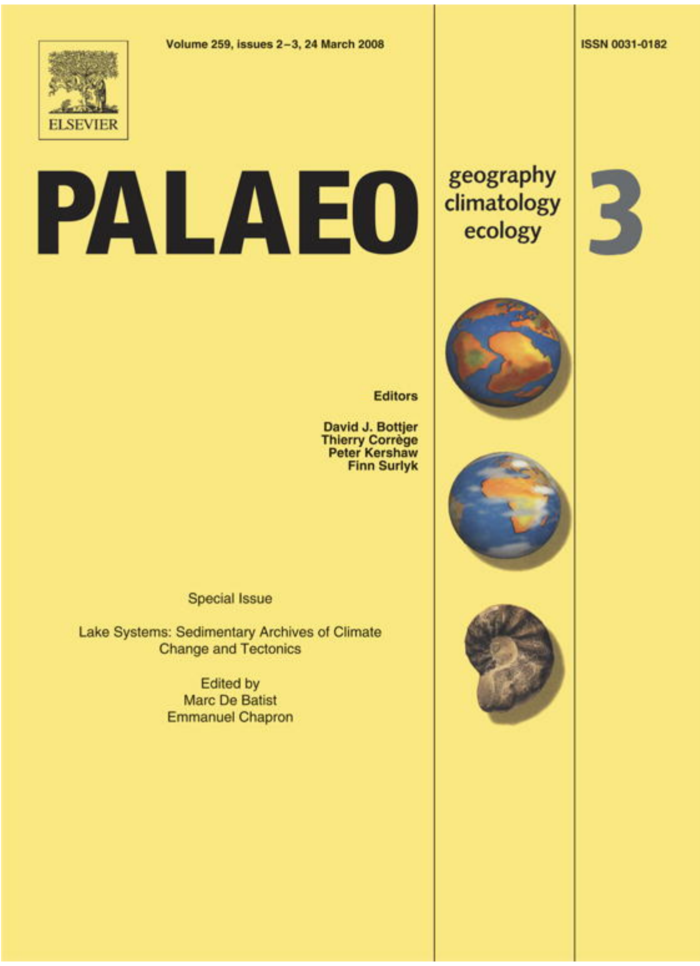
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Megaturbidite deposits in the Holocene basin fill of Lake Como (Southern Alps, Italy)

Daniela Fanetti [a,*], Flavio S. Anselmetti [b], Emmanuel Chapron [b], Michael Sturm [c], Luigina Vezzoli [a]

[a] Dipartimento di Scienze Chimiche e Ambientali, Università degli Studi dell'Insubria, via Valleggio 11, I-22100 Como, Italy
[b] Geological Institute, Swiss Federal Institute of Technology, ETH Zentrum, CH-8092 Zürich, Switzerland
[c] EAWAG, Überlandstrasse 133, CH-8600 Dübendorf, Switzerland

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Abstract

For the first time, limnogeological investigations have been carried out in Lake Como, the deepest lake of the Alps, combining a bathymetric survey (multibeam Simrad 3000) with a high-resolution seismic reflection study (single-channel 3.5 kHz sub-bottom profiler) and a coring campaign (gravity corer). This data set enables detailed characterization of the sedimentary subsurface in the western branch of the lake, the Como branch, which has a typical fjord morphology. This paper focuses on the deepest part of the Como branch (Argegno basin), in which up to 3.5-m-thick turbidite deposits are identified. The basin fill of the Como branch is characterized by well-layered draping and onlapping pelagic sediments that are locally affected by creeping and that are intercalated with mass-wasting deposits, in particular with two large debris-flow deposits evolving into megaturbidites in the deepest part of the basin. The multibeam data together with the acoustic-facies distributions and the volumes of these two major sedimentary deposits MT1 ($\sim 3 \times 10^6$ m^3) and MT2 ($\sim 10.5 \times 10^6$ m^3) indicate that they resulted from large slides at the northern tip of the Como branch along the steep slopes of a sub-lacustrine plateau. The estimated ages of these events, around the mid-12th (MT1) and early 6th (MT2) centuries, are extrapolated from mean sedimentation rates based on radiocarbon (^{14}C) and radionuclide (^{137}Cs) analyses from short cores in the Argegno basin. Possible trigger mechanisms leading to these catastrophic events in the Como branch include a combination of steep-slope overloading, with significant lake-level fluctuations related to Holocene climate change and/or earthquake shaking. The tentative age assignment places the age of both major mass movements near two other events: MT1 near the occurrence of a major earthquake in the Po Plain in 1222 AD (Intensity IX MCS, macroseismically derived magnitude 6.2) and MT2 near a megaturbidite triggered in ~700 AD in a proglacial lake in southeastern Switzerland [Blass, A., Anselmetti, F., Grosjean, M., Sturm, M., 2005. The last 1300 years of environmental history in the sediments of Lake Sils (Engadine, Switzerland). Eclogae Geologicae Helvetiae 98, 319–332]. Since dangerous, tsunami-like waves (seiches) can be generated by large sub-aqueous landslides leading to such megaturbidites in this fjord-like basin, future studies are required: 1) to constrain the age of these catastrophic events; 2) to document the stabilities of the steep slopes in the Como branch, 3) to assess the expected frequency of such catastrophic events and 4) to model the propagation of large waves in the Como branch and their potential damage along the highly populated lake shore.

Keywords: Deep lacustrine sedimentation; High resolution seismic profiling; Multibeam bathymetry; Slope failure; Debris flows; Megaturbidites

* Corresponding author. Fax: +39 031 326230.
E-mail address: daniela.fanetti@uninsubria.it (D. Fanetti).

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1. Introduction

Megaturbidite deposits are well known and extensively studied in the marine environment (Cita et al., 1984; Kastens, 1984; Bouma, 1987; Weaver et al., 1992; Cita and Aloisi, 2000; Rebesco et al., 2000; Rothwell et al., 2000; Shanmugam, 2000). Such types of deposits can be characterized by their considerable thickness (several meters), by extensive surface areas (thousands of km^2) and by their large volumes (hundreds of km^3). Because they may represent exceptional events in the depositional history of a basin, the term 'megaturbidite' has been previously used for events that stand out prominently against regular background sedimentation (Bouma, 1987).

Although turbidity currents have been originally postulated in lakes (Heim, 1876, 1888; Forel, 1885), lacustrine turbidites are less frequently investigated than their marine equivalents (Sturm and Matter, 1978; Sturm et al., 1995; Shiki et al., 2000; Schnellmann et al., 2002). On an absolute scale, lacustrine turbidites are at least one order of magnitude smaller compared to their marine counterparts (Kelts and Hsü, 1980; Siegenthaler et al., 1987). Because large lacustrine turbidite events, however, still represent unique and exceptional events on a basinal scale, we use the term 'megaturbidites' also for these events.

