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THE LANDSLIDE-DAMMED PALEOLAKE OF MONTELAGO (NORTH MARCHE APENNINES, ITALY): GEOMORPHOLOGICAL EVOLUTION AND PALEOENVIRONMENTAL OUTLINES

ABSTRACT: SAVELLI D., TROIANI F., BRUGIAPAGLIA E., CALDERONI G., CAVITOLO P., DIGNANI A., ORTU E., TEODORI S., VENERI F. & NESCI O., *The landslide-dammed paleolake of Montelago (North-Marche Apennines, Italy): geomorphological evolution and paleoenvironmental outlines*. (IT ISSN 0391-9838, 2013).

In the early Holocene a small lake formed by landslide-damming of the Fosso del Lago stream close to Montelago (Sassoferrato, Province of Ancona), a village of the northern Marche sector of the Adriatic side of the Umbria-Marche Apennines (central Italy). A targeted comprehensive and multidisciplinary project, consisting of a geomorphological survey, seismic tomography, and sediment core drilling, was carried out in this area and complemented by radiocarbon dating and pollen analysis. Geomorphological, chronological and paleoenvironmental constraints for the lake formation, evolution and extinction, also accounting for some apparently contradictory information from the Gregorian Cadastre (1816-1835 AD), were thus obtained and are presented and discussed in this work.

We propose an evolutionary frame where the damming landslide (Montelago Landslide, MLL) is the reactivation of a larger «first time landslide» post-dating the upper Pleistocene coldest stages. Large amounts of calcareous breccia boulders incorporated into the MLL runout caused an effective stream blockage and the formation of a small lake. The radiocarbon dating of the lacustrine sediment was useful for roughly constraining the landslide blockage at about the Boreal-Atlantic transition.

Both the stream blockage and some secondary landslide movements brought about important changes in the Fosso del Lago catchment. Besides the production of the lacustrine trough, key modifications include a marked convexity of the longitudinal stream profile, an associated epigenetic gorge and distinctive knickpoints on residual landslide boulders. Our study allowed the reconstruction of a preliminary Holocene pollen sequence that, to date, is unique for this sector of the Central Apennines.

The pollen record revealed that in the Montelago site, a pre-forest environment with *Corylus*, *Ulmus*, *Fraxinus* and *Tilia* characterizes the early stages of lake existence and is followed by a beech forest expansion culminating at about 6640-6490 cal. BP with a delayed spread of *Abies*. Starting from 5910-5750 cal. BP, an increasing human agro-forestry-pastoral activity is recorded in association with beech forest reduction and concomitant expansion of xerofile and herbaceous taxa. The major environmental modifications recorded by the sediment core can be related to climate changes as well as to human activity, displaying both specific behaviours and similarities with already known sites of the Mediterranean area.

Although the age of the landslide-dammed lake extinction is not strictly constrained, it is yet ascertained that the water pond represented in the 19th century Gregorian cadastral maps a little further upstream the paleolake site, far from being a relic of the landslide-dammed lake, is rather a small man-made reservoir dug long after the former lake dried up.

KEY WORDS: Landslide-dam, Lacustrine sediments, Holocene, Palinology, Montelago, Marche Apennines, Italy.

RIASSUNTO: SAVELLI D., TROIANI F., BRUGIAPAGLIA E., CALDERONI G., CAVITOLO P., DIGNANI A., ORTU E., TEODORI S., VENERI F. & NESCI O., *Il lago di sbarramento per frana di Montelago (Appennino nord-marchigiano, Italia): evoluzione geomorfologica e inquadramento paleoambientale*. (IT ISSN 0391-9838, 2013).

Lo sbarramento per frana del Fosso del Lago nei pressi di Montelago (Sassoferrato, Provincia di Ancona), un piccolo nucleo abitato dell'Appennino nord-Marchigiano (Italia centrale), ha determinato all'inizio dell'Olocene la formazione di un piccolo lago. Questo sito è stato oggetto di uno studio multidisciplinare, consistito in un rilevamento geomorfologico, indagini geognostiche, analisi palinologiche e datazioni radiometriche su una carota dei sedimenti lacustri. Per l'analisi delle fasi evolutive più recenti, sono state prese in esame anche le informazioni contenute nelle mappe del Catasto Gregoriano (1816-1835 AD).

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Le ricerche hanno permesso di ricostruire le fasi di formazione, evoluzione ed estinzione del lago, definendone il contesto geomorfologico, cronologico e paleoambientale. La presente nota propone un quadro evolutivo nel quale la frana che ha prodotto lo sbarramento (*Montelago Landslide*, MLL) è la riattivazione di un movimento di massa preesistente, di maggiori dimensioni ed età successiva alle fasi più fredde del Pleistocene superiore. La formazione di uno sbarramento persistente del corso d'acqua, con conseguente creazione del piccolo lago, è stata favorita dall'abbondanza all'interno del materiale franato di un gran numero di blocchi costituiti da brecce calcaree resistenti all'erosione. Le datazioni dei sedimenti lacustri ottenute col metodo del radiocarbonio hanno permesso di riferire lo sbarramento per frana approssimativamente alla transizione Boreale-Atlantico.

L'ostruzione del corso d'acqua, insieme ad alcuni franamenti secondari, ha determinato importanti modificazioni nel bacino del Fosso del Lago. Oltre la formazione della depressione lacustre, si evidenzia una marcata convessità nel profilo longitudinale del corso d'acqua associata a un solco epigenetico, oltre a caratteristiche rotture di pendenza del profilo stesso in corrispondenza dei blocchi residuali di brecce calcaree responsabili dello sbarramento.

L'analisi pollinica dei campioni prelevati dai sedimenti lacustri ha permesso di ricostruire una sequenza preliminare che, a tutt'oggi, è la sola disponibile per l'Olocene di questo settore dell'Apennino centrale. Il contenuto pollinico del sito di Montelago, ha rivelato che le fasi iniziali di esistenza del lago sono state caratterizzate da una fase di prebosco a *Corylus*, *Ulmus*, *Fraxinus* and *Tilia* alla quale è seguita una espansione della faggeta che ha raggiunto il suo massimo circa 6640-6490 cal. BP con la diffusione di *Abies*. A partire da 5910-5750 cal. BP, in associazione con una riduzione della faggeta e contestuale diffusione di specie xerofile ed erbacee, si registra un incremento delle attività agro-silvo-pastorali. Le maggiori modificazioni ambientali registrate nei sedimenti carotati possono essere collegate a cambiamenti climatici e ad attività umane, mostrando sia aspetti specifici che somiglianze con altri siti già noti dell'area Mediterranea.

Sebbene non sia stato possibile stabilire con certezza l'età di estinzione del lago di frana, si è tuttavia accertato che lo specchio d'acqua rappresentato nelle mappe del Catasto Gregoriano del 19° secolo, ubicato un po' più a monte rispetto al sito dell'antico lago di sbarramento, non è tanto un relitto dello stesso, ma piuttosto un piccolo invaso artificiale scavato molto tempo dopo la sua estinzione.

TERMINI CHIAVE: Lago di sbarramento da frana, Sedimenti lacustri, Olocene, Palinologia, Montelago, Appennino marchigiano, Italia.

INTRODUCTION

Slope failures play a primary role in controlling both hillside and valley floor/streambed morphology within hillslope-channel systems of mountain areas (Korup & *alii*, 2010). Among a great variety of landforms produced by slope failures, landslide dams are the most influential on hydrography (Costa & Schuster, 1988; Korup, 2002). This type of stream blockage, besides a practical importance due to geomorphological hazards associated (Evans, 2006; Korup & Clague, 2009; Gregoretti & *alii*, 2010; Sattar & *alii*, 2010; Chen & *alii*, 2011), is also capable of producing important constraints and long-lasting legacies in the evolution of mountain hillslope-stream systems (Korup, 2005 and 2006; Ouimet & *alii*, 2007; Hewitt & *alii*, 2008; Pánek & *alii*, 2010).

Landslide dams, even though not the best acknowledged among the great variety of landforms produced by slope failures, have been repeatedly reported in the Italian Alps and Apennines (Elmi, 1990; Bromhead & *alii*, 1996; Casagli & Ermini, 1999; Nicoletti & Parise, 2002; Soldati & *alii*, 2004; Carton, 2005; Crosta & *alii*, 2006; Ermini & *alii*, 2006). However, few specific studies are so far available about landslide-dam lakes in the Marche Apennines, with the exception of small upper Pleistocene lakes produced by temporary damming of the Chienti River (Dramis & *alii*, 1988) and the lake of Colfiorito (Galadini & *alii*, 2003), both within the southern sector of the region.

With regard to the northern Marche Apennines, only preliminary works on the paleolake of Montelago are available at date (Massoli-Novelli, 1960 and 2008; Savelli & *alii*, 2012). It is just the Montelago site the object of our investigation, the results and findings of which will be described in detail in the present paper.

State of the art and aims of this work

Montelago (stands for Mountain of the Lake) is a small village in the municipality of Sassoferrato (Marche Region, central Italy), on the SW hillsides of the Mt. Strega massif (fig. 1). The reported area (cf. figs. 2, 3 and 4) consists of the broad head sector of the Fosso del Lago (i.e. Stream of the Lake) where a small topographic depression named Il Lago (i.e. The Lake) is enclosed (toponyms according to the Italian Military Geographical Institute*, s*heet n° 116 - II N.W. «Serra S. Abbondio», scale 1:25,000). These toponyms hint at the existence of a former lake in this area. The first attestation to the toponym of Montelago appears in historical documents dated to the 13th-14th century, while the first cartographic representation accounts to the Gregorian Cadastre (1816-1835), where water-ponds are distinctly represented. However, it is only in relatively recent times that geological evidence for a paleolake came to light with the finding of thinly bedded blackish clays outcropping along the Fosso del Lago (Massoli-Novelli, 1960). Just following this finding, subsequent geological maps and related explanatory notes (Centamore & *alii*, 1975a and 1975b; Various Authors, 2000; Sarti, 2003) will refer to lacustrine deposits, remaining for a long time the only scientific documentation available on the paleolake.

Our research started in 2008, in the frame of a project addressed to geo-naturalistic exploitation of the site. Detailed field geomorphological surveying, analysis of historical documentation, and laboratory analyses were performed in order to constrain the geomorphological evolution of the area, as well as to assess the stratigraphy, palaeo-environments, and chronology of the site. In the meantime Massoli Novelli (2008) refocused on the paleolake and, based on geomorphological evidence, assumed landslide damming as the formative process. A first step in the output of the results of our researches was a geomorphological map at the scale 1:12,000 accompanied by a sketchy description of the site (Savelli & *alii*, 2012).

The purpose of this paper is to discuss for the first time thoroughly the geomorphological arrangement and evolution of the site, focusing on the origin and development of the paleolake and related landforms framed in the local Holocene environments. We support the geomorphological interpretation with seismic tomography, sediment core drilling, radiocarbon dating, and pollen analysis. The first part of this work consists of a brief introduction to the

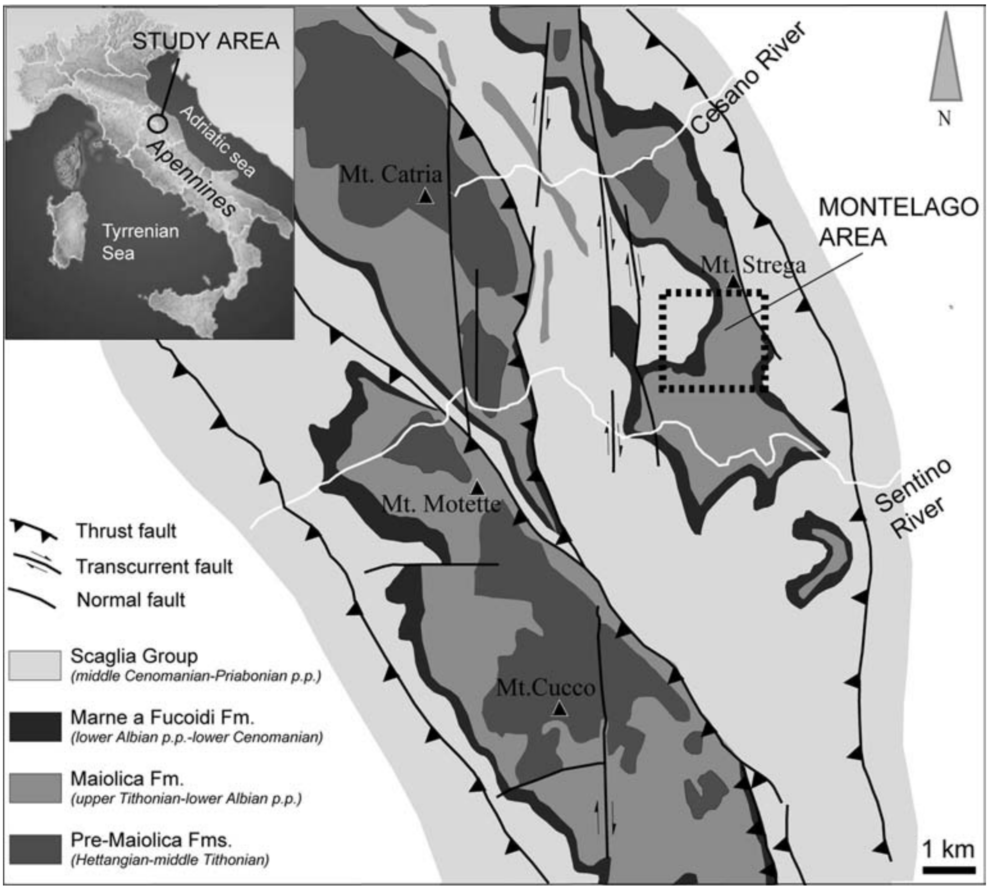


FIG. 1 - Geological sketch of the area surrounding the Montelago site.

geological and physiographical setting of the site. The successive sections report both key geomorphological appraisals and the results of the seismic tomography and drilling at the paleolake site, discussed also on the light of the geomorphological map by Savelli & *alii* (2012). The last section presents and discusses the development of the lake and related landforms on the basis of the results of both radiocarbon dating and pollen analysis. New data on the Holocene environmental variability within this sector of the Apennines are provided, and for the first time a preliminary Holocene pollen sequence is outlined for the Marche Region.

