at the end of the flood event.

Dark-coloured SE in Lake Ledro are thus interpreted as hyperpycnal flood deposits largely composed of soil material and vegetation debris eroded from the drainage basin and brought in the lake by heavy precipitation and/or snowmelt events. Because Massangla and Pur rivers are temporary torrential tributaries draining steep slopes, dark-coloured SE in Lake Ledro are likely reflecting flash-flood events (Lambert and Giovanoli, 1988; Bornhold et al., 1994; Gilli et al., 2013). The large flood deposits marked by dark-coloured SE J is thick enough to be mapped along seismic profiles (Figure 7c). It reaches up to $6.4.10^5$ m² of area, is extending from the Massangla and Pur delta slopes towards the central basin where it forms an up to 50 cm thick depocenter (Figure 7b) and develops onlaping geometries at the eastern edge of the central basin (Figure 7c).

5.2. Flood events and soil erosion

Since flood deposits in Lake Ledro are essentially composed of soil-derived material, it is necessary to estimate the amount of pedological material eroded during exceptional flood events from the catchment area, in order to test if their occurrence in the lake basin can be used as a good proxy to reconstruct the paleohydrology of the study area.

The spatial extensions of the hyperpycnal floods recorded into Lake Ledro are given by their eastern onlap configurations of their high-amplitude reflections in the central basin (Figures 2D and 7c). Densities of soil surface-layers sampled in the catchment area vary from 1.04 to 1.7 $g.cm^{-3}$ (on average 1.3 $g.cm^{-3}$) and are close to ones measured in flood deposits from sediment cores (on average 1.4 $g.cm^{-3}$). The calculated volume of terrestrial fine fraction eroded during a flash-flood is thus assumed as representative of the total terrestrial material eroded within the erodible surface of the catchment area. It is calculated multiplying the mean thickness of a specific dark-event deposit by the mean spatial extent of Lake Ledro hyperpycnal flood events (evaluated to $3.3x10^5$ m² on average, Figure 7b) and by the percentage of terrestrial material inside (determined by QOP). Such an approach is only slightly underestimating (by 7%) the accurate volume of event J which could be precisely mapped on seismic sections (Figure 7b).

For each flood event, this volume represents mechanical erosion of an unknown thickness of soil within a certain percentage of the erodible surface source of terrestrial material. De Ploey (1991), Cerdà (1998 and 1999), Le Bissonnais et al. (2001), Souchère et al. (2003) and Girard et al. (2011) described that the cumulative effects of gullying on the thalwegs and on slopes steeper than 30% are the two main factors controlling soil erosion within a drainage basin under a given vegetation cover. Analysing the digital elevation model, we consider that the topography was constant during all the Holocene period and intersect the two key criterions (thalwegs and slopes >30%, Figure 1B, orange and yellow areas, respectively) in order to map source areas of terrestrial material (~23.3 km² in the catchment). Flat alluvial valleys slopes (0-5%; Figure 1B, hatched red areas, 0.8 km² in the catchment) are mainly sites of accumulation processes; however, the material stored in these valleys can be remobilized during flood events (Girard et al., 2011). We consider therefore that slopes between 0 and 5% can also be affected by erosion processes during a flash-flood event. The equivalent thickness of soil eroded corresponding to 100% of these source areas affected by erosion represents the minimum equivalent soil thickness which can be eroded by a given flood event. It is more difficult to determine this value for thinner flood events, which represent low terrestrial volumes (black curve, flood event of 2 cm thick in LL082, Figure 9) than for thicker events (grey curve, flood event J, 38 cm thick in LL082, Figure 9). The pre-historical major hyperpycnal flood event F (18 cm thick into core LL082, Figure 10b) is the example presented in Figure 9. It is on average composed of 90 % of allochtonous components, which correspond to 53460 m^3 of accumulated terrestrial material. Considering this volume, 2.6 mm of equivalent soil thickness, within the catchment area of Lake Ledro, are at least eroded by this flash-flood event (blue curve, Figure 9). Similarly, we can estimate that events G and J (Figure 10b) eroded at least 3 mm and 4,9 mm of equivalent soil thickness in the watershed of Lake Ledro, respectively.