We observed in Lake Como (northern Italy) for the first time in southern Alpine lakes, two turbidite deposits that, due to their exceptional thickness and extent, can be termed megaturbidites. Similar lacustrine deposits have been described in the literature only in a few cases (Sturm and Matter, 1978; Siegenthaler and Sturm, 1991; Chapron et al., 1999; Schnellmann et al., 2002). Lacustrine megaturbidite deposits are of particular interest, not only because they document unique depositional processes, but also because their mass-transport processes may represent a significant natural hazard. The sub-aquatic slope instabilities that cause these megaturbidite deposits can induce large water movements with propagating tsunami waves of significant height (Siegenthaler and Sturm, 1991; Schnellmann et al., 2002).

In this study we use new geological and geophysical data to investigate the lacustrine basin of Lake Como. The goals of this study are to evaluate characteristics and evolution of the recent and past sedimentation, to show the spatial distribution of the different types of deposits, to identify and map deposits related to sub-lacustrine landslides, and to investigate possible source areas and trigger mechanisms of such events.

2. General setting

Lake Como is located in northern Italy (average latitude: 46°10′ N; longitude: 09°16′ E) at an altitude of 198 m a.s.l. and occupies a southern Alpine valley transversal to the main axis of the Alps. With a maximum water depth of 425 m, Lake Como is the deepest lake in Europe and is the third largest Italian lake (142 km^2). It is in a central position within the Alps (Fig. 1): its drainage basin includes Valtellina (Adda River, 2600 km^2) and Valchiavenna (Mera River, 750 km^2) and corresponds to one of the major pathways between northern and southern Europe linking the core of the Alpine Chain with the Po Plain.

The lake is characterized by a 'lambda' shape (Fig. 1a) with three lake branches. The northern branch (or Alto Lario) has an N–S trend, is 23 km long and up to 4 km wide. Southward, it splits into two branches: i.e., the deep, narrow and steep western branch (Como branch) and the more open eastern branch (Lecco branch) (Figs. 1 and 2). Between Menaggio and Bellagio a bathymetric sill (named 'Bellagio plateau' in this study) at 140 m water depth separates the Como branch from the rest of the lake (Figs. 1b, 2a and b). To the SW, over a short distance of only ~3 km, the lake floor drops to a water depth of over 400 m and forms the Argegno basin. This basin has a relatively constant water depth of ~400 m over a distance of ~12 km until Laglio, where a relatively steep slope raises the lake floor to ~200 m water depth (Figs. 2a and b). Further to the SW, water depth decreases gradually and the lake floor gently rises towards the town of Como, were the Breggia and Greggio rivers (Fig. 1a) form well-developed Gilbert-type deltas. The Como branch has no outflow and its deep basin is hydrologically closed. The only water exchange with the main lake occurs over the Bellagio plateau in the NE. In contrast, the Lecco branch is shallower and has a more regular bathymetry, which continuously shallows from a maximum water depth of 250 m towards the town of Lecco. The only outflow of Lake Como, the Adda River, is located at the southern tip of the eastern branch.

Geologically, Lake Como is located in the Central Alps. One of the most significant structural elements in this area is the Insubric line (Gansser, 1968; Heitzmann, 1991), an E–W trending fault along the Adda valley representing the boundary between the Austroalpine and Penninic units to the N, and the southern Alpine basement to the S (Fig. 1a). The Insubric line cuts Lake Como at its northern edge (Alto Lario) so that almost the entire lake lies in the southern Alpine unit, a gently southwestward-dipping homocline. The southern Alpine crystalline basement consists of paragneiss and

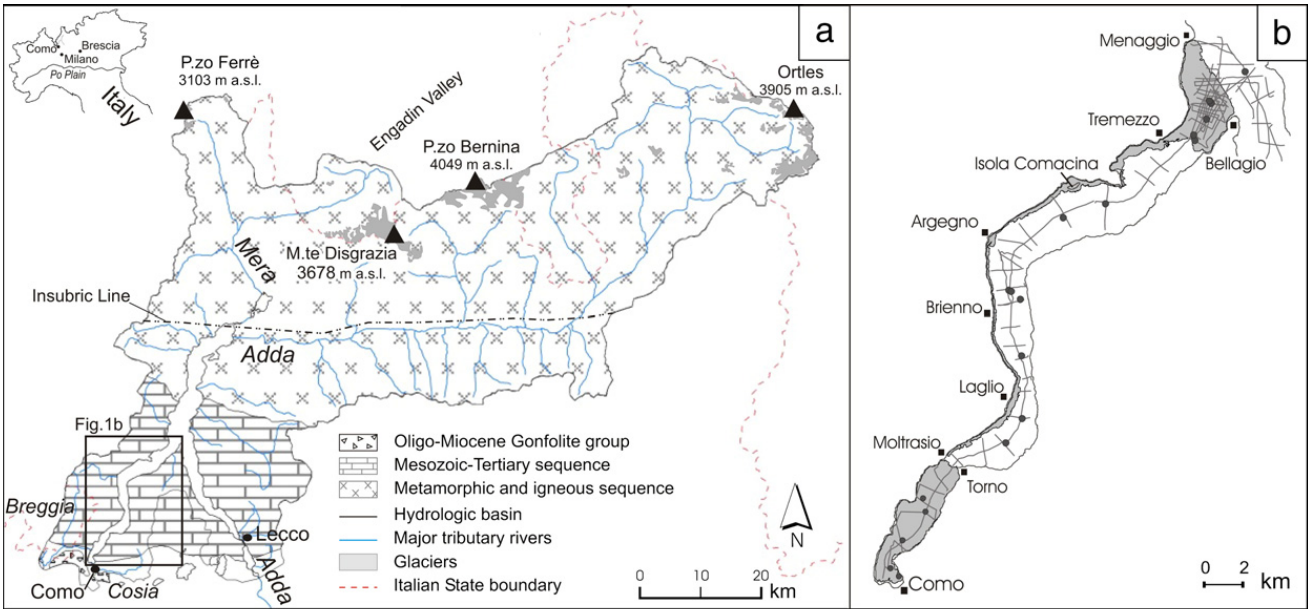


Fig. 1. General location of the Como branch. (a) Geological and regional setting of Lake Como catchment area, its main tributary rivers and the current distribution of the glaciers. (b) The database used in this study: 3.5 kHz seismic grid (black lines), location of the 19 gravity cores (black points) and the area surveyed with the multibeam (grey).