GEOLOGICAL AND PHYSIOGRAPHICAL SETTING

The study area is located in the Umbria-Marche sector of the Apennines (fig. 1), consisting of NW-SE-trending asymmetric, thrusted folds (Calamita & Deiana, 1987) detached from the underlying basement (Barchi & *alii*, 2001). Thrust-faults affect a Jurassic-Paleogene, mainly carbonate and marly-carbonate, multilayer (Deiana & Pialli, 1994), propagating upward and northeastward into the overlying Neogene terrigenous and evaporitic terrains (Mazzoli & *alii*, 2002).

From a geomorphological standpoint, the northern Marche sets on the Adriatic side of the Apennines, characterized by a relief largely matching uplifting tectonic structures (Nesci & *alii*, 2005). The topography is therefore primarily constrained by both lithology and geological structure (Bisci & Dramis, 1991), commonly creating suitable conditions for deep-seated gravitational slope-deformations *sensu* Dramis & Sorriso-Valvo (1994) and Soldati (2004) and landslides to play crucial roles in hillslope shaping (Coppola & *alii*, 1978; Farabollini & *alii*, 1995; Guzzetti & *alii*, 1996; Dramis & *alii*, 2002; Aringoli & *alii*, 2010). The inland mountain areas were also affected by late Pleistocene cold-climate morphogenesis, essentially reflected in periglacial hillslope features and deposits (Coltorti & *alii*, 1979; Nesci & Savelli, 1986).

The Montelago site

The inland sector of the Marche territory is characterized by two regionally extended carbonate anticlinorial ridges (Umbria-Marche Ridge, to the SW, and Marche Ridge, to the NE) separated by a terrigenous synclinorial depression where minor carbonate anticline reliefs also rise (Bisci & Dramis, 1991). Montelago sets within the Umbria-Marche Ridge, whose complex anticlinorial structure can be locally approximated by three major NW-SE striking anticlines displaced by oblique-strike slip faults (fig. 1). The anticlines culminate respectively (roughly from the west) in mounts Cucco (1566 m a.s.l.), Catria

(1701 m) and Strega (1276 m) and are separated by narrow thrusted synclines. The study area (figs. 1, 2, 3 and 4) covers about 4 km^2 near the headwaters of the Fosso del Lago (a left tributary of the Sentino River).

The bedrock of the Montelago area consists (figs. 1 and 2) of the *Maiolica* Fm. (upper Tithonian - lower Aptian p.p.), *Marne a Fucoidi* Fm. (lower Aptian p.p.-lower Cenomanian), and *Scaglia* Group (middle Cenomanian-Priabonian *p.p.*). Such units are part of the Umbria-Marche stratigraphic succession, with local lithological characteristics matching those described by the current scientific literature (Cresta & *alii*, 1989). In the study area only the uppermost *Maiolica* Fm. daylights and, as regards the *Scaglia* Group, only the *Scaglia Bianca* and *Scaglia Rossa* Fms. crop out, being the latter merely represented by its lowermost half. Directly important for the geomorphology of the area as a whole, and for the landslides in particular, are some lithological characteristics of the above units. Namely, the outcropping portion of the *Maiolica* Fm. is characterized by plane-bedded limestone inter-bedded with shale up to several centimetres in thickness, more abundant and thicker upwards. The cherty-limestone

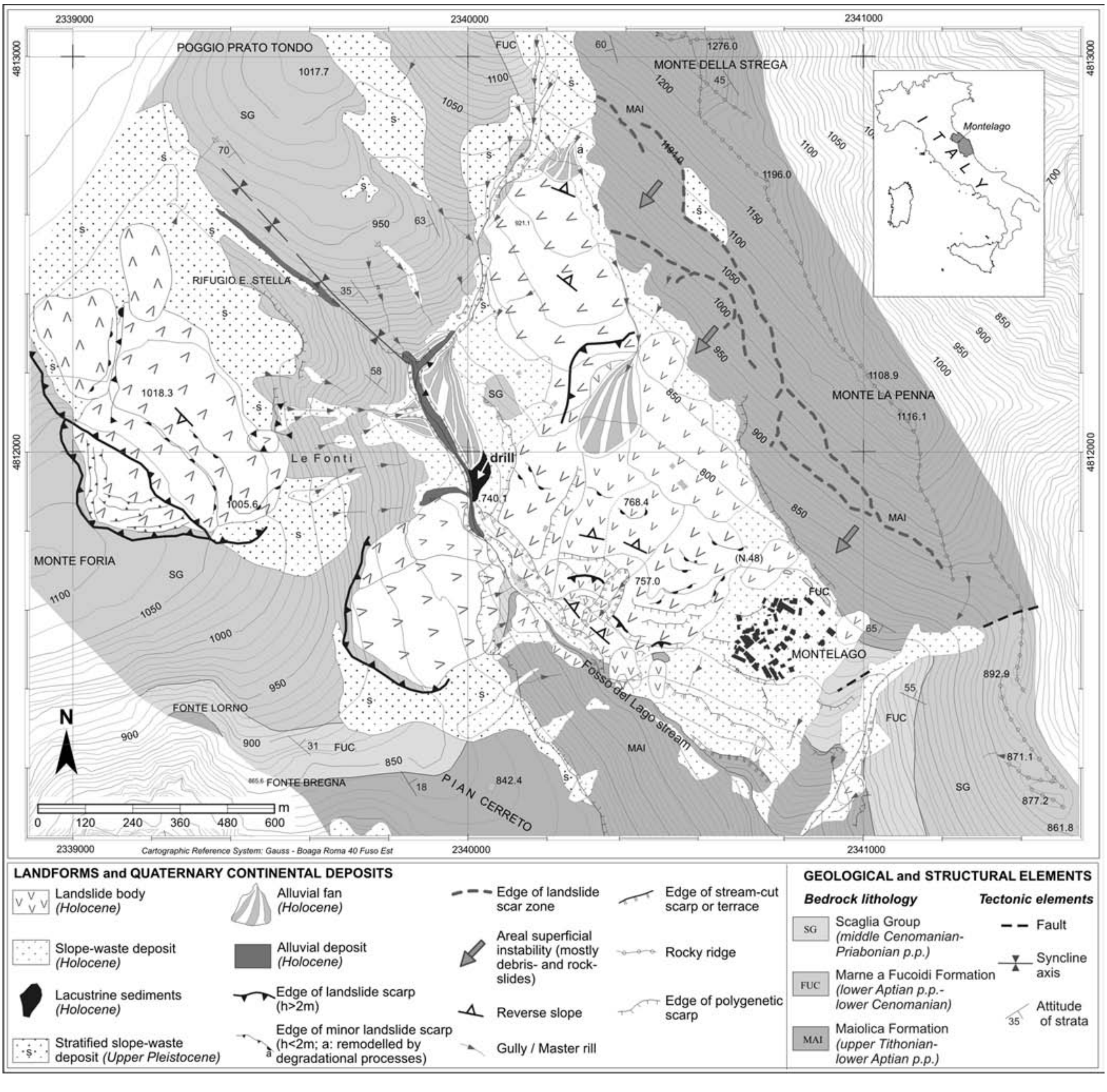
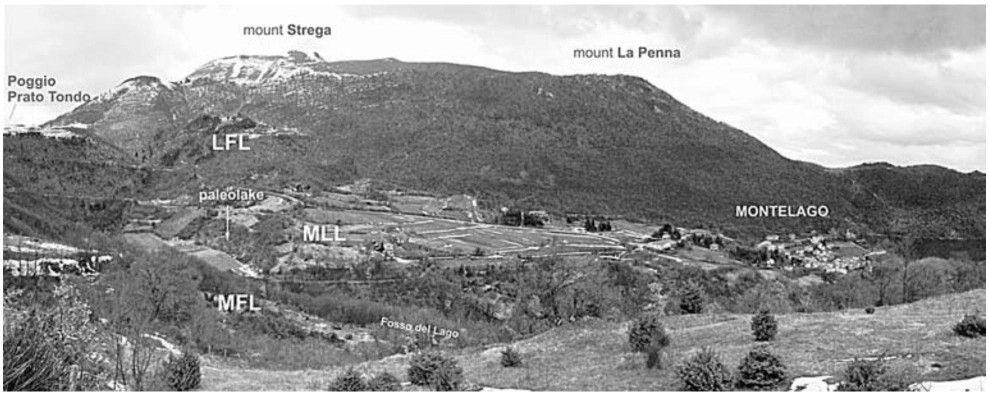


FIG. 2 - Geomorphological map of the Montelago area (after Savelli & *alii*, 2012, simplified).

FIG. 3 - Panoramic view of the Montelago site with the key elements and toponyms cited in the text. LFL = Le Fonti Landslide; MLL = Montelago Landslide; MFL = Monte Foria Landslide.



forming the lowermost part of the *Scaglia Rossa* Fm. is separated from the limestone of its intermediate portion by a 5-10 m-thick marly-limestone layer. Such characters both reveal as crucial in predisposing the downslope-dipping layers of these units to sliding. Moreover, being the limestone of the *Maiolica* Fm. and *Scaglia* Group particularly prone to frost shattering, they experimented a severe weathering during the upper Pleistocene cold stages, originating thick mantles of debris, which represent another important landslide predisposing factor.

METHODS AND MATERIALS

Field survey

An accurate check of available geological data was performed coming to some minor adjustments and an *ex-novo* detailed geomorphological mapping, including continental Quaternary deposits, was carried out. A preliminary fieldwork was performed in order to choose the better sites for prospecting and drilling the paleolake. Successively, after geophysical profiling, drilling, and laboratory analyses, a new detailed field reconnaissance was carried out, aimed at both validating data interpretation and elaborating a well-constrained evolution model. Data from historical maps of the 19th century Gregorian Cadastre were taken into account for assessing the more recent stages of the paleolake existence. Fieldwork has been accomplished by the analysis of: 1) aerial-borne imagery at the scale of ca. 1:33,000 (year: 1984); 2) ortho-photo imagery at the scale of 1:10,000 (year: 1997-1998); 3) a 20x20 gridded Digital Terrain Model (DTM) elaborated starting from the altimetry data contained in the digital topographic maps available for the study area in vector format at the scale of 1:10,000.