This approach highlights that extreme events eroded at least few millimetres of soil over the watershed and correspond to values described by Raclot and Albergel (2006) for areas affected by modern water erosion and runoff. Their recurrence in time can be problematic and can affect the pedogenesis process at long time scales since Duchaufour (1983) stated that well-developed soil pedogenesis as those described in Lake Ledro catchment area is relatively slow. However, events F, G and J are exceptional in intensity since they are the only ones to reach such thicknesses during the Holocene. This indicates that the pedogenesis in Lake Ledro watershed is not significantly affected by the recurrence of flash-flood events and suggests that Lake Ledro flood sequence offers a reliable record to track the evolution of precipitation regimes during the Holocene in this part of the Alps.

5.3. Climatic significance of flash-flood deposits in Lake Ledro.

It is well known that rainfall events have to reach a certain threshold in magnitude, duration, intensity or discharge to trigger erosional processes and flooding in drainage basins (De Ploey et al., 1995; Mudelsee et al., 2003; Marchi et al., 2010). According to Mulder et al. (2003) there is also a positive relationship between the flood-deposit thickness, the river discharge and the rain intensity. Several recent studies focusing on modelling of snowmelt erosion have, however, shown that this process could export a large amount of soil particles (60%) especially on grasslands where the snowmelt runoff coefficient is higher (Ollesch et al., 2006; Tanasienko et al., 2009 and 2011). Consequently, we suggest that Holocene flash-flood deposits in Lake Ledro are resulting from the combination of heavy rainfalls and snowmelt phenomena.

5.4. Climate and human interactions on terrestrial and lacustrine Holocene environment at Lake Ledro

The most important parameters discussed below are depicted in Figure 10, where the hyperpycnal flood occurrences and thicknesses documented by Lauterbach et al. (2012) in nearby Lake Iseo (Figures 1A and 10a) are compared to the hyperpycnal flood occurrences and thicknesses identified in Lake Ledro (Figure 10b). This comparison suggests the occurrence of wetter periods favouring flooding activity at a regional scale in the Italian Southern Alps (Figure 10). During the first half of the Holocene, the mean flood intervals from lakes Iseo and Ledro are equalled to 4.8 and 4 events by millennia, respectively, whereas after around 5000 cal. yrs BP, they increased to 8.4 and 9.2 events by millenia, respectively. These changes in flood return times suggest that (i) the two lakes are sensitive to the same climatic influences and that (ii) the second half of the Holocene was wetter, which is in agreement with the higher lake-levels documented by Magny et al. (2009 and 2012) at Lake

Ledro. Over the last 500 years, the last wetter period recorded by hyperpycnal flood deposits in the Southern Alps (Figure 10b) occurred between ca. AD1600 and AD1850 and matches the second phase of the well-documented Little Ice Age period (Chapron et al, 2002; Wanner et al. 2011; Magny et al., 2010).

Furthermore, the ratio rAP/LCF (see section 4.3), the S2 curves from Rock-Eval pyrolysis and the HI index are compared and discussed between the results obtained from samples taken in the background sedimentation or in flood events (Figure 10c, d, e). In the background sediment, the ratio rAP/LCF allows to reconstruct the long-term evolution of the vegetation cover within a watershed, using the respective contribution of soil (rAP) and litter (LCF) material in the terrestrial organic matter fluxes delivered to the lake by runoff on topsoil layers (Di Giovanni et al., 2000, Simonneau et al., 2013), whereas in flood events, values of the ratio rAP/LCF can reflect the source areas of material eroded during a flood event. The significance of the rAP/LCF ratio in flood SE is further supported by the shape of the S2 curves from flood SE samples (see section 4.3., unimodal or bimodal S2 curves) which can be typical of grassland or forest soils, respectively (Figure 10d)).

<u>During the Early Holocene: from 10000 to 8000 cal. yrs BP.</u>

Between 10000 and 8000 cal. yrs BP, the ratio rAP/LCF from background sediment fluctuated (Figure 10c) resulting from variations in litter and soil particles supply. HI values (Figure 10e) show exactly the same trend. This pattern suggests that the soils present through the drainage basin of Lake Ledro were not stabilized yet and that runoff processes could affect grassland areas (essentially delivering rAP particles) as well as forested ones (essentially delivering LCF particles). This is in agreement with Magny et al. (2012) and Joannin et al. (this issue) who documented the progressive reforestation of the area during this period. Around 8200-8000 cal. yrs BP, high values of the rAP/LCF ratio are measured in background sediment samples. This indicates a period of enhanced grassland soil erosion, which matches a cold and wet period such as the 8.2 event, frequently documented in western Europe (von Granfenstein et al., 1999) and notably at Lake Ledro (Magny et al., 2012).