subordinate orthogneiss and amphibolites of Variscan age (Spalla et al., 2002). The Variscan rocks are unconformably overlain by Palaeozoic–Mesozoic sediments (Bertotti, 1991) that surround the southern two thirds of Lake Como. Previous studies have shown that, since the late Pliocene, the Lake Como area was subjected to 13 glacial episodes during which the glaciers extended to the upper Po Plain (Bini, 1987, 1997; Bini et al., 1996). The lake is today partly dammed by the frontal moraines of the Last Glacial Maximum. The Lake Como basin is thus a combined product of glacial erosion and inherited tectonic structures (Riva, 1957; Castelletti and Orombelli, 1986; Florineth and Schluechter, 1998). Today only 2.2% of the catchment area of the Adda River is covered by the glaciers Bernina, Disgrazia, Ferré and Ortles (Fig. 1a). Geological and geomorphological evidence suggests that Quaternary structures within the thrust belt of the southern Alpine foothills surrounding the lake are still active (Giardina et al., 2005). In particular, neotectonic activity was recognized E of the city of Como within a sequence of glacial and fluvioglacial middle Pleistocene deposits uplifted along the foothills between Como and Lecco across the forelimb of an active anticline (Orombelli, 1976; Zanchi et al., 1995; Giardina et al., 2005).

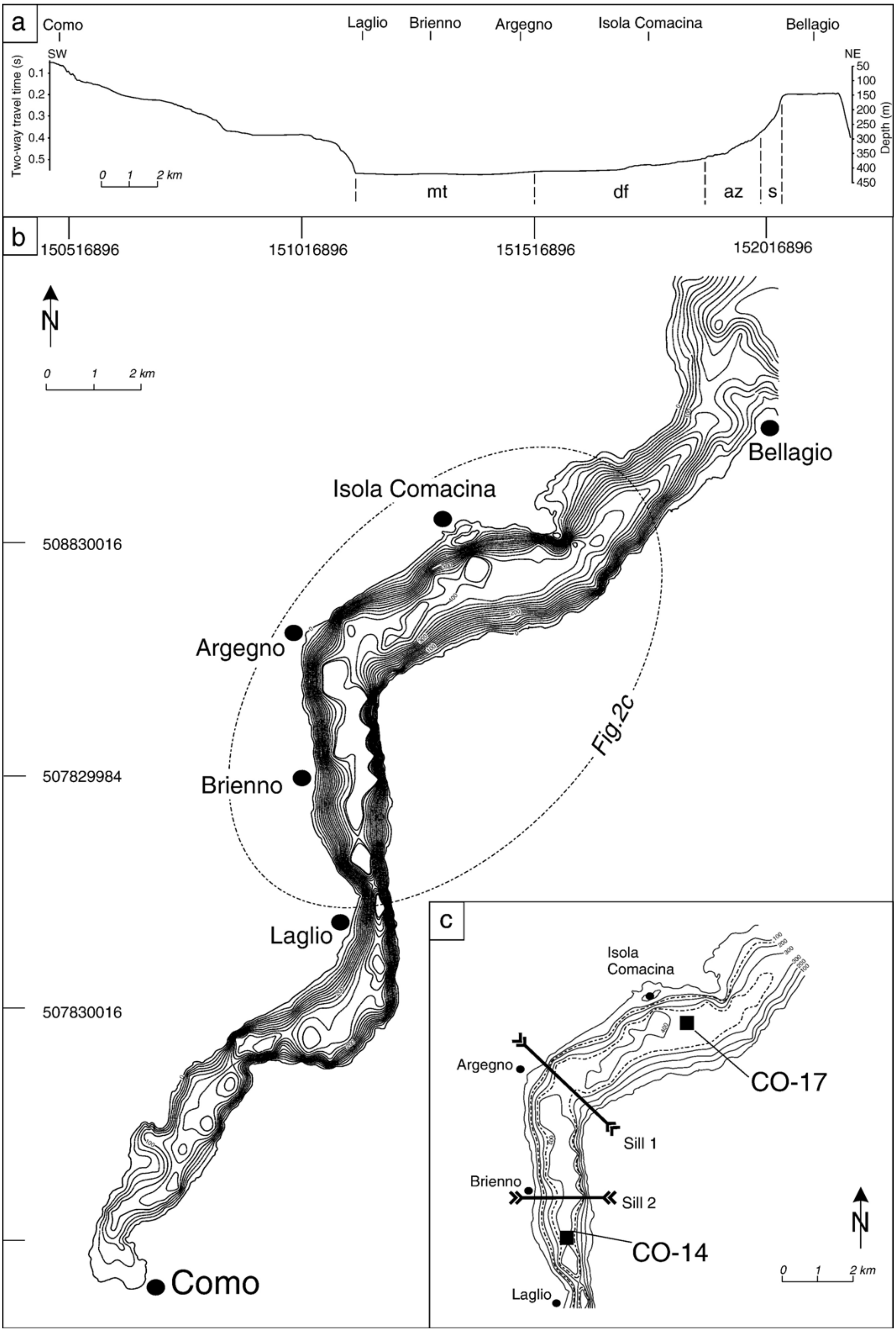
The subsurface of Lake Como was previously investigated by Finckh (1978) and Finckh et al. (1984). A series of transverse and longitudinal deep-penetrating reflection seismic profiles along and across the lake axis provided information on the bedrock depth below the lake level (between −756 and −886 m) and on the total thickness of sediments (~460 m). Finckh (1978) recognized the presence of three main units in the sedimentary infill based on seismic reflection and refraction data. The upper one (14 m thick) was defined as post-glacial and Holocene mud and silt with the possible presence of sand. The middle unit (maximum thickness of 330 m) corresponds to water-saturated alluvium and till deposits. The deepest stratum is interpreted as compacted gravels and/or other well-cemented sediments, with a variable thickness of several hundreds of meters, below which limestones form the basement.

3. Methods

The data used in this work are part of a broad scientific project of the Università degli Studi dell'Insubria focussing on the limnogeology of Lake Como, which includes three different types of geophysical and sedimentological investigations.