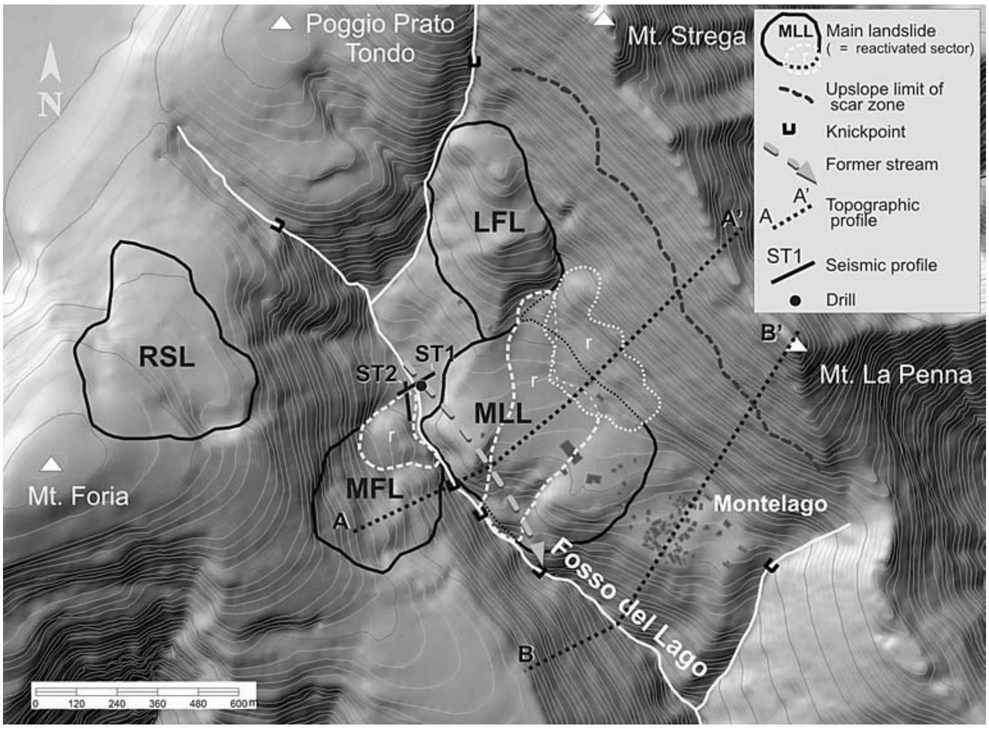


FIG. 4 - Shaded relief of the Montelago area (derived from a 20x20 DTM) displaying the main toponyms and sketching the principal landslides and key landforms described in the text. LFL = Le Fonti Landslide; MLL = Monte Lago Landslide; MFL = Monte Foria Landslide; RSL = Rifugio Stella Landslide. Topographic and seismic profiles are represented respectively in figs. 10 and 11.

Seismic tomography

Seismic tomography data, aimed at achieving information about the subsurface morphology at the paleolake site, were recorded along two perpendicular profiles having a standard length of 110 m (ST1 and ST2 profiles in fig. 4). The profile ST1 strikes NE-SW, whereas ST2 is oriented in NW-SE direction, along with the course of the Fosso del Lago stream. Data acquiring was made by means of a 12-channels seismograph. The data processing, as well as the creation of the seismostratigraphical model shown in fig. 5, were performed through the Reyfract® software that bases on Wavepath Eikonal Traveltime (WET) tomography processing (Schuster & Quintus-Bosz, 1993; Watanabe & *alii*, 1999). The depth of data acquiring is 46 m below the ground surface along the profile ST1, and 23 m along ST2. Three main seismic units were identified (fig. 5)

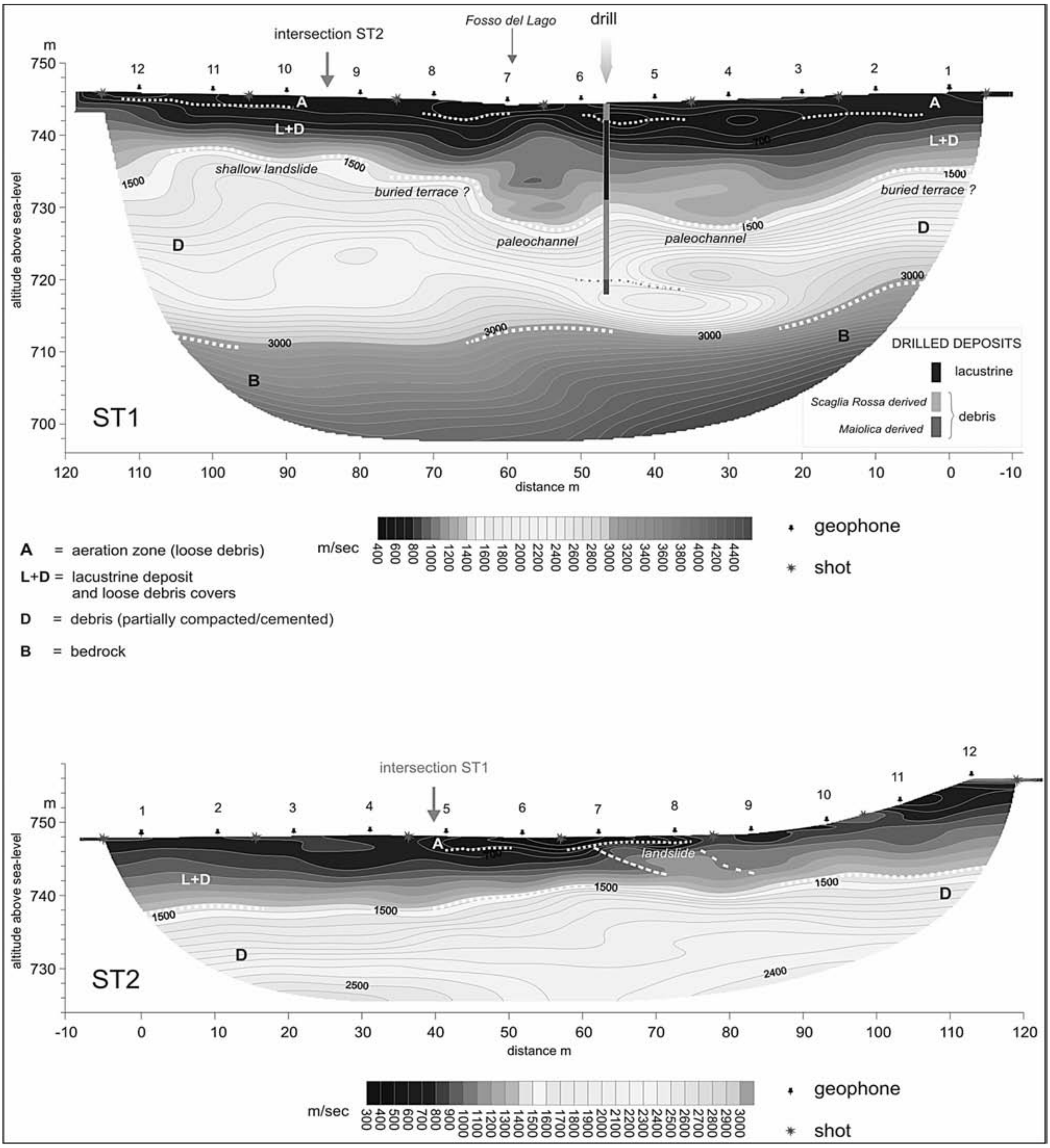


FIG. 5 - Seismic tomography of the landslide-dammed paleolake. ST1 = transversal profile; ST2 = longitudinal profile. Traces of profiles in fig. 4.

and, also basing on data from the sediment core, physically correlated to as many lithostratigraphical bodies.

Sediment core drilling

A 26.40 m-long sediment core was taken by means of a continuous rotary drilling into the small plain forming the downvalley border of the topographic depression where, based on geomorphological data and seismic tomography (figs. 2 and 5), the maximum thickness and continuity of the lacustrine deposits were expected. Sediment samples were taken out from the core for radiocarbon dating and pollen analysis. The sediment core and sample distribution are shown in fig. 6.

^{14}C readings, C/N and ^{13}C/^{12}C ratios

The ^{14}C ages, obtained from 6 samples of the lacustrine sequence (figs. 6 and tab. 1) through the LSC (Liquid Scintillation Counting) technique, were calculated according to conventions and recommendations after Stuiver & Polach (1977) and reported, at the ± 1σ level of uncertain-

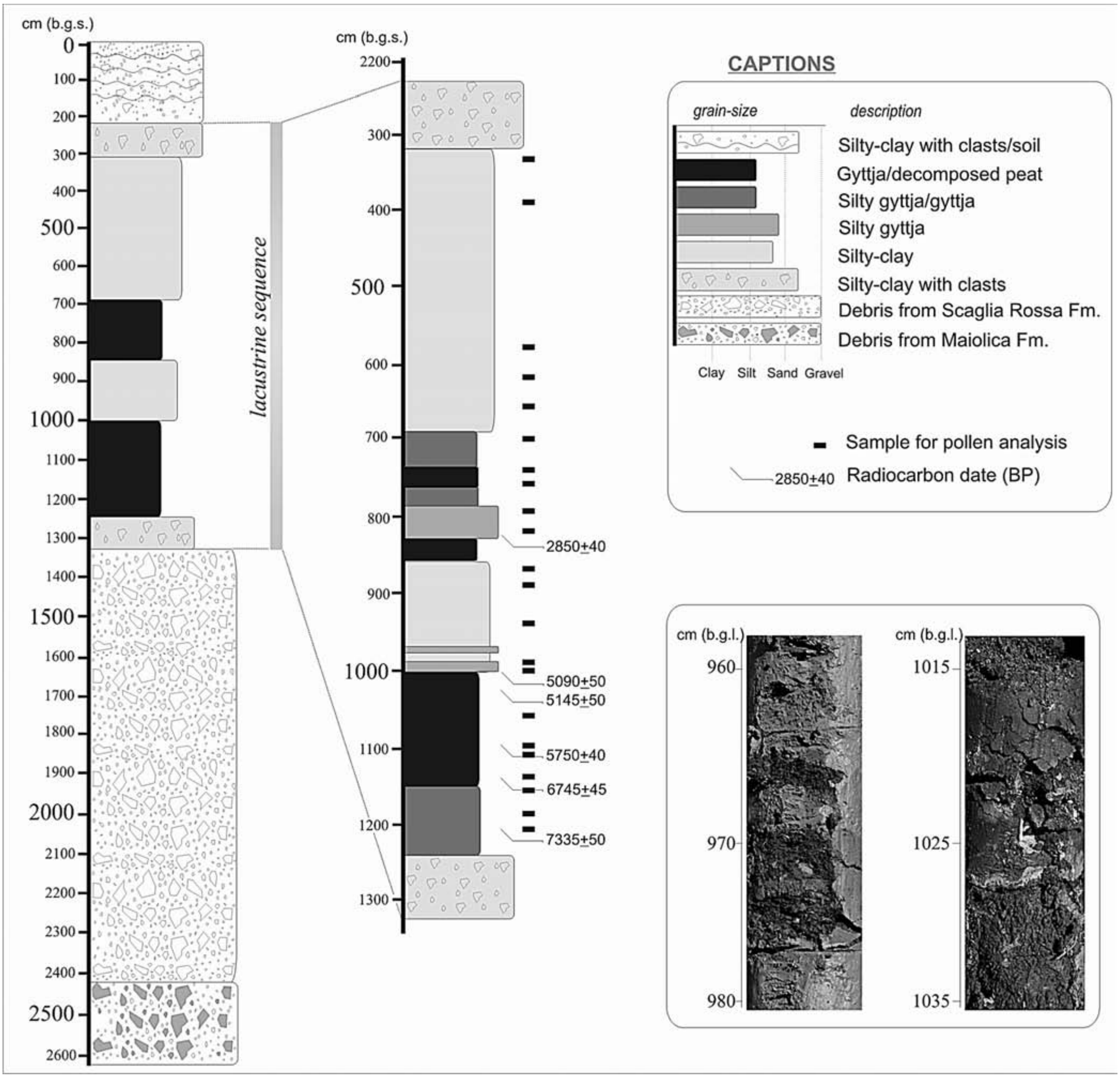


FIG. 6 - Lithostratigraphy of the sediment core from the landslide-dammed paleolake at Montelago. Position of the samples for laboratory analyses is reported. Drill location in figs. 2 and 4.