In flood events, the ratio rAP/LCF is always high (Figure 10c) suggesting that soil particles (rAP) are essentially exported. S2 curves from the flood events dated from this period are unimodal and symetric (Figure 10d) and therefore typical of runoff on superficial layers from grassland soil suggesting that high altitude areas (or still not reforested ones) were preferentially affected by flash-floods during the Early Holocene.

<u>During the Mid-Holocene: from 8000 to 4200 cal. yrs BP.</u>

Between 8000 and 4200 cal. yrs BP, the ratio rAP/LCF from background sediment is low (Figure 10c) indicating that litter material is preferentially exported comparing to soil particles by runoff processes. This suggests (i) that the catchment area of Lake Ledro was essentially forested during this period, which is in agreement with Joannin et al. (this issue) and (ii) that this reforestation stabilized the soils. The lower erosion rate documented here is further supported by the lower lake-levels documented by Magny et al. (2009 and 2012) at Lake Ledro during this period. Indeed, these conditions resulted from a drier and warmer climate, which among others limited the runoff. HI values (Figure 10e) are higher than 300 mgHC.g^{-1}TOC over this period, reflecting both the lower soil supply into lake sediment and the higher contribution of lacustrine algal production (correlation between HI and algal productivity: $R=0.67$, $p<0.001$), certainly favoured by the warmer climate.

In flood SE, the ratio rAP/LCF is high (Figure 10c) and the shape of the S2 curve is unimodal and symmetric (Figure 10d) during this second period. This indicates that during the Mid-Holocene, the organic material exported during flood events is still essentially made of soil particles from grassland (high-elevated) areas.

<u>During the Late Holocene: from 4200 to 3100 cal. yrs BP.</u>

Between 4200 and 3100 cal. years BP, the high rAP/LCF ratio in Lake Ledro background sediment reflects enhanced soil erosion from non-forested areas topsoils. This is further supported by the HI values measured in background sediment which decrease below 300 mgHC.g^{-1}TOC (Figure 10e) suggesting higher terrestrial contribution into lake sediment by runoff processes (correlation between HI and soil particles: R=0.71, p=0.03). Moreover, this higher terrestrial supply is contemporaneous to the increase of lacustrine sediment magnetic susceptibility interpreted by Vannière et al. (this issue) as the result of higher soil erosion. These results probably reflect the cumulative effects of (i) the climate shift to wetter conditions (Magny et al., 2012) and thereby higher runoff and of (ii) the human-induced land openness documented by Joannin et al. (this issue). Indeed, this time interval is matching a period of well-documented human settlements along the shores of several lakes from the Southern Alps, including Lake Ledro (Magny et al, 2009, 2012, Figure 2B). Bronze Age in Italy is particularly known for a sustained increase in human impact (Cremashi et al., 2006). These human-induced soil destabilisations could favour the soil erosion under wetter climatic conditions.

In flood SE, a high rAP/LCF ratio is measured (Figure 10c) suggesting that the material from open landscapes was remobilized. However, the shape of the S2 curve from flood deposits is bimodal and dissymmetric (Figure 10d) and therefore typical of forested areas. These two results suggest that the superficial layers from former forested soils were preferentially destabilized and eroded during the Bronze Age flash-flood events. Both the increase of the mean flood frequency from 4 to 9.2 events per millennia (Figure 10b) and the increasing thickness of the floods recorded in the central basin of Lake Ledro during this period (events F and G for example, Figure 10b) may thereby have resulted from a combination of more humid climate conditions and human-induced soil destabilization and erosion.

<u>During the Late Holocene: from 3100 to present-day.</u>

During the time interval 3100-1200 cal. years BP, the ratio rAP/LCF from background sediment and flood deposits is progressively dropping (Figure 10c), suggesting reduced soil particles erosion over the catchment area which is in agreement with the slight drop in zirconium influx coming from soil erosion documented by Vannière et al. (this issue). This reduction of erosion processes could indicate a certain stabilization of the soil within the drainage basin or changes in human land-use. After 1200 cal. yrs BP, the interpretation of the ratio rAP/LCF in background sediment is however becoming more difficult. The lower values of the ratio rAP/LCF seem to indicate that the erosion processes essentially exported litter material from forested topsoil layers (Figure 10c). During the same time-interval, Vannière et al. (this issue) described higher minerogenic supply coming from soil erosion (zirconium influx) and land openness from 950 cal. yrs BP. Both increase in minerogenic supply and decrease in rAP/LCF ratio in background sediment are typical of the remobilization of deeper soil layers where the rAP/LCF ratio is constant whatever the vegetation cover (Graz et al., 2010). In this case, both minerogenic and organic results suggest drastic landscape disturbances over the catchment probably associated with ploughing activities and intensive human impact that affected deeper soil layers over the last millennium.