3.1. Multibeam bathymetry

In winter 2001, Lake Como was surveyed with a high-resolution shallow-water Simrad EM 3000 multibeam system. The survey and the data processing was conducted by the GAS of Pianoro- BO (Italy) using the motorboat "Rondine" of the "Navigazione Lago di Como". The maximum water depth investigated was ca. 250 m, with a vertical resolution of 5 cm within a 5 × 5 m grid. Positioning was achieved with a DGPS. The average ship speed was 8 km/h during good-weather conditions and 5.5 km/h during windy weather. Three



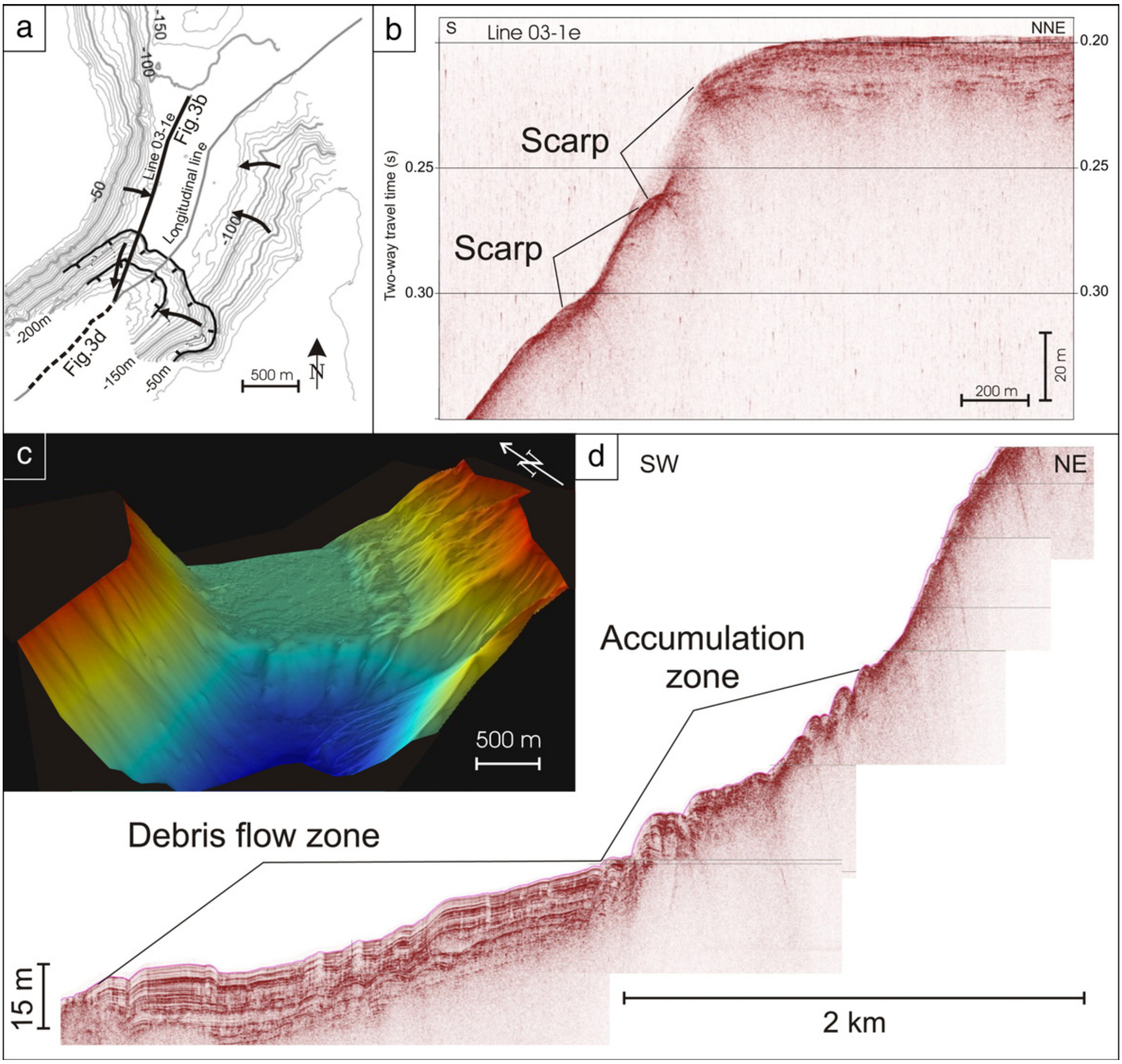


Fig. 3. The subsurface of the Bellagio plateau. (a) Detailed bathymetric map of the plateau based on multibeam data and location of seismic section presented in 3b and 3d (black and dotted lines). Also indicated are the run-off marks and the preferential sediment-transport pathways (black arrows) and the extension of two large scars along the southwestern slope of the plateau defined through the combined seismic and bathymetric analyses (indented black lines). (b) Seismic section illustrating the basin fill of the Bellagio plateau and the occurrence of two large scars along its southwestern slope. (c) DEM of the plateau area with a vertical exaggeration of 1.5 and a grid of 5 × 5 m that illustrates the complex morphology of the SW flank of the plateau. (d) Seismic section showing the recent accumulation of slides and slumps at the foot of the southwestern slope of the plateau that evolve towards the basin into two main debris-flow deposits intercalated with the background sedimentation.

key areas located in the north, central and southwestern sectors of Lake Como were surveyed (Fig. 1b, grey areas). Data processing was conducted with the SIMRAD Neptune processing system, including filtering and data correction (navigation and positioning), spike filtering and statistical-based data cleaning (noise

Fig. 2. Bathymetry of the Como branch. (a) Topographic profile of the Como branch obtained by the longitudinal 3.5 kHz seismic line showing the Bellagio plateau, the deep Argegno basin and the shallower Laglio–Como basin discussed in the text. Dotted lines indicate the extension of the four stages of the large slope failures associated with MT1 and MT2 in the deep basin: the large slide scars (s), the ~2.4-km-long accumulation zone (az), the ~4.8-km-long debris-flow deposits (df) and the ~5.5-km-long megaturbidites (mt). (b) Bathymetric map (isobaths each 25 m) of the Como branch re-elaborated by C. Carcano and C. Cattaneo on the base of the Vassena punctual measurements (1948). (c) Zoom of the bathymetric map of the Argegno basin shown in 2b, locating cores CO-14 (coordinates: 1511434.71 and 5083088.97 in Gauss-Boaga system) and CO-17 (1515025.25 and 5089532.19) and the sills offshore of Argegno and Brienno discussed in the text (sills 1 and 2).

and STD). As a result, several detailed bathymetric contour maps were produced (Fig. 3a) using the ArcMap 8.1 ESRI software.