TABLE 1 - Radiocarbon dates obtained from the Holocene sediment core at Montelago. Sample positions in fig. 6

Core # (depth in core, m)	**Sample identifier** (laboratory)	**Material**	**Conventional ^{14}C age** (yr BP)	**Calibrated age**$^{(1)}$ (cal BC)	**Calibrated age**$^{(1)}$ (cal BP)	**δ ^{13}C**$^{(2)}$ (‰, *vs*. PDB)	**C/N**
ML-11 **8,18÷8,25**	Rome-2025	Organic mud	2850±40	1110-930	3060-2880	–24,8	15.4
ML-16 **10,00÷10,10**	Rome-2026	Organic mud	5090±50	3960-3800	5910-5750	–23,1	12.8
ML-wf **10,25÷10,32**	Rome-2028	Wood fragment	5145±50	4040-3800	5990-5750	–25,0	//
ML-18 **10,90÷11,00**	Rome-2024	Organic mud	5750±40	4690-4540	6640-6490	–26,0	16.0
ML-20 **11,40÷11,49**	Rome-2027	Organic mud	6745±45	5715-5620	7665-7570	–23,7	13.4
ML-23 **12,17÷12,33**	Rome-2023	Organic mud	7335±50	6230-6090	8180-8040	–21,7	15.6

(1) Calibration performed with the software after Ramsey (2005)
(2) Uncertainty ranges from ± 0.25 to ± 0.15 ‰

ty, as «yr BP» (conventional age Before Present, 1950 being the reference year) and «cal. bC» (calibrated age, before Christ). The calibration software Oxcal 3.10 after Ramsey (2005) has been used (details on the analytical protocol are reported by Calderoni & Petrone (1992). The C/N and ^{13}C/^{12}C ratios of the organic matter (tab. 1) were determined by means of an elemental C and N analyser and a Finnigan mass-spectrometer, respectively. At last, the radiocarbon readings were plotted on a depth-age diagram (fig. 7) allowing to roughly estimate the depth-age model function useful, in turn, to derive the averaged sedimentation rates for the considered time span.

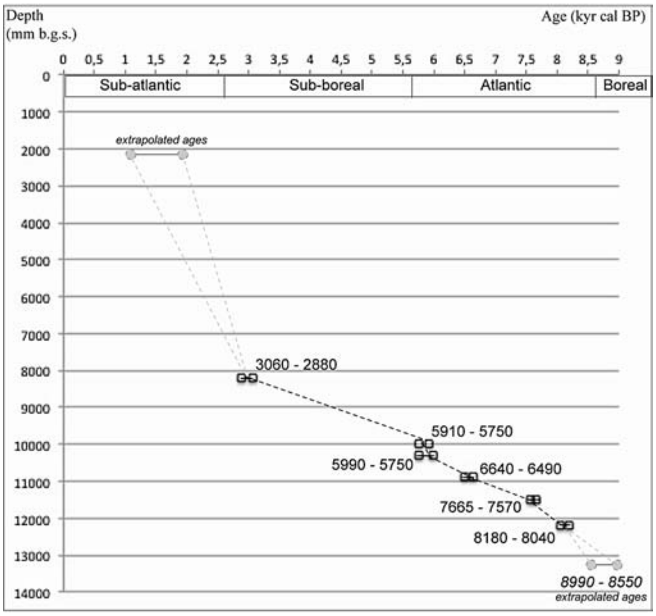


FIG. 7 - Age-depth curve for the lacustrine sequence of Montelago. Extrapolated ages for lake initiation and extinction are reported. For details on the sedimentation rates used for the extrapolation see the text. Holocene chronology after Orombelli & Ravazzi (1996). Ages are in conventional calibrated form.

Pollen analysis

Pollen analysis was performed on 22 samples of the drilled lacustrine sediments (figs. 6 and 8). According to the method of Erdtman (1936), each sample was weighed and treated with HCl, HF, NaOH and acetolysis, and the residue was stored in glycerine. For each slide, 150-200 pollen grains on average were counted, and the absolute values were calculated by the volumetric method (Goeury, 1992). The diagram thus obtained was processed and plotted through the program GpalWin (Goeury, 1992). Aquatic taxa, spores and *Cyperaceae* were excluded from the total sum, so that the pollen sum reflects only terrestrial taxa. The state of preservation of pollen grains was moderate in the peaty-clay, while the grains from the silty-clay were strongly altered. The pollen grains concentrations were, on average, 42x10^3 p/g in the peaty layers, 18.4x10^3 p/g in the organic-rich silty-clay, and 6.2x10^3 p/g in the silty-clay poor in vegetable matter at the top and in the lowermost part of the lacustrine sequence. The results of pollen count were plotted in a diagram, which was subdivided into 6 different pollen zones with homogeneous composition of pollen taxa (fig. 8).

KEY LANDFORMS AND DEPOSITS AT THE MONTELAGO SITE

The upper sector of the Fosso del Lago valley, encircled by Mt. Strega (1276 m, NE), Poggio Prato Tondo (1017 m, NW) and Mt. Foria (1115 m, SW) (figs. 2, 3 and 4), was dammed by a landslide that originated a small lake at present dried out (Savelli & *alii*, 2012). Slope-waste and alluvial deposits almost completely conceal the paleolake depression. Part of these deposits are slightly terraced by stream incision (fig. 2), an important clue for deciphering the latest evolution stages of the lacustrine depression, as discussed in the final section of this paper.

The Fosso del Lago stream crosses the paleolake site flowing to the SE within a relatively broad strike-valley,

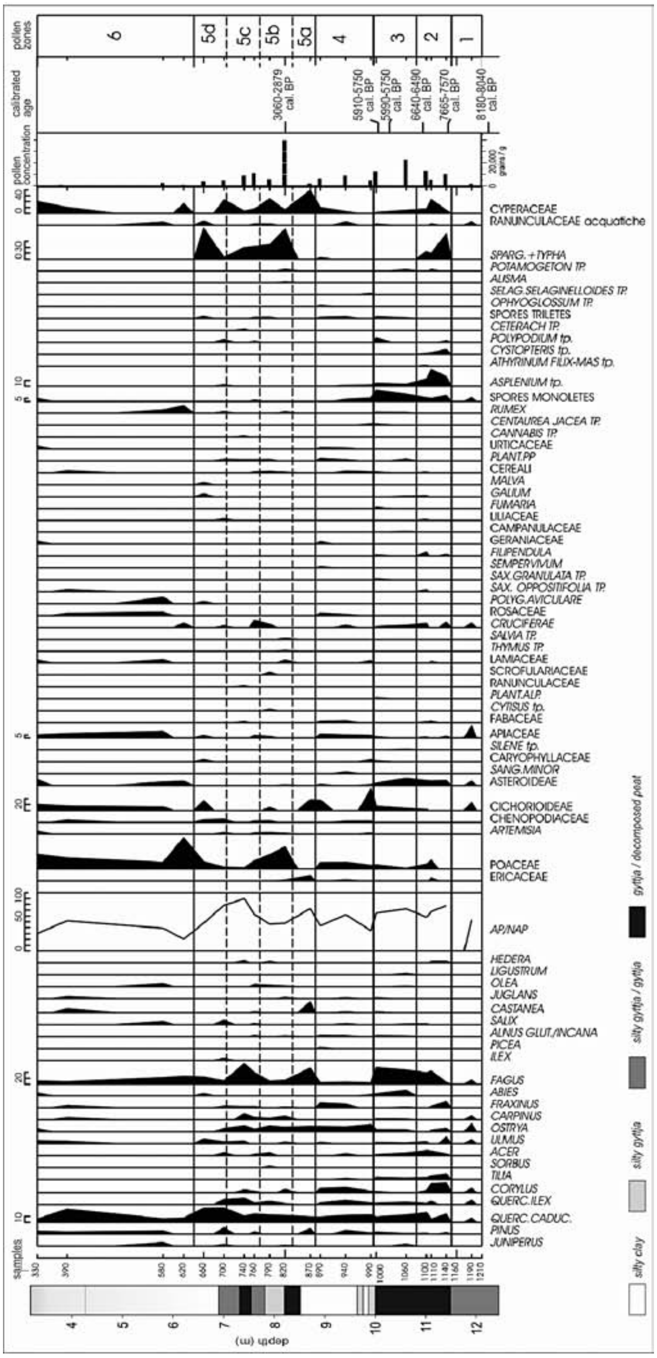


FIG. 8 - Percentage pollen diagram from the landslide-dammed paleolake. Core location in figs. 2 and 4.

which gouges out the axis of a narrow syncline. Downstream of the paleolake site, it keeps flowing to the SE entrenched in a narrow and deep valley cut in bedrock. The longitudinal profiles of the Fosso del Lago and its major tributaries (fig. 9) display a great deal of irregularities, reflecting both litho-structural constraints and sedimentary supply and storage. The major convexity matches the paleolake plus the related landslide dam, as discussed in a next section. The distinctive slope break which separates the Poggio Prato Tondo reach from the lacustrine depression (fig. 9), can be regarded as the result of slope retreat by selective erosion astride the weak *Marne a Fucoidi* Fm. A similar, although less pronounced configuration, is apparent in a left-tributary downstream Montelago (fig. 9). Other minor irregularities are plainly explained by bedrock differential resistance and/or local debris supply from hillslopes.

The head sector of the Fosso del Lago displays some key landforms, crucial for adequately tracing a morpho-evolutive history of the site. The area is strongly characterized by landslide morphology: landslides, however, juxtapose a range of smoothed hillslopes often associated with upper Pleistocene slope deposits (fig. 2) and/or join flats carved out by selective erosion on weak rock-units. In detail, the steep rectilinear Mt. Strega-Mt. La Penna upslope, sharply joins a footslope consisting of a wide, gently undulating terrace-like bench (fig. 3) carved out on the weak *Marne a Fucoidi* Fm. The bench is separated from the active stream by a steep toe-slope scarp gradually increasing in height downvalley, from ca. 20 m to over 120 m (figs. 4 and 10). The downvalley sector, where the village of Montelago stands, is blanketed by hummocky debris, partly derived from the reworking of minor landslide deposits; the upvalley sector is instead buried by the stream-damming landslide (cf. fig. 10). Rectilinear slopes (higher parts of the Mt. Strega-Mt. La Penna hillside) and uphill rounded/smoothed landforms (Poggio Prato Tondo and environs) hint at an extensive upper Pleistocene frost-shattering. The downslope redistribution of cryoclasts produced stratified slope-waste deposits (cf. Castiglioni & *alii*, 1979; Coltorti & *alii*, 1979; Nesci & Savelli, 1986) (fig. 2) of the *éboulis ordonnès* type (Tricart & Cailleux, 1967). At present, only a part of such relict deposits, locally exceeding 20 m in thickness, is undisturbed and well preserved, being large sectors broken and displaced by mass movements.

The reworking of the *éboulis ordonnès* and other materials involved in landsliding, besides supplying Holocene slope-waste deposits, has also delivered large amounts of gravel to streams, facilitating the growth of the fan-like bodies partially infilling the paleolake depression (fig. 2).

LANDSLIDES AND RELATED LANDFORMS

Le Fonti Landslide (LFL) - *Montelago Landslide* (MLL)

At the origin of the lake-forming failure is a «first time landslide» *sensu* Soldati & *alii* (2004), Borgatti & Soldati (2010), which at present consists of a compound landslide area covering a major portion of the Mt. Strega-Mt. La Penna hillslope (figs. 2, 3 and 4). Two individual sectors (LFL and MLL) can be distinguished, thus hinting to as many stages of activation, the younger of which (MLL) was responsible for the stream damming. The comprehensive landslide area is ca. 0.9 km^2 with a thickness of the slid-mass locally exceeding 40 m. The landslide involved thick piles of stratified slope-waste deposits partially ce-

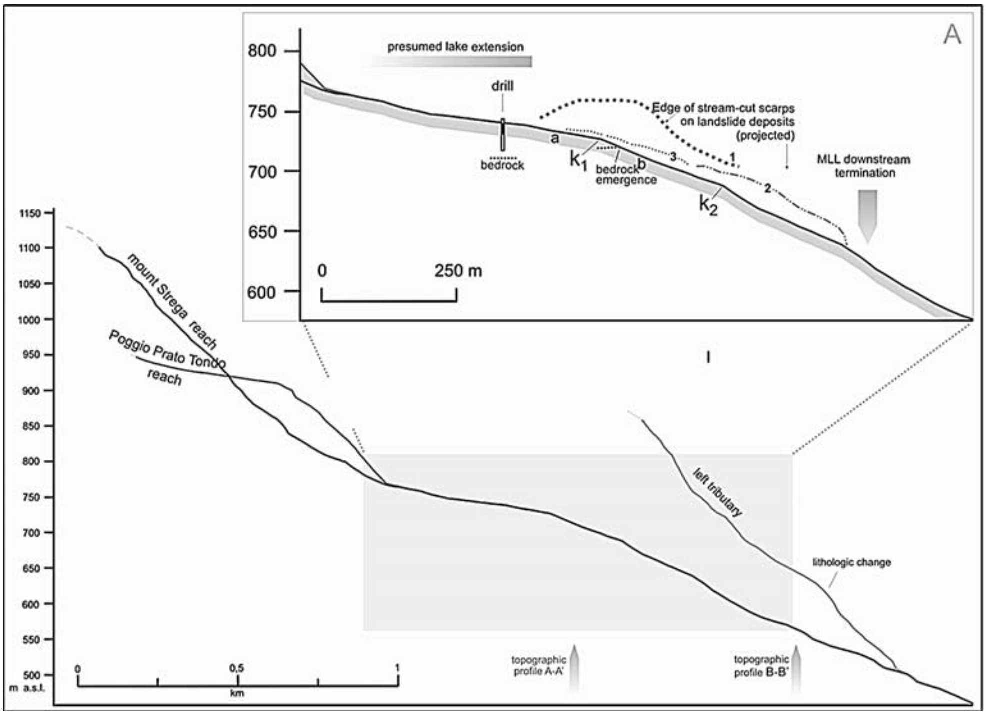


FIG. 9 - Longitudinal profile of the Fosso del Lago stream. Inset A: particular of the convexity resulting from landslide damming and associated upstream filling. The drill is shown with lacustrine deposits in black. Key-features described in the text are: k1, k2 = knickpoints; 1 = scarp on the Montelago Landslide (MLL); 2 = scarp on the reactivated sector of MLL; 3 = other scarps; *a* = reach matching the former spillway; *b* = reach steepened by headward erosion. Topographic profiles are represented in fig. 10.