In flood SE, a low rAP/LCF ratio is also measured (Figure 10c) and the shape of the S2 curve from flood deposits is bimodal and dissymmetric (Figure 10d) which is typical of forested areas. Combined with our previous hypothesis on the background sediment signal, these two results suggest that the deeper layers from former forested soils could be destabilized and eroded during recent flood SE. Moreover, frequent but finer hyperpycnal flood deposits are recorded during this period (Figure 10b). They may result from an anthropogenic reorganisation of the drainage basin. The last hyperpycnal flood deposit recorded in our sediment cores is dated to AD1920±20 and is 2 cm thick. It is interesting to note that Lake Ledro does not record any other hyperpycnal flood after this date. This suggests either a primary climate signature (Pfister, 2009), or that regulating activities during hydropower production since AD1929 can modify the temperature of the water column and maybe prevent from generation of hyperpycnal flood or more probably that recent human infrastructure on river corrections in the catchment area have been very efficient to reduce the impact of flash-flood events on lacustrine environments.

6. Conclusions

In Lake Ledro, the combination of high-resolution seismic profiling with physical and organic analyses of sediment cores, soils and river-bed samples allows (i) characterizing the sensitivity of Holocene lacustrine sedimentation to changes in vegetation cover within the drainage basin and (ii) distinguishing the origins of the contrasted sedimentary events which regularly interrupted the background sedimentation. Up to 73 catastrophic hyperpycnal flood deposits (>1 cm) resulting from the combination of heavy rainfalls with snowmelt have especially been discriminated from 14 subaquatic mass-wasting deposits.

Distal mass-flow deposits in the central basin of Lake Ledro are generally associated with numerous coeval mass-movements along the steep slopes of the basin affecting not only deltaic environments. Half of these coeval mass movements matching chronologically either historical regional earthquakes (in AD2004; 1901; 1891 and 1117 or 1046) or coeval mass-movements in nearby Lake Iseo documented by Lauterbach et al. (2012) around 2525±110 and 4490±110 cal. yrs BP, providing new evidences that the Southern Italian Alps have been frequently affected by large regional earthquakes. Similar coeval mass-movements dated around 3350±80; 3815±85; 5890±90; 7190±130; 9185±85 and 11495 ±340 cal. yrs BP are supposed to be related to previously undocumented (and eventually more local) earthquakes.

The longterm evolution of the vegetation cover in the drainage basin of Lake Ledro has been deduced from the respective contributions of soil and litter fluxes delivered to the lake by runoff in background sediments. During the first half of the Holocene, the drainage basin was forested and hyperpycnal floods occurring during springs essentially affected grassland areas. Inversely, after around 5000-4500 cal. yrs BP, climate variability favoured the development of flash-floods during the snow season and the intensification of human activities increased soil erosion, especially between 4000 and 3100 cal. yrs BP. Enhanced occurrence of natural hazards such as earthquakes and flash-floods during this period may have, in addition, contributed to the decline of the lake-dwelling at Lake Ledro. Our results also suggest that over the last millennium, changes in human land-use, such as ploughing activities, may have affected the deeper soil layers.

This study highlights that if present-day climate or modern river corrections apparently succeeded to diminish the development of hyperpycnal flood events in Lake Ledro: Land use combined with future climate changes may have irreversible consequences on soil erosion and on the pedogenesis preserved until now.

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Figure Captions:

Figure 1

Location of Lake Ledro in the Italian Alps (A) and geomorphological characteristics of its catchment area (B). The Trento area is an active seismic region highlighted by historical earthquakes (yellow stars). Catchment area of Lake Ledro is mainly defined by temporary rivers and steep slopes where soils and rivers samples have been collected.

Figure 2

Seismic stratigraphy of Lake Ledro, based on a dense grid of profiles (A). The bathymetric map is generated from the seismic data (B). Three main profiles: C, D and E are selected to show the different acoustic facies. Numbers 1 to 14 correspond to some light-coloured sedimentary events identified in cores.