3.2. High-resolution seismic reflection surveys

In 2002 and 2003, the subsurface of the Como and Lecco branches were imaged with 170 km of digitally recorded seismic profiles (Fig. 1b, black lines) using a single-channel seismic profiling system with a 3.5 kHz Geoacoustic pinger of the Limnogeology Laboratory of the ETH Zürich (Switzerland). The source/receiver was mounted on an inflatable cataraft that was pushed by a small motorboat. Positioning was achieved by a regular GPS system. The system achieved a maximum acoustic penetration of ~22 m on the plateau area, ~16 m in the deepest basin and ~14 m in the basin offshore of the city of Como (assuming a mean p-wave velocity of 1450 m/s in the sediments). The seismic grid consists of a longitudinal line that follows the lake axis and of several transversal profiles crossing from coast to coast. The line density was increased in the Bellagio plateau area, where a dense grid was acquired with an average line spacing of 200 m. Data processing was carried out with the SPW™ software package and included band-pass filtering (2–6 kHz) and automatic gain control. Neither bottom muting, spiking deconvolution nor migration were applied to the data. The 2d/3dPAK-EarthPak® software of Kingdom Suite© was used for data interpretation.

3.3. Sediment cores

The seismic profiles were used to locate 19 sites for short gravity cores in the Como branch. These cores reach a maximum length of 1.65 m (Fig. 1b, black dots, and Fig. 4). Before opening, the cores were scanned with a Geotek multi-sensor core logger (bulk density, magnetic susceptibility (MS), acoustic velocity). Cores were then split in half, sedimentologically described and photographed before being sampled. Laser grain-size and total organic carbon (TOC) analyses were performed on core CO-14 using a Malvern Mastersizer 2000 and a Coulomat system, respectively. All these analyses were performed at the ETH Zürich. The recent age-depth model in the Argegno basin of the Como branch is based on ^{137}Cs measurements on the upper 34 cm of core CO-14 with a sampling rate of 1 cm and on one AMS radiocarbon date from a wood fragment sampled at the depth of 125 cm in core CO-17. ^{137}Cs activities in the freeze-dried samples were determined at the EAWAG (Duebendorf-CH) with a well-type GeLi detector for a minimum of 24 h by direct γ-measurement and calculated using accumulated counts at 662 keV. AMS radiocarbon analyses were performed at the Beta Analytic Radiocarbon Dating Laboratory in Miami (USA). Additional specific investigations (i.e., mineralogy, pollen, diatoms and heavy-metal analysis) are in progress.

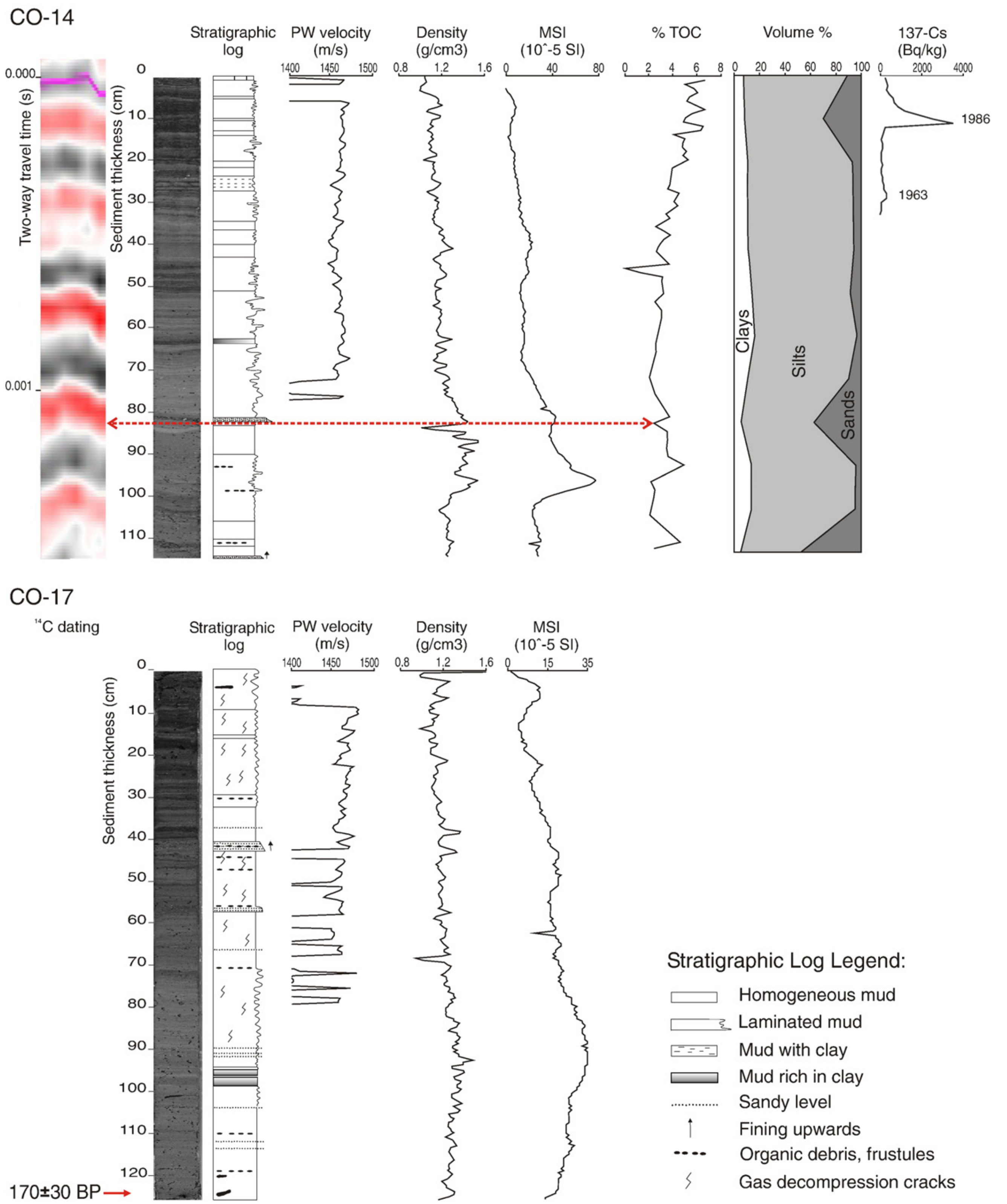
4. Results

4.1. Seismic stratigraphy of the Como branch

The subsurface of the Bellagio plateau is seismically characterized by continuous and horizontal high-amplitude reflections with a draping pattern (Fig. 3b). This well-stratified unit is intercalated by lens-shaped bodies with low-amplitude to chaotic internal reflections. The seismic and bathymetric data along the steep SW flank of the Bellagio plateau (Fig. 3) document two morphological scarps: the main one extends from ~150 to ~180 m water depth and follows the isobaths over a distance of ~2,500 m, while a second one occurs at ~210 m water depth and is approximately 500 m wide. The SW slope, connecting the plateau with the deep Argegno basin, is less than 1 km wide, very steep (~18°) and the acoustic substratum barely displays any seismic reflections, due both to the steepness of the slope and to the limited accumulation of sediments. At the foot of the steep SW slope of this plateau below ~250 m water depth, the lake floor is characterized by a hummocky topography and the subsurface contains tilted blocks of stratified sediments and lens-shaped bodies with chaotic to transparent internal reflections (Fig. 3d). In the Argegno basin, regularly-layered high-amplitude and continuous reflections fill the basin floor (Figs. 5 and 6) between the very steep slopes of the basin