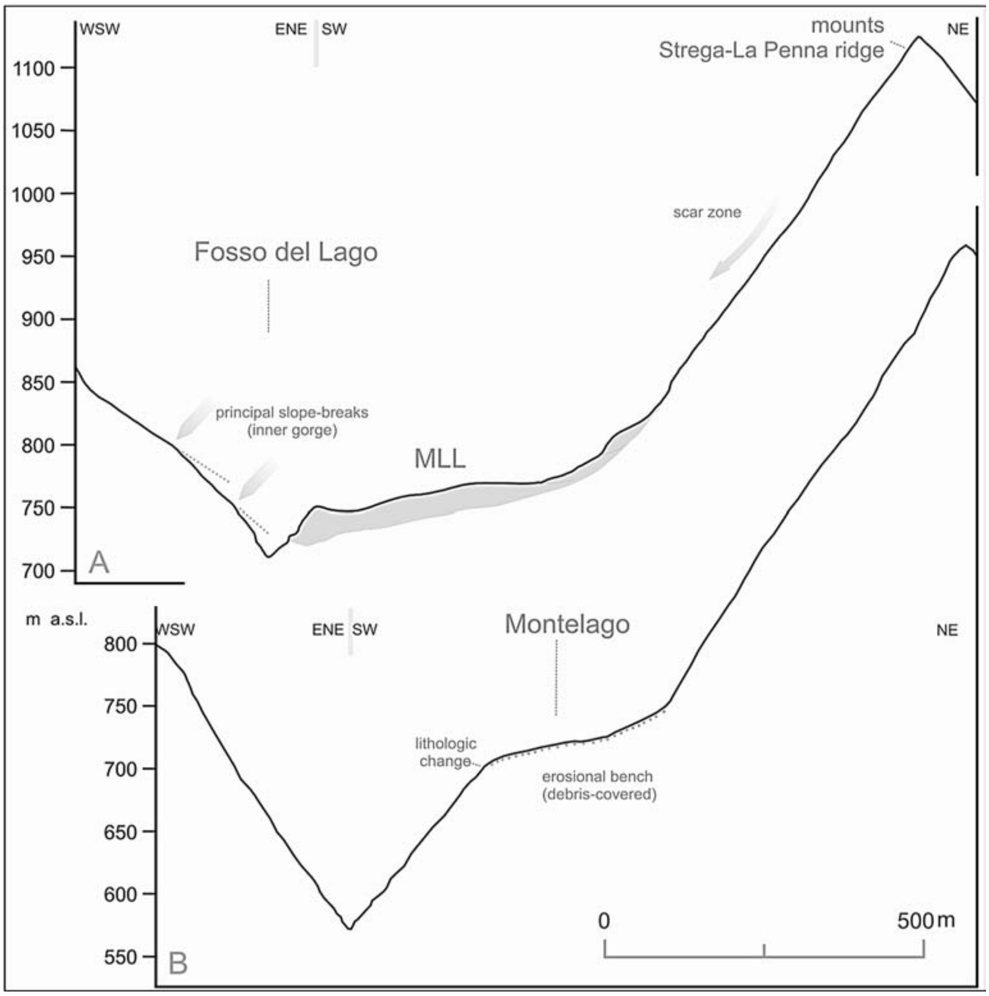


FIG. 10 - Transversal profiles across the Fosso del Lago valley. Key-features described in the text are reported. The grey color represents the supposed body of the Montelago landslide. Location of profiles in fig. 4.

mented by calcium-carbonate and, to a lesser amount, the underlying cherty-limestone of the *Maiolica* Fm. The bulk of the slide mass moved to the SW, controlled by bedding planes dipping out of the slope free-face with dip-angles fairly lesser than the slope. The detachment zone is revealed by series of small discontinuous scarps produced by the dislodgement of bedrock strata. The depletion zone is characterized by an overall planar configuration, locally stepped by small bedding-related scarps.

Le Fonti Landslide (LFL) is the oldest, perched portion of the LFL-MLL landslide, left behind by the MLL failure. Its geomorphic signature is a characteristic prominence on the Mt. Strega hillslope (figs. 2 and 4) that, according to the oldest geological cartography (Centamore & *alii*, 1975a), entirely consists of fine debris associated to various amounts of cobbles and breccia boulders (fig. 11a). The debris, derived from the *Maiolica* Fm. and locally cemented by calcium carbonate, shows at the outcrop a chaotic internal arrangement and/or detritic layers deformed by gravitational displacements. The toe of the LFL is rather smoothed and merges into equally smoothed calcareous bedrock. Hence, the possibility exists that portions of the toe area were slightly reshaped by late Pleistocene frost action, and also possibly covered by thin undisturbed veneers of *éboulis ordonnès* (fig. 2): if effective, it would be a significant constraint to the age of the failure.

The *Montelago Landslide* (MLL), much like the LFL as internal constitution (fig. 11), involves a total area of ca. 0.6 km^2, with a ca. 350 m runout onto the foothill erosional bench. The MLL major failure was followed by secondary movements that further displaced the landslide body (figs. 2 and 4), also producing a minor damming of the Fosso del Lago stream, as discussed in the next section. The displaced mass consists of sizeable blocks (locally >4-5 m) of calcareous breccia derived from the cemented stratified talus deposits involved in the movement. They are generally associated with subordinate and smaller blocks (usually <1 m) of cherty-limestone derived from the *Maiolica* Fm. beds (fig. 11). The dislodged blocks are always associated with abundant loose calcareous debris consisting of millimetric to decimetric angular clasts mostly derived from both poorly cemented breccias and uncemented talus deposits.

Monte Foria landslide (MFL)

This rotational slide covers an area of ca. 0.3 km^2 and lacks an appreciable runout. It involves an upper Pleis-

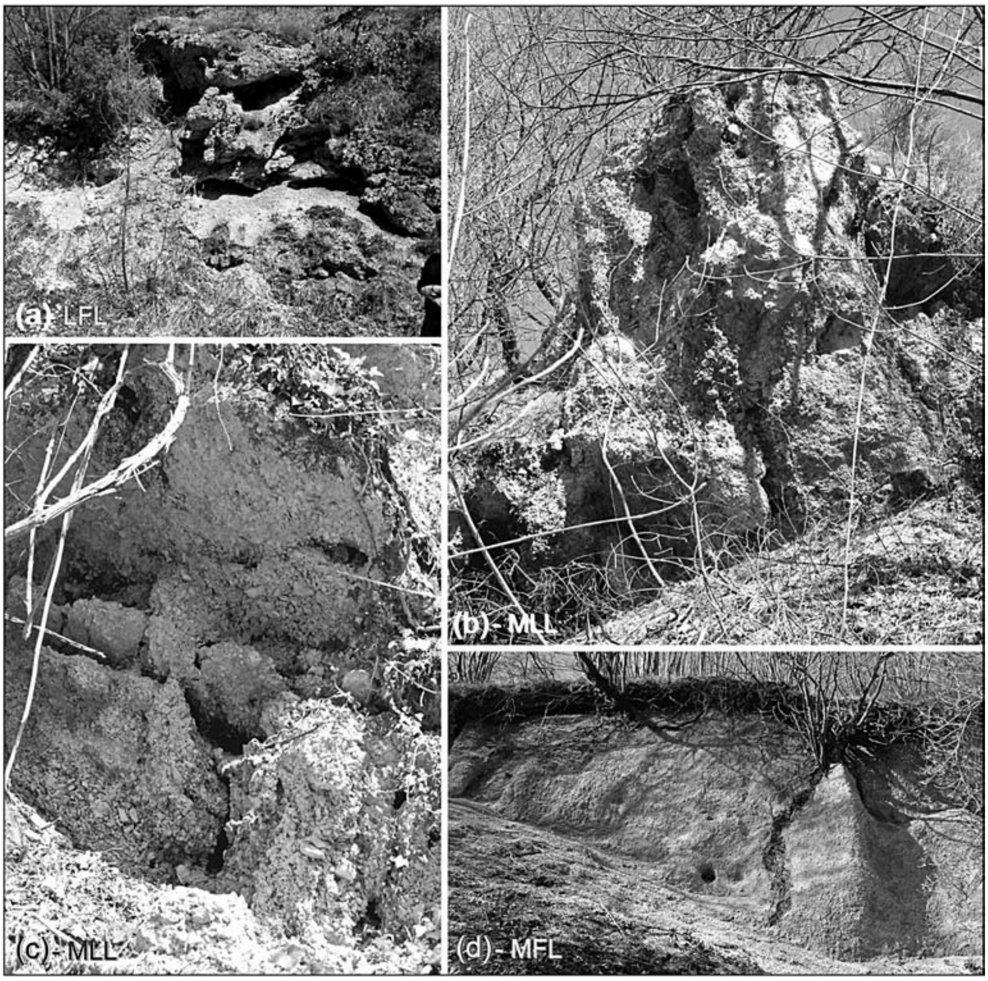


FIG. 11 - Internal characteristics of the landslide deposits at Montelago. (a), (b), and (c) = calcareous breccia boulders of Le Fonti Landslide (LFL) and Montelago Landslide (MLL); (d) = displaced frost-shattered debris in the Monte Foria Landslide (MFL).

tocene talus-slope (figs. 2 and 11d) and bedrock slabs of the *Marne a Fucoidi* Fm. and *Scaglia* Group. Care has been taken to evaluate the MFL, since it has been previously regarded as the responsible for the paleolake formation (Massoli-Novelli, 2008; Dignani, 2009). The landslide toe remains perched over the streambed, here entrenched in bedrock. A minor rotational slide reactivating the MFL upvalley sector (figs. 2 and 4), developed a lesser runout that reached the valley floor. An active fluvial scarp, up to 10 m-high, cuts the runout (fig. 11d) indicating a retreat of the landslide toe of ca. 30 m by stream erosion.

Rifugio Stella Landslide (RSL)

It is a ca. 0.4 km^2-wide rotational slide that, although not related with the paleolake, affects a large sector of the study site involving both bedrock and upper Pleistocene slope-waste deposits (figs. 2 and 4). The landforms freshness in the depletion zone attests very recent stages of activity, whilst tilted blocks with different degrees of remoulding underline its complex development.

GEOMORPHOLOGICAL EFFECTS OF LANDSLIDE-DAMMING

Starting from the core stratigraphy and from the complementary data obtained by seismic tomography and geomorphological fieldwork, the next section will focus on the landslide-damming and lake formation, as well as on the major modifications of the surrounding area. We will also definitely demonstrate that the MLL runout must be regarded as the only responsible for both stream deflection and lake formation.

The former valley and the origin of the lake

The drilled deposits (fig. 6) display that the lacustrine sediments overlie two individual gravel layers separated by an unconformity. The basal layer consists of greyish-whitish clasts of cherty-limestone derived from the *Maiolica* Fm., extensively cropping out on the SW hillslope of Mt. Strega-Mt. La Penna. The drilling stopped within such deposits without reaching the base (bedrock) that, based on the geophysical prospecting (fig. 5) and on the core projection on the stream profile (fig. 9), lies 3-5 m below.