Figure 3

Core to core correlation between LL081 and LL082 (a) and selected digital photographs of core sections (b) illustrating the occurrence of sedimentary events intercalated within the background sedimentation. The chemical composition of both the background sedimentation and the sedimentary events is also illustrated. Black stars are showing the depths of available dates given in Table 2 and black triangles are locating samples analysed by organic geochemistry in this study.

Figure 4

Grain-size parameters and sediment bulk density profiles are given in (a) for selected dark-coloured Sedimentary Events (Events D, G, I and J) and in (b) for selected light-coloured Sedimentary Events (Events 4 and 12).

Figure 5

Rock-Eval results (A) of soils and river-beds samples are represented by the diagram S2 *versus* Total Organic Carbon (TOC, %). The two linear domains of Hydrogen Index (HI= 750 and HI = 300mgHC.g^{-1}TOC) corresponding to algal and terrestrial poles, respectively, are represented. S2 curve (B) from Rock Eval analysis on superficial layers from forested and grassland soils are also presented. Thermal cracking of the hydrocarbon compounds are represented by the temperature. Organic particles identified by quantitative organic petrography are illustrated in (C): red Amorphous Particles (rAP) in soil layers, river beds and lacustrine sediment; grey Amorphous Particles (gAP); ligno-cellulosic fragments (LCF) non-altered or oxidized; and the standard added in transmitted and reflected light modes.

Figure 6

Organic geochemistry of core LL082. Rock-Eval results (A) are represented by the diagram S2 *versus* Total Organic Carbon (TOC, %). White triangles and black squares represent samples taken in light-coloured events or in dark-coloured ones, respectively. Samples taken within the background sedimentation are represented by white diamonds. Solid lines indicate the regressions line for background sediment samples and dark-coloured events samples, respectively. Specific organic signature is given by quantitative organic petrography (B) represented on a triangular diagram showing the mass percentage of grey amorphous particles, red ones and ligno-cellulosic debris making up each sample. In this diagram, the red squares represent samples taken in the clay caps, which cover the top of two dark-coloured events.

Figure 7

Grid of 3.5 kHz seismic survey acquired for this study in Lake Ledro and windows of no acoustic penetrations (due to coarse and gas-rich deltaic sediments or bedrock occurrence) are localized (a). (b) is illustrating the distribution and thickness of hyperpycnal flood event J characterized by an erosive base and the development of onlap configurations on seismic profiles (c). In (d) and (e) the distribution and thickness of mass-flow deposits caused by historical earthquakes event 4 and by prehistorical event 11 (e) are illustrated and clearly contrasting with the ones of flood event J.

Figure 8

Illustration of mass-flow occurrence, thickness and age in core LL082 (a). Some mass flow deposits superior to 1.5 cm thick are contemporaneous to historical earthquakes (#) and prehistorical earthquakes (+) documented in nearby Lake Iseo by Lauterbach et al (2012). Holocene lake-level evolution from Lake Ledro (b) reconstructed by Magny et al. (2012)

Figure 9

Illustration of the steps used to estimate the equivalent soil thickness eroded over the catchment area associated with a flood deposit in Lake Ledro.

Figure 10

Chronology and thickness of Holocene hyperpycnal flood events in the Southern Alps documented by Lauterbach et al (2012) in Lake Iseo (a), and higher than 1 cm thick in core LL082 from Lake Ledro (b), the evolution of the source of material remobilized by runoff processes within Lake Ledro watershed is given in (c) and calculated by the ratio rAP (red Amorphous Particles) on LCF (Ligno Cellulosic Fragments) for background sediment (white dots) and flood sedimentary events (black dots) in core LL082. The S2 curves from flood deposits (marked by a star in b) are given in (d) and indicate the type of organic matter present in these events as discussed in the text. The hydrogen index (HI) given in (e) is measured in background sediment (white dots) and flood sedimentary events (black dots) from core LL082.

Table 1

Historical earthquakes documented by Guidoboni et al. (2007) close to Lake Ledro. (http://storing.ingv.it/cfti4med/)

Table 2

Radiocarbon dates obtained from Lake Ledro sediment sequences LL082 and LL081, respectively. Age calibration was done using the program Calib 6.06 (Reimer et al., 2009). The date in italic (POZ-27888) has been rejected (see Vannière et al., this issue, for more details).

Table 3

Estimated ages and characteristics of sedimentary events (SE) interpreted as sub aquatic mass movements triggered in Lake Ledro by regional earthquakes as discussed in the text.