Fig. 4. Lithology and stratigraphy of cores CO-14 (upper panel) and CO-17 (lower panel) from the Argegno basin. Lithology, stratigraphic log, p-wave velocities, bulk density, magnetic susceptibility (MS), total organic carbon (TOC), and laser grain-size measurements in these cores suggest a rather regular hemipelagic sedimentation of clayey silts. This normal sedimentation is only locally interrupted by 1-cm-thick sandy layers at 10, 80.4 and 113 cm in core CO-14, while core CO-17 is characterized by two centimeter-scale sandy graded beds at 41 and 56 cm, by three silty-to-clayey sharp-based layers at 15, 95 and 97 cm and by seven thin organic rich layers. ^{137}Cs peaks represent the years 1986 (Tschernobyl) and 1963 (atmospheric bomb fall-out). The first high-amplitude reflection at 1 ms two-way travel time (~75 cm) can be correlated to the sandy layer and the sharp drop in density at 80 cm b.l.f. in core CO-14. The radiocarbon age of a piece of wood debris sampled at the base of core CO-17 is also indicated and given in calibrated years before present.

(Fig. 7). This succession of high-amplitude reflections is interrupted by two thick units with a chaotic to contorted internal configuration at the foot of the plateau (Fig. 3d). In the deeper basin they are seismically semi-transparent to transparent (Figs. 5 and 7). The semi-transparent units occur below ~350 m water depth between the foot of the plateau and a small sill offshore of Argegno (sill 1 in Figs. 2c and 5), and get thinner close to the sill (below



~410 m water depth). They are characterized by irregular upper and lower boundaries, the latter being locally erosive (Fig. 6). The transparent units onlap the basin edges, thicken in the deepest sub-basins and are characterized by sharp upper and lower boundaries, the lower one being highly-reflective (Figs. 5 and 7).

In the Laglio–Como basin the infill is well-bedded, similar to the one occurring in the Argegno basin. The acoustic penetration decreases towards the city of Como. The infill is affected by successive listric faults where slope breaks occur (Fig. 8a). On a few transversal profiles, a wide channel can be seen below ~200 m water depth along the lake axis (Fig. 8b), and successive listric faults are visible on both sides of the channel.

4.2. Sedimentology of short cores

Core CO-14 (Figs. 2, 4, 5) is a representative core of the stratigraphy in the Argegno basin. This core, retrieved from a water depth of 425 m, is 114.5 cm long and is composed of a regular alternation of laminated and homogeneous mud free of carbonates, and characterized by rather low MS values and p-wave velocities oscillating around 1450 m/s. The darker upper 34 cm contain high amounts of TOC (between 4 and 6.5%). Three sandy layers less than 1 cm thick are intercalated in these clayey silts at the depths of 10 cm, 80.4 cm and at the bottom of the core (113.9 cm). No major excursions can be seen in the petrophysical logs, suggesting that the recentmost sedimentation is rather stable in this part of the lake. The coarse sand level, 1.1 cm thick, recorded between the depth of 80.4 and 81.5 cm, has sharp limits and corresponds to increases in density and MS. Based on the p-wave velocity measurements on CO-14, the high-amplitude reflection at ~72 cm below the lake floor (b.l.f.) can be correlated with the sandy layer at 80 cm in CO-14. At 95 cm b.l.f., a change in TOC, an increase in clay content and the occurrence of several horizons rich in organic fragments coincide with a change in density and MS. Core CO-17, retrieved in the Argegno basin offshore of Isola Comacina at 412 m water depth (Figs. 2, 5), is 125 cm long and has a general lithology similar to the one of core CO-14. The core contains two centimeter-