The basal gravel, which is in places compact and/or slightly cemented by calcium carbonate, consists of granulometrically heterogeneous angular fragments with maximum grain-size of 3-5 cm. This gravel is consistent with the debris blanketing the erosional bench around Montelago and derived by mass-movements and slope wash affecting the hillsides of Mt. Strega-Mt. La Penna (cf. fig. 10B). Similar debris coverings, hence, are likely to have occurred throughout the whole bench since long before the MLL failed, thus explaining the presence of *Maiolica*-derived angular debris at the bottom of the core.

Gravel consisting of angular-subangular centimetric clasts (distinctively finer than those of the underlying horizon) unconformably overlays the basal unit (fig. 6). Such gravel, pink to reddish in colour, is derived from the *Scaglia* Group, which outcrops both at the head and on the SW side of the valley (fig. 2). The morphometric and granulometric characteristics of the clasts match those of frost-shattered debris of the *éboulis ordonnés* blanketing wide sectors of the hillslopes. Hence, most likely the clasts were supplied from these deposits and redistributed within the ancient valley-floor by mass movements and/or runoff on the SW hillside, also with possible along-valley stream reworking and terrace formation (fig. 5). In such regard, small valleys filled-up by *éboulis ordonnés* and successively terraced by stream re-incision are already known in similar sites of the northern Marche Apennines (Nesci & Savelli, 1986).The onset of the peaty-clayey lacustrine facies (fig. 6) points to the stream damming by the MLL failure. Starting from the radiocarbon ages, we roughly derived by extrapolation the lake initiation (and consequently the MLL failure) at 8990-8550 cal. BP (fig. 7). On the other hand, the age of the «first time landslide», the partial reactivation of which produced the MLL failure, is more difficult to ascertain. Some constraints, however, come from the disposal with respect to the LFL (i.e., the remain of the «first time landslide») of the *éboulis ordonnès* that, within the northern Marche Apennines, are ascribed, for the most part, to the upper Pleistocene coldest stages (Coltorti & Dramis, 1988 and 1995). Besides being extensively involved in both LFL and MLL failures, such deposits form thin, partially cemented veneers on the rectilinear rock-slope uphill the scar zone of the two landslides (fig. 2). Here, they are truncated downvalley, never lying undisturbed above landslide scarps and/or depleted materials. Consequently, since in the study area no field evidence for *éboulis ordonnès* older than upper Pleistocene is likely to exist, the LFL reasonably post-dates the last-glacial coldest stages.

Montelago is placed in a seismically active area (De Luca & *alii*, 2009; Piccinini & *alii*, 2009), where earthquake-induced mass movements should be expected (Keefer, 1994; Burbank, 2002). Thus, the problem arises of investigating possible correlations between the MLL triggering and seismic events, correlations that several examples from neighbour areas suggest (Farabollini & *alii*, 1995; Esposito & *alii*, 2000; Malamud & *alii*, 2004). Possible direct connections of the MLL failure with recently activated fault traces and seismic events, however, cannot be discussed on the basis of the data so far obtained. Since landslides can be related to climate change (Soldati & *alii*, 2004; Borgatti & Soldati, 2010; Crozier, 2011), a climatic control of the MLL failure is likewise plausible. In fact, the MLL is roughly constrained at the Boreal-Atlantic transition, thus within a time span that, in the Alpine-Apennine area (Abele, 1997; Ivi-Ochs & *alii*, 2009; Borgatti & Soldati, 2010), as well as throughout Europe (Berrisford & Matthews, 1997; Starkel, 1997; Dikau & Schrott, 1999), is acknowledged as a period of enhanced climate-driven landslide activity. However, apart from the above inferences, the question of whether climate and/or seismic activity played the key role in triggering the landslides eventually leading to the lake formation remains still open, needing wider targeted analyses to be unravelled.

Valley blockage and stream modifications

The MLL formed a stable landslide dam that is, accordingly to Ouimet & *alii* (2007), a dam that, regardless of successive outburst or breaching, was able to block and stabilize the river valley for hundreds to thousands of years. As the dam spanned the entire valley floor, it is ascribable to the Type II of Costa & Schuster (1988), that is the sub-type IIa of the two-dimensional types, as revised by Hermanns & *alii* (2011). Specifically, the MLL runout shifted the Fosso del Lago 60-80 m eastward, pushing it to the opposite valley side and originating a slight bend (figs. 2 and 4). Field evidence for a rather deep furrow in bedrock buried below the landslide mass (Fosso del Lago former course?) is also perceptible in form of a local thickening of the landslide deposits on the downstream rim of the MLL.

Incision along the shifted channel started producing an epigenetic gorge *sensu* Ouimet & *alii* (2008) (figs. 9 and 10): the channel-deepening resulted in hillslope undermining and consequent footslope steepening (fig. 10A), eventually generating an inner gorge *sensu* Kelsey (1988). Undermining and footslope steepening likely favoured the MFL failure (or reactivation) and further downslope movements of minor sectors of the MLL, as hereafter discussed.

The longitudinal profile of the dammed stream displays a marked convexity with a major low-gradient reach upstream the blockage (fig. 9). A sharp knickpoint (k1 in fig. 9) marks the abrupt transition from upstream low-gradient reach to the steep profile along the landslide outer rim. Field surveying demonstrated that the knickpoint corresponds to breccia boulders of the MLL. Occurrence of knickpoints corresponding to dramatic downvalley steepening across the landslide runout is commonly associated with channel-bed armouring by residual resistant boulders as the weaker and finer material is washed away by stream erosion in breach and/or spillway channels from the former landslide deposits (Ouimet & *alii*, 2007; Wang & *alii*, 2010). It is most likely the case of this specific segment of the Fosso del Lago stream. In fact, since the MLL moved downslope in a direction oblique to the valley floor, the outermost landslide tip is more advanced upstream (fig. 2). Hence, the stream could overtop the MLL deposits just in this point, while flowing downstream along the perimeter of the landslide. In this latter sector, the Fosso del Lago flows on bedrock with only scattered boulders within the channel and its gradient remains high, as usually reported for stream channels diverted on bedrock (Ouimet & *alii*, 2008). The undermining of the MLL deposits on the left valley side, besides causing minor landslide reactivations, induced recurring block failures. These phenomena, by supplying boulders to the channel and/or causing minor damming, contributed to further slowing and modulating the stream incision rates along the steepened epigenetic reach/inner gorge downvalley the blockage.

A secondary knickpoint (k2 in fig. 9) matches a reach floored by breccia boulders over a distance of several tens of metres. Here, several ruptures and counter-slopes on the MLL are faced on the opposite valley side by a 5-8 m-thick patch of calcareous breccia boulders (fig. 2), suggesting marginal reactivations that, at least in one occasion, crossed the stream and ran up the opposite hillslope. Notably, the local instability seems to relate with a local maximum thickness (more than 30 m) of the MLL incoherent material, possibly associated with the downstream emergence of the filled-up paleovalley.

The role of the Monte Foria Landslide (MFL)

When previous work on the paleolake is taken into account, the role of the MFL emerges as a crucial issue for reconstructing stream damming and valley evolution. In fact, Massoli Novelli (2008) indicated «*the talus landslide failed from Mt. Foria*» (i.e., the MFL of this paper) as the responsible for the damming. Similarly, the very first release of our work on Montelago, i.e. the preliminary technical report by Dignani (2009), drafted a likewise explanation. Critical data review and detailed fieldwork (Savelli & *alii*, 2012), however, compelled us to revise the role of the MFL as follows. *(1)* Deflection and convexity of the Fosso del Lago (figs. 2, 4 and 9) are clearly related to the MLL. *(2)* The freshness of landslide-related landforms has stimulated the «at first glance» interpretation of the MFL as responsible for stream damming: however, if compared with the radiocarbon chronological constraints, it reveals as evidence to the contrary. *(3)* The MFL consists of loose, fine-grained *éboulis ordonnés* (fig. 11d), hence unfavourable materials for dam maintenance over a time span comparable to the lake record (Costa & Schuster, 1988; Casagli & Ermini, 1999). *(4)* Only the reactivated sector of the MFL has a runout (fig. 2), but its size is too small to produce an effective stream damming. *(5)* The beheading of the runout by stream erosion, more than consistent with damming, rather highlights ordinary interference between slope-movements and stream action. Summing up, a near-damming phenomenon (Korup, 2002), at most, rather than a complete blockage of the stream, could have been in case generated by the MFL.

FILLING OF THE LAKE AND PALAEOENVIRONMENTAL REMARKS

The lacustrine sequence reveals recurrent facies variations (fig. 6), likely related to changes in basin configuration, land-use and lake-level. In such contexts the feasibility of ^{14}C chronology is heavily hampered by the availability of materials matching the compulsory prerequisites of ^{14}C dating, in terms of both origin and nature. A previous study (Calderoni & *alii,* 1997) reported several examples of biased ages yielded by organics scattered in a deltaic sedimentary suite due to alternating organic matter inputs from higher vegetation and floating/submerged pondweeds reasonably blooming in the former local marshes. To ensure against this risk we checked, by means of the $^{13}C/^{12}C$ and C/N ratios, if the dated organic debris were derived from vegetal ancestors actually grown through assimilation of tropospheric CO_2 and therefore suitable for radiocarbon dating. With the exception of a unique wood fragment (Rome-2028), the remaining five samples consisted of fine-grained mineral matrix containing variable content of peat, peat debris and/or scattered organic matter; all such constituents, in part humified, were affected to a variable extent by the first diagenesis. In some samples (Rome-2023 and Rome-2027) the occurrence of macroscopic vegetal litter debris was not evident: their uniform black colour, however, depended on the notable humic matter content, which likely originated *in situ* from the breakdown of the ancestor biomass. It is noted that the organic matter survival of the most refractory fractions (e.g., humic acids and humine) dispersed at macromolecular level, was favoured by the acid pH values (because of the carboxylic groups of the first formed humic matter) coupled with the reducing conditions which established as the fine grained sediments were an effective barrier against the oxygen penetration.

The C/N ratio of the dated organic matter ranges from 16.0 (Rome-2024) to 12.8 (Rome-2026), thus matching the values reported for organic relicts resulting from the breakdown of sub-aerial vegetal biomass (Prahl & *alii,* 1980). The variability of the C/N ratios is accounted for by the different decomposition pathways experienced by the vegetal debris, which resulted in a selective removal of the constituents of the primitive organic matter input. The C/N ratios are suggestive that the dated organic matter reasonably derives from only one source that is sub-aerial vegetation. Consistently, also the $\delta^{13}C$ values, ranging from –26.0 (‰) (Rome-2024) to –21.7 (‰) (Rome-2023), are typical of higher vegetation (C-3 pathway cycle) remnants, which underwent a mild early diagenesis producing just a slight ^{13}C enrichment due to the well known selective removal of the ^{12}C-enriched constituents.

As a whole, the ^{14}C readings yielded a fair coherent chronostratigraphy for the studied sedimentary sequence, thus ruling out any reworking as well as exceptional input processes (e.g., inwash from the hillslopes). Even the age of the wood sample (Rome-2028) fits the chronostratygraphic sequence, providing sound evidence on its autochthonous origin and synchronous deposition into the basin.

Based on the 6 radiocarbon ages the depth-age diagram in fig. 7 was elaborated. This diagram allowed us to roughly estimate the averaged long-term sedimentation rates for the time span from 8180-8040 cal. BP to 3060-2880 cal. BP. A medium rate of 0.80±0.05 mm yr^{-1} was obtained. Minimum rates are 0.51-0.65 mm yr^{-1}, obtained for the spans 7665-7570 cal. BP and 6640-6490 cal. BP; maximum rates, in turn, are 1.15-1.87 mm yr^{-1}, for the period from 8180-8040 cal. BP to 7665-7570 cal. BP. Although the estimated sedimentation rates are well close to the mean value, an outlier value of 4.1 mm yr^{-1} has been derived from the level dating between 5990-5750 cal. BP and 5910-5750 cal. BP. At any rate, the values obtained for Montelago are consistent with those proposed by the current literature for Holocene lake siltation in the central-northern Apennines (Watson, 1996; Magny & *alii*, 2007). On the basis of the sedimentation rates we also roughly derived, by linear extrapolation, the possible ages of both lake initiation and extinction. In particular, we used the sedimentation rates ranging from 1.15 to 1.87 mm yr^{-1}, which are the values recorded for the first period of lacustrine deposition, to estimate lake initiation. Hence, considering the base of lacustrine deposits lying at about -13.30 m (figs. 5 and 6), we estimated an age of 8990-8550 cal. BP for lake initiation, which is at the Boreal-Atlantic transition. More difficult is the evaluation of the lake extinction, given the lack of radiocarbon ages for the uppermost lacustrine deposits (too poor in organic matter), which makes it difficult to choose a realistic value of sedimentation rate. Actually, we can only tentatively extrapolate it adopting a unique mean sedimentation rate for the whole time span, and also assuming that this rate did not vary during that time. The first age we can hypothesize is 1000-700 cal. BP, obtained using rates of 2.8-3.1 mm yr^{-1}, which are the maximum values observed during the Holocene by Watson (1996) and Magny & *alii* (2007) in central-northern Apennines. A second option is the age of 1560-1230 cal. BP, calculated using the value of 4.1 mm yr^{-1}, which is the maximum rate obtained from the depth-age model function elaborated at Montelago.

Pollen record and lake filling

The stratigraphy, radiocarbon dating, and pollen analysis of the core provided information and chronological constraints on the paleolake Holocene evolution, also allowing palaeoenvironmental considerations.

A pebbly-clayey interval, perhaps hinting at a very first, stream-influenced filling stage, precedes the plainly lacustrine sequence (fig. 6). Silty-clay with abundant vegetable debris then starts filling the lacustrine trough. The lowermost lacustrine suite is extremely poor in pollen: the spectra (zone ML1, fig. 8), point to a vegetation represented by a beech forest, an oak forest with mesic species (*Corylus*, *Ostrya* and *Carpinus*), and pastures with Cichorioideae, Asteroideae, Apiaceae and Brassicaceae. The absence of aquatic taxa, with the exception of the Ranunculaceae, most likely confirms that the lake was rather deep, with the deeper zones directly joining the shore. The beech forest was at high altitudes, while oaks were found in lower areas. With regard to such outcomes, it is worth emphasizing that during the time span covered by the ML1 zone, vegetation of northern-central Italy was characterized by *Abies* (Lowe & *alii*, 1994, Vescovi & *alii*, 2007; Bellini & *alii*, 2009) and *Quercus* (Drescher-Schneider & *alii,* 2007), depending on the altitude. However, as discussed below, *Abies* appearance at Montelago is delayed at about 6640-6490 cal. BP.

The principal phase of organic-rich sedimentation, marked by a ca. 1.5 m-thick peaty-clay (fig. 6), corresponds to pollen zones ML2 and ML3 (fig. 8) and spans 7665-7570 cal. BP to 5910-5750 cal. BP, that is roughly until the transition from Atlantic to Sub-Boreal chronozone. Pollen spectra of zone ML2 hint at a development of hydrophytes, with *Sparganium/Typha* (50%) and Cyperaceae. However, the impossibility of any specific distinction of the latter and, specifically, of the genus *Carex* precludes to establish whether terrestrial or aquatic species are responsible for the peak at –1140 cm. Forest vegetation, characterized by *Corylus* mixed with *Fraxinus* and *Ulmus*, remained stable for about 900 years, i.e. roughly until 6640-6490 cal. BP. As for *Corylus*, it is worth noticing that, at present, hazel vegetation strongly depends on soil moisture and humification and also plays a role of stabilizing and improving the soil, thus favouring new arboreal species to colonize the area. Accordingly, in this span, *Corylus* probably grew in the more humid, organic-rich zones, most likely as a pioneer for beech forest. Other forest species in this zone, as *Tilia*, *Ulmus* and *Acer*, are to be regarded as components of the cenosis referred to *Tilio-Acerion*, i.e. an alliance including pioneer plant associations of gorges and fresh valleys with debris at the foot of rock-cliffs. Such forest formation was probably spread throughout the Fosso del Lago valley, where an undergrowth with different species of ferns grew, as suggested by the high percentage of monoletes and triletes spores, *Asplenium* tp., *Cystopteris* tp., *Polypodium* tp.

The peaty-clay deposition keeps on between 6640-6490 cal. BP and 5910-5750 cal. BP (zone ML3, fig. 8), when *Fagus* increases and *Abies* appears (8%). The latter taxon has a low distance of pollen dispersal (De Beaulieu, 1977): hence it presumably grew close to Montelago, most likely around the lake, since the peculiar morphology of this area protected it from regional pollen inputs. The spread of *Abies* around 6640-6490 cal. BP is consistent with a humid stage, which characterized Central Italy and the Mediterranean basin (Kelly & Huntley, 1991; Magny, 2004; Drescher-Schneider & *alii*, 2007). The delay recorded by the Montelago site is probably to be related to the distance of the refugee areas, which were placed in the Tuscan-Emilian Apennines during the last glacial maximum (Lowe, 1992). At Montelago, a maximum expansion of beech forest was also recorded during this phase: such taxon probably expanded over the areas previously occupied by *Corylus*, *Tilia*, *Acer* that, in turn, suffered a decline. Increased moisture could have also produced a lake-level rise which brought about the disappearance of species living in near-shore shallow waters. In fact, *Sparganium/Typha* underwent a drastic reduction while *Potamogeton* tp., able to live in deeper waters, was still present. Notably, such water-level changes are highlighted by pollen analysis, but have no evidence in the core that, apart for a peat concentration at about –1024 cm, remains quite unvaried throughout zones 2 and 3. Finally, clear evidence of human activity starts in this stage, as revealed by the beginning of a continuous curve of cereals and by the presence of *Plantago*, *Rumex*, *Centaurea*, *Castanea* and *Juglans.*

Summing up, based on the composition and present-day ecological needs of the above taxa, a more humid climate with respect to the present day can be assessed for the phase bracketing 7665-7570 cal. BP to 5910-5750 cal. BP. This appraisal is coherent with a period of high precipitations recorded throughout the Mediterranean area (Kelly & Huntley, 1991). It seems also consistent with data by Giraudi & *alii* (2011) who, although fixing maximum precipitation rates between 9000 and 7000 cal. BP, also place the end of the wetter climate around 5000-6000 cal. BP. It also fits several records from cave and lacustrine sediments in central Italy (Magny & *alii*, 2007; Zanchetta & *alii*, 2007; Zhornyak & *alii*, 2011).

At –1000 cm vegetable matter gradually decreases and, at ca. –965 cm, grey silty-clay replaces the blackish peaty-clay up to ca. –850 cm. Such interval, roughly bracketing the ages of 5910-5750 cal. BP and 3000 BP, corresponds to pollen zones ML4 and ML5a (fig. 8). The decrease in organic matter roughly matches the drastic decline of *Abies*, *Fagus*, monoletes spores and *Asplenium* tp. that characterize the onset of zone ML4. An increase of *Pinus*, *Quercus ilex*, *Corylus*, *Fraxinus*, *Alnus glutinosa* and herbaceous species, namely Poaceae, Apiaceae and Rosaceae, is the main characteristic of the interval in issue. Although the relatively low sampling density hampers precise correlation, reliable connections with other sites of central Italy can be reasonably outlined. Namely, comparable situations occur at the Colfiorito area, near the Umbria-Marche boundary (Brugiapaglia & De Beaulieu, 1995), at the Lago dell'Accesa (Drescher-Schneider & *alii*, 2007), at the Lago di Massacciuccoli (Mariotti Lippi & *alii*, 2007) and in Versilia, Tuscany (Bellini & *alii*, 2009), at the Lago Alimini Piccolo, Puglia (Di Rita & Magri, 2009), and at the Lago Pergusa, Sicily (Sadori & Narcisi, 2001). Since the expanding taxa (*Fraxinus*, *Acer*, *Corylus*, *Quercus ilex, Pinus*) consist of both thermophilic and pioneer species, the palynological analysis alone does not allow to definitely assessing the causes of the vegetation change in the considered interval. Nonetheless, a connection of this interval with a phase characterized by relatively intense, short-term climate fluctuations with pronounced dry periods, already recognized throughout the Mediterranean (Baroni & *alii*, 2006), is conceivable. Furthermore, the bulk of the change recorded at Montelago is roughly falling within the period of complex climatic oscillations bracketing 4300-3800 cal. BP postulated for the central-western Mediterranean by Magny & *alii* (2009). Possibly, it records the climatic transition to drier conditions characterizing the event at 4200 cal. BP, i.e. the Bond event 3 (Bond & *alii*, 1997) already recognized for Italian peninsular sites and other Mediterranean areas (Jalut & *alii*, 2000; Carriòn & *alii*, 2003; Caroli & Caldara, 2007; Giraudi & *alii*, 2011; Peyron & *alii*, 2011). On the other hand, standing on data at disposal, an important human impact resulting in the destruction of forest vegetation cannot be ruled out. However, since archaeological findings required for corroborating such hypotheses are not yet known in the study area (Silvestrini, *in verbis*), the most conceivable explanation for the drastic reduction of beech forest is a concurrence of climate and human activity, this latter supported by the increase of cereals, *Plantago* pp., Chenopodiaceae and Urticaceae (fig. 8).

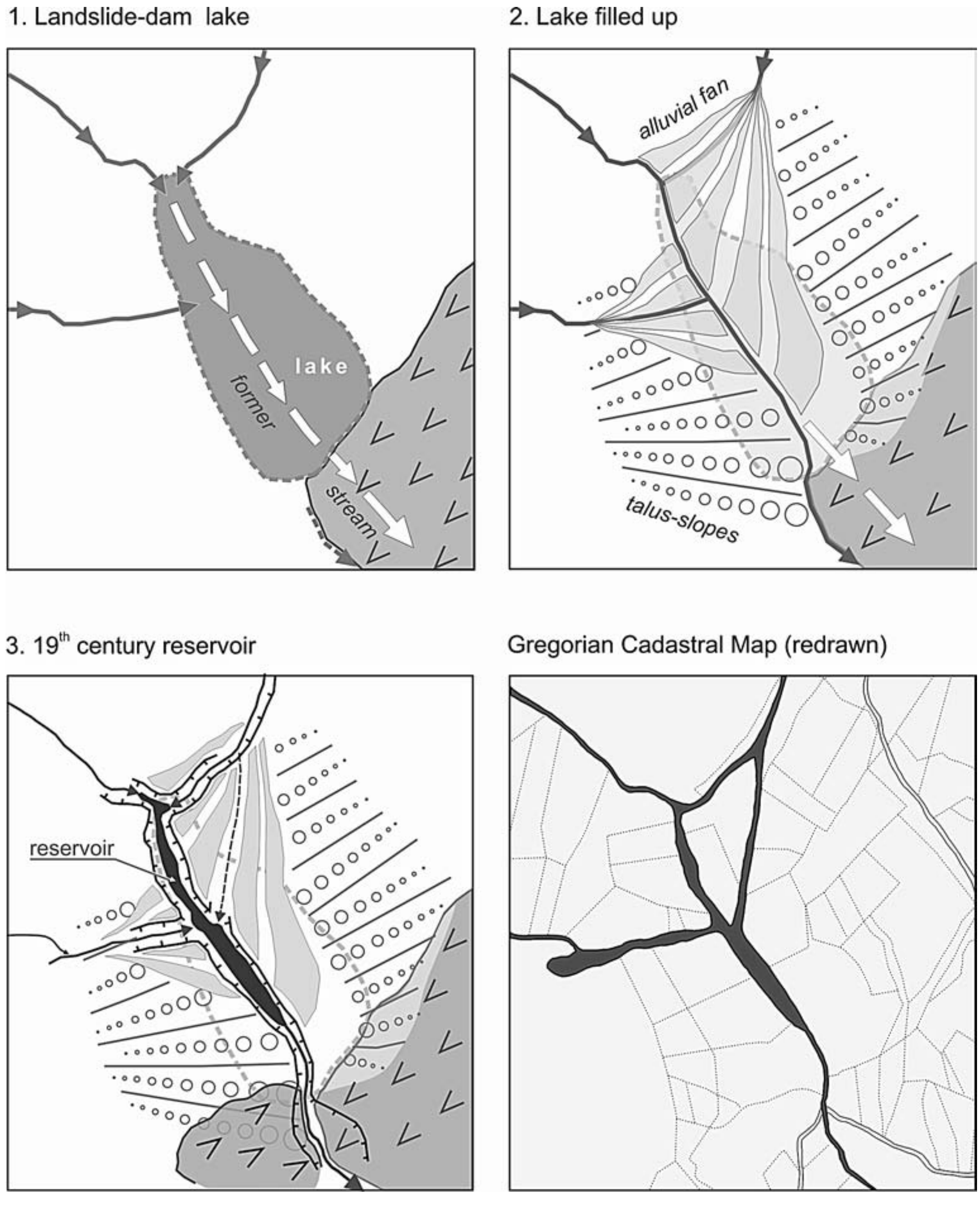
From –850 cm up to –690 cm a second level of organic-rich sediments with peaty-clay occurs (fig. 6) within pollen zone 5 (i.e., from subzone 5b to the lowermost part of 5d). The age of 3060-2880 cal. BP was obtained for the lowermost part of the organic-rich level, roughly amid subzone 5b. This latter is characterized by a new reduction of *Fagus*, much less abundant here than in zone 4. Such reduction is most likely related to human activities, as suggested by the increasing of Cereals, *Plantago* pp., *Rumex*, *Artemisia*, Chenopodiaceae, *Olea* and *Juglans*. The flourishing of aquatic vegetation, consisting of *Sparganium/Typha*, Cyperaceae, *Potamogeton*, *Alisma* and aquatic Ranunculaceae, is also apparent. Hence, a fringe of aquatic vegetation was largely reconstituted after the great reduction of aquatic taxa in subzones 3 and 4. Subzone 5c, entirely represented by peaty-clay and organic-rich silty-clay, is characterized by an increase of arboreal species, particularly *Fagus*, *Quercus ilex*, *Carpinus*, *Ostrya*, *Corylus* and *Salix*, whilst Poaceae, *Artemisia*, Chenopodiaceae, Apiaceae, Brassicaceae and aquatic species are reducing. Significantly, pollen of *Cannabis* tp. appears, suggesting that it was probably grown and worked close the lake-shores for producing tissues, as reported for sites of Northern Italy (Mercuri & *alii*, 2002; Brugiapaglia, 1996). Finally, within subzone 5d organic-rich sediments definitively disappear: a substantial reduction in percentages and absolute values of *Fagus* occurs, while those of deciduous *Quercus* and *Ulmus* increase. The augmented concentration of grass species and the ratio AP/NAP in favour of these latter suggest a strong reduction of the tree cover. Such assertion does not conflict with the curve of the deciduous oak forest, which exhibits an increase just in subzone 5d, after maintaining roughly constant throughout the pollen diagram. In fact, such behaviour most likely accounts for forest-free areas at higher altitudes, with pollens carried from below by winds.