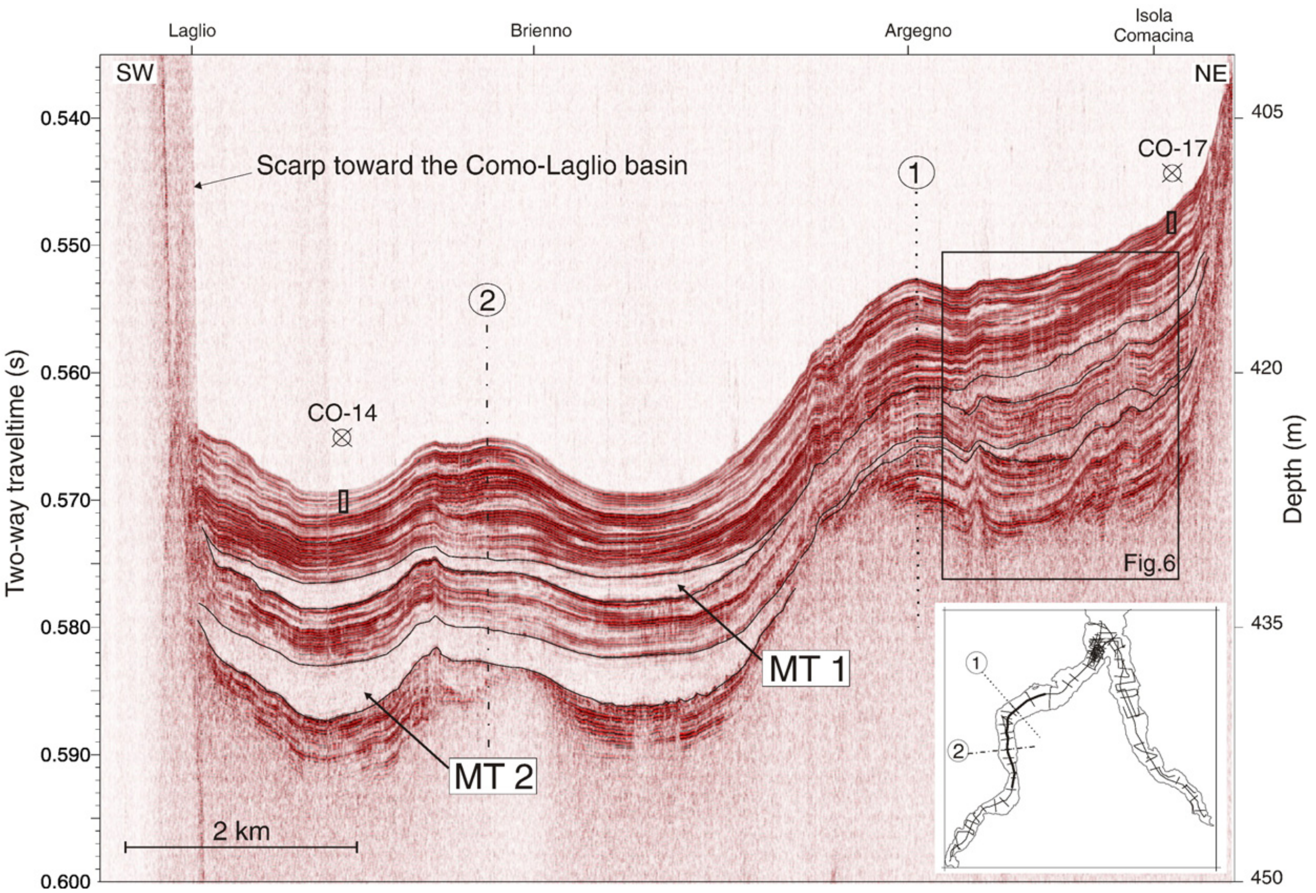


Fig. 5. Seismic section of the basin fill in the deep Argegno basin and location of cores CO-14 and CO-17. Note the difference between the two large ponded megaturbidites (MT1 and MT2) and the well-stratified hemipelagic sedimentation draping the basin morphologies. The megaturbidites can be correlated to two large debris-flow deposits at the NE of the sill offshore Argegno (sill 1). The location of Fig.6 is also indicated.

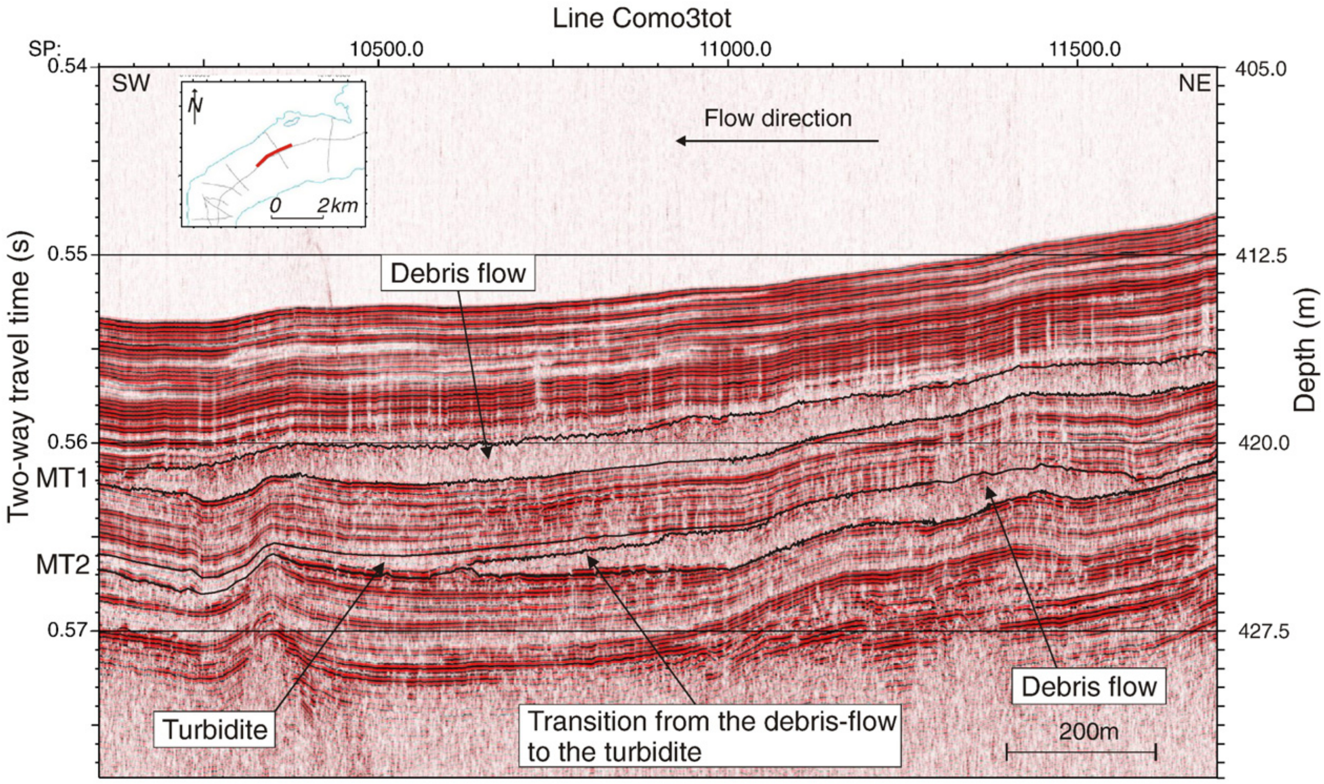


Fig. 6. Detailed seismic section illustrating debris-flow deposits in the Argegno basin and the downstream evolution of the debris flow into turbidites.

scale sandy graded beds, three slightly thicker silty-to-clayey layers with a sharp base, and seven millimeter-scale layers rich in organic debris, intercalated with background sediments. Two pieces of wood debris (i.e., thin branches) occur at 5 and 125 cm. The lower one was used for ^{14}C dating.

4.3. Chronology

The wood fragment sampled at the depth of 125 cm in core CO-17, provided an AMS radiocarbon age of 170±30 yr BP corresponding to a calibrated date of 1730 to 1810 AD, based on the INTCAL 98 database (Stuiver et al., 1998). Measurements of ^{137}Cs radioactivity in the upper 34 cm of core CO-14 highlight the occurrence of a well-defined and very strong peak at 11.5 cm (3500 Bq/Kg) and a second much smaller peak (250 Bq/Kg) at 29.5 cm (Fig. 4). The first peak is related to the high contamination in northern Italy induced by the Tchernobyl nuclear reactor meltdown in 1986 (Ukrania), whereas the second peak reflects the peak level of atmospheric nuclear weapon tests in the northern hemisphere in 1963 (Appleby, 2001). These interpretations are in good agreement with fall-out data of soils in Europe following the Tchernobyl accident (CRIIRAD and Paris, 2002) and in the recent sediments of a nearby mountain lake (Kulbe et al., 2005).