The zone 6 is entirely comprised in the ca. 3.5 m-thick grey silty-clay poor in vegetable matter topping the lacustrine sequence. Only a few samples were collected within such level because the bad preservation of the core, thus allowing only some provisional assumptions. The cultivation of cereals, associated with the growing of olive trees, chestnut, walnut and willow, was possibly a major activity during this stage. Evidence for extensive agricultural, forestry, and pastoral practices is the presence of taxa as nitrophilous *Rumex*, Urticaceae, Cichorioideae, Asteroideae: they possibly expanded even in former lacustrine areas, as suggested by the disappearance of aquatic plant communities, with the only exception of aquatic Ranunculaceae probably surviving in a shrinking pond. Also the drastic lithologic change at about –690 cm, i.e. immediately below zone 6, may account for a substantial reduction in plant covering with consequent fall in vegetable debris delivery and, perhaps, a concomitant (anthropic?) destruction of the lake-shore fringe of aquatic vegetation (Bloesch, 2004; Perry & Taylor, 2007). Even changes in bottom dynamics, water chemistry or oxygenation conditions cannot be ruled out in controlling the lithologic and vegetational change, but the available dataset does not allow any inference about this option yet. Otherwise, alternative explanations should be sought in different directions, e.g. a substantial and long-lasting lake-level rise, accordingly to current interpretations of peaty-inorganic sediment transitions (Magny, 2007; Finsinger & *alii*, 2010). In this case, the vanishing of aquatic communities would be merely explained by the submersion of a former shore area, thus involving changes in the physiography of the lacustrine trough. Since the depression was formed by landslide-damming and underwent a gradual shrinking because of sediment accumulation, a further damming and/or a human intervention in boosting the natural dam seems the only effective mechanism for a deepening of the trough. Actually, on the seismic line ST1 evidence of a failure from the right hillside is apparent: such landslide (a MFL reactivation?), however, only accounts for slightly pushing the right side of an already formed lake toward the valley axis, as demonstrate by the geometric relationships between the landslide hanging wall and the lacustrine footwall (fig. 5). A further landslide-damming and/or anthropic modifications stay therefore as issues not yet substantiated by any reliable evidence.

Lake extinction

Apart from a gradual shrinking of the lake, a water mass persisted for over seven millennia close to the dam. Hence, owing to geological, physiographical and hydrological favourable conditions (Cohen, 2003), the clastic supply to the lacustrine trough must have been relatively low. In this respect, field and drill data (figs. 2 and 6) reveal that coarser material remained restricted to the up-lake sector and, to a lesser extent, to the right side, whilst in the down-lake zone only organic matter and silty-clay were deposited. The main reason for this seems to be the prevailing coarse debris generated by the carbonate bedrock and accompanied, in the down-lake sector, by a low hillslope-lake connectivity mainly due to the poorly organized drainage on the hillslopes. Nonetheless, pseudo-karst (*sensu* Halliday, 2004) underground circulation through landslide-produced fractures and crevices that characterize the area makes an important contribution to water subtraction to the surface runoff. Pollen record also suggests lake level fluctuations: in such regard, it would be crucial to decipher whether the upper inorganic siltation accounts for positive lake level fluctuations or, as more likely, it depends on a mere deterioration of the forest cover. Significantly, the same overflow/breach mechanism would be further clarified if this issue were known. In fact, plausible mechanisms for lake extinction could be either a complete sedimentary filling of the trough and/or a breaching by overflow erosion, this latter being one of the most common mechanisms of landslide-dam removal (Costa & Schuster, 1988). If the assumption that peaty sediments would have to mark the ultimate shallowing of the lake (Magny, 2007) is true for Montelago, hence a breaching is necessary to explain the emptying of a still relatively deep-water basin. But if a large human pressure causing forest degradation and land denudation is advocated, a sedimentary fill without appreciable formation of peaty sediments may also be put forward. In such a frame, geomorphological data underline that the stream channel became entrenched atop the alluvium overfilling the lake (fig. 2), but the entrenchment affected only a few decimetres of the topmost lacustrine sequence. Hence, the entrenchment can be a mere readjustment of the stream-profile following the lake extinction. Actually, a key element for establishing reliable mechanisms for the overflow/breach of the dam and lake extinction is the bouldery knickpoint k1 (fig. 9) on the MLL deposits, which sets ca. 100-120 m downstream the down-lake termination. The channel reach (*a* in fig. 9A, slope 6-8%) joining this latter with the knickpoint k1 roughly matches the former spillway/breaching channel. Conversely, the steepened reach downstream the k1 (*b* in fig. 9A) is related with headward erosion on the MLL body and/or on its partial reactivations, and never joined directly the down-lake termination (cf. fig. 9A) to open a breach. Summing up, data so far available do not allow to establish whether filling up alone and/or combined with not better definable emptying processes caused the lake extinction and started the dissection of the up-lake alluvium. Anyhow, no dramatic outbursts produced by a complete dam removal/breaching seems to have occurred.

Based on the age extrapolations previously discussed, the lake vanished in a span ranging between the first few centuries AD up to about 1300 AD. A relatively long time thus spans between the extinction of the landslide-dammed lake and the 19th century maps of the Gregorian Cadastre, which testify for a water pond along the Fosso del Lago valley (fig. 12). Such historical documentation, seemingly contradictory if compared with the dataset as far achieved and with the results of the above discussion, clearly hampers any plain conclusion on the ultimate evolution steps of the lacustrine area. Nonetheless, general in-


1. Landslide-dam lake

2. Lake filled up

3. 19th century reservoir

Gregorian Cadastral Map (redrawn)

FIG. 12 - Evolution sketch after Savelli & *alii* (2012) of the Montelago lacustrine depression framing the small reservoir reported by the 19th century Cadastre. Unless otherwise specified, symbols are the same as in fig. 2.

ferences can be drawn by coupling field and historical data. Specifically, according to Savelli & *alii* (2012), the pond on the 19th century Gregorian Cadastre is definitely entrenched in the up-lake alluvial and lacustrine sediments, thus post-dating the paleolake fill and following the post-lake Fosso del Lago downcutting. Furthermore, the 19th century pond is rimmed by straight scarps and does not match the ultimate paleolake position, but is visibly shifted upstream (figs. 2 and 12). Such outcomes reveal that the pond is a small man-made reservoir exploiting important, at present dried out springs (fig. 2). Neither historical nor field evidence, instead, is so far known for marshes or ponds re-formed in the former down-lake area to indicate a survival or restoration of the paleolake. In this frame, several questions remain still open, which need further investigations to be performed. What is still unclear is *a)* when the reservoir was made, *b)* if and how the 19th century ponds were related to wet areas possibly survived to the lake extinction, *c)* why the reservoir is placed upstream with respect to the former lake, and *d*) what is the meaning of the odd planform of streams, characterized by local intersecting channels (fig. 12). As regards these latter, did they have the function of preventing excessive sediment supply to the reservoir during flood stages, as suggested by Savelli & *alii* (2012)? Or other explanations must be envisaged? Whatever the future assessments, it is certain that two distinct lakes existed in different times roughly in the same depression along the Fosso del Lago: the older was a direct consequence of landslide damming, while the younger one was a small reservoir exploiting local springs.

CONCLUSIONS

The present work reports the results of a multidisciplinary research carried out at Montelago, in the northern Marche Apennines (central Italy), where a lake was formed by landslide-damming. Detailed geomorphological fieldwork, seismic tomography and sediment-core drilling were performed, accomplished by radiocarbon dating and pollen analysis in order to establish characters, palaeoenvironments and evolution of the site. Key modifications within the Fosso del Lago valley resulting from the stream blockage and secondary landslide movements were also investigated. The Montelago Landslide (MLL) was definitely acknowledged as the responsible for landslide-damming. Specifically, the MLL is a partial reactivation of a larger «first time landslide» post-dating the upper Pleistocene coldest stages and the present-day remnant of which is Le Fonti Landslide (LFL), a slid-mass perched high on the left-valley side. The failure involved a thick, partially cemented talus deposit overlying downslope-dipping well-stratified bedrock. A stable dam of calcareous breccia boulders was thus formed. The damming caused important modifications in the Fosso del Lago valley, both along the stream profile and on the hillsides. Namely, along the stream profile the damming produced a marked convexity associated with a distinctive knickpoint on residual landslide boulders. Downvalley of the dam, the epigenetic deepening of the Fosso del Lago, diverted to the opposite hillside, originated an inner gorge where a marked knickpoint matching a secondary landslide reactivation is also found.

^{14}C readings of sediment core records from the ancient lake deposits and derived depth-age extrapolations proved that the lacustrine environment lasted over seven millennia. The landslide blockage has been constrained at the Boreal-Atlantic transition (i.e., 8990-8550 cal. BP), which is a period characterized by enhanced landslide activity presumably connected with peaks in rainfall throughout the Alpine and Apennine regions.

The vegetational pollen analysis proved to be crucial to obtain information on the local palaeoenvironment and ancient land-use, especially for the first period of the lake's existence. Also intriguing is the detection within the paleolake of a sedimentary record suitable for future thorough palynological analyses. At present, in fact, palaeovegetal reconstructions are extremely rare for the Holocene of the Adriatic side of the Apennines, due both to the scarcity of suitable sedimentary sites and, as for Montelago, to the disappearance of former lakes. The pollen record of Montelago, which is so far unique for the Marche Apennines, revealed environmental changes possibly correlated with important climatic fluctuations already acknowledged for the Holocene. Namely, pollen data provided a local record for a humid phase spanning 7665-7570 cal. BP to 5910-5750 cal. BP, which at the regional scale is coherent with a period of high precipitations documented for the whole Mediterranean area. Pollen data also indicate a local environmental modification at 4200 cal. BP., coherent with a well known global aridification event already recognized in the Italian peninsula. A synergy of human factors in forcing the change recorded at Montelago, however, cannot be ruled out on the basis of data so far available.

The age of lake extinction, barely achieved by extrapolation from derived sedimentation rates, is rather uncertain, spanning from the very first centuries AD up to about 1300 AD. Some questions also arose about the lake extinction in that the Gregorian cadastral maps (1816-1835 AD) report a long water pond close to the paleolake site, the form and position of which do not allow to regard it as a relic of the former lake. Such pond rather originated long after the landslide-dammed lake extinction, by a human intervention addressed to create a small reservoir.

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