5. Interpretation and discussion

5.1. The Holocene basin fill of the Como branch

5.1.1. Hemipelagic sedimentation

Regularly-layered high-amplitude and continuous reflections draping the morphology of the Como branch are interpreted as resulting from the background lacustrine sedimentation consisting of clayey-to-silty hemipelagic sediments. Taking into account the rather low productivity of this mesotrophic lake (Binelli et al., 1997) and the dominating mineralogy of the catchment surrounding the Como branch, these hemipelagic sediments that are free of carbonates probably originate mostly from the settling in the water column (i) of fine grained river-derived clastic particles mainly originating from the Adda River, and (ii) of organic debris. In this regularly-layered seismic facies, higher-amplitude reflections can be related to the development of centimeter-scale sandy layers intercalated in the host mud, such as the one retrieved in core CO-14 at a depth of 80 cm. In the sediment cores collected at different

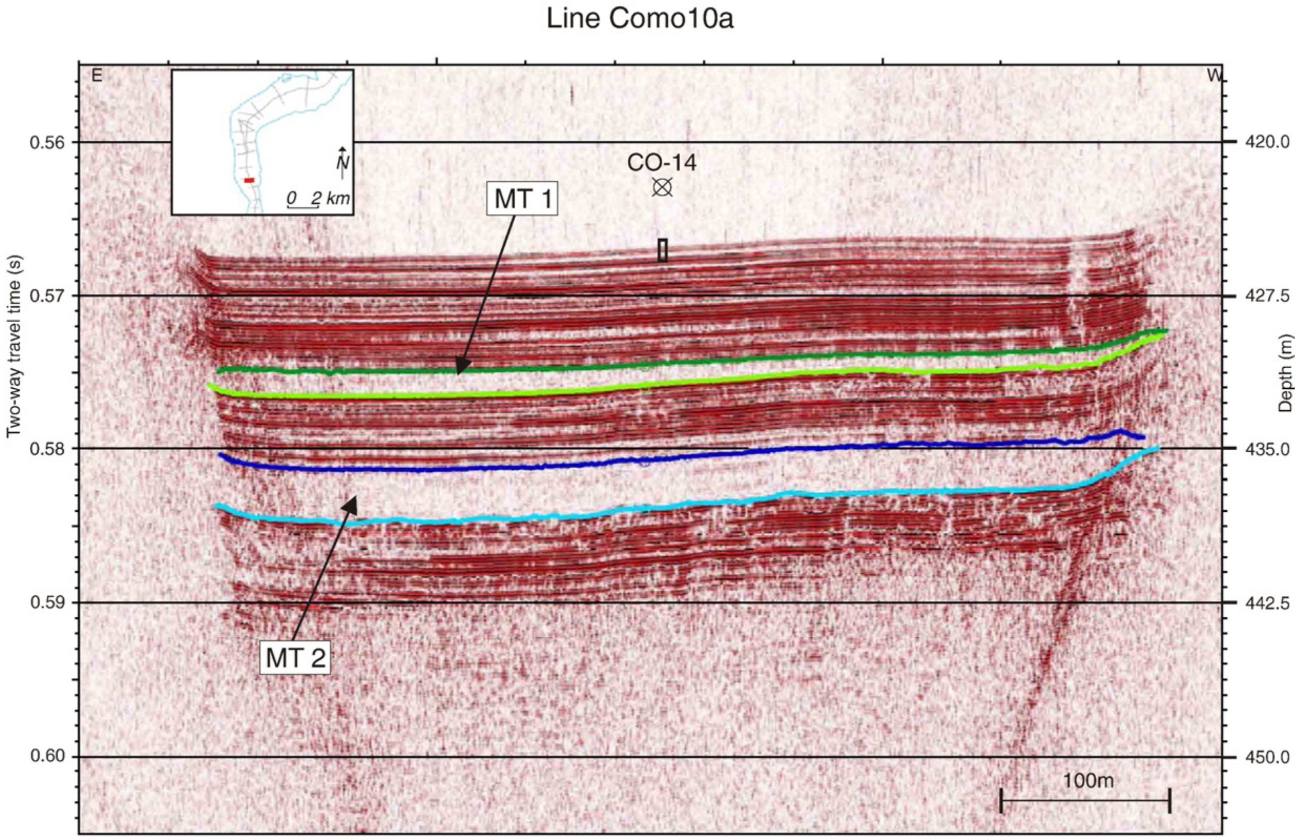


Fig. 7. Seismic section across the deepest part of Argegno basin illustrating the ponded facies of the background sedimentation with the two intercalated megaturbidites (MT1 and MT2).

water depths, such sandy layers and centimeter-scale clayey layers with sharp bases are frequently detected. These layers can both be related to the development of flood events producing turbiditic underflows (Sturm and Matter, 1978; Sturm et al., 1995; Chapron et al., 2002, 2005) and to littoral erosion and the development of turbidity currents along the steep basin slopes. The littoral erosion events can be triggered by lake-level fluctuations or by recurrent storm waves along the shores produced by strong winds and significant fetch (i.e. tempestite). A trend towards low magnetic susceptibility (MS) values but higher TOC content occurring after the 1960s, reflect the recent increase of anthropogenic influences on the trophic state of the lake, with an epilimnion enriched in phytoplankton and a hypolimnion depleted in oxygen (Bettinetti et al., 2000).

The transition from a draping pattern on the plateau (Fig. 3b) to a draping-to-ponding pattern in the narrow deeper basins (Figs. 5, 7) is interpreted as resulting from the occurrence of very steep slopes along most of the Como branch that prevent any accumulation of hemipelagic sediments. Sediment can therefore only accumulate in the basin floor and develop a ponded geometry on profiles perpendicular to the axis of the basin, but a draping geometry along the axis of the Como branch. The lack of carbonates in the composition of the hemipelagic sediments from the Como branch, suggests that this part of the lake basin that is deeply incised into Mesozoic limestones (Fig. 1) accumulates most of the fine-grained clastic particles from the Adda River, which drains a crystalline catchment. Such a long-distance transport of fine-grained clastic particles over the Alto Lario basin, above the Bellagio plateau and finally into the Como branch requires a significant interaction of currents in the lake waters and sediment plumes initiated in front of the Adda delta.

5.1.2. Sedimentation rate and age model

On the base of the ^{14}C data from core CO-17, one can calculate the mean background sedimentation rate at this coring site. It is, however, necessary to subtract the cumulated thickness of the 12 turbidite layers (i.e., 11 cm), which lay above the position of the radiocarbon sample. According to the radiocarbon date the mean sedimentation rate in core CO-17 ranges between 0.42 cm/yr and 0.59 cm/yr.

The ^{137}Cs analyses of core CO-14 show also two distinct peaks in the upper sediments (1986 and 1963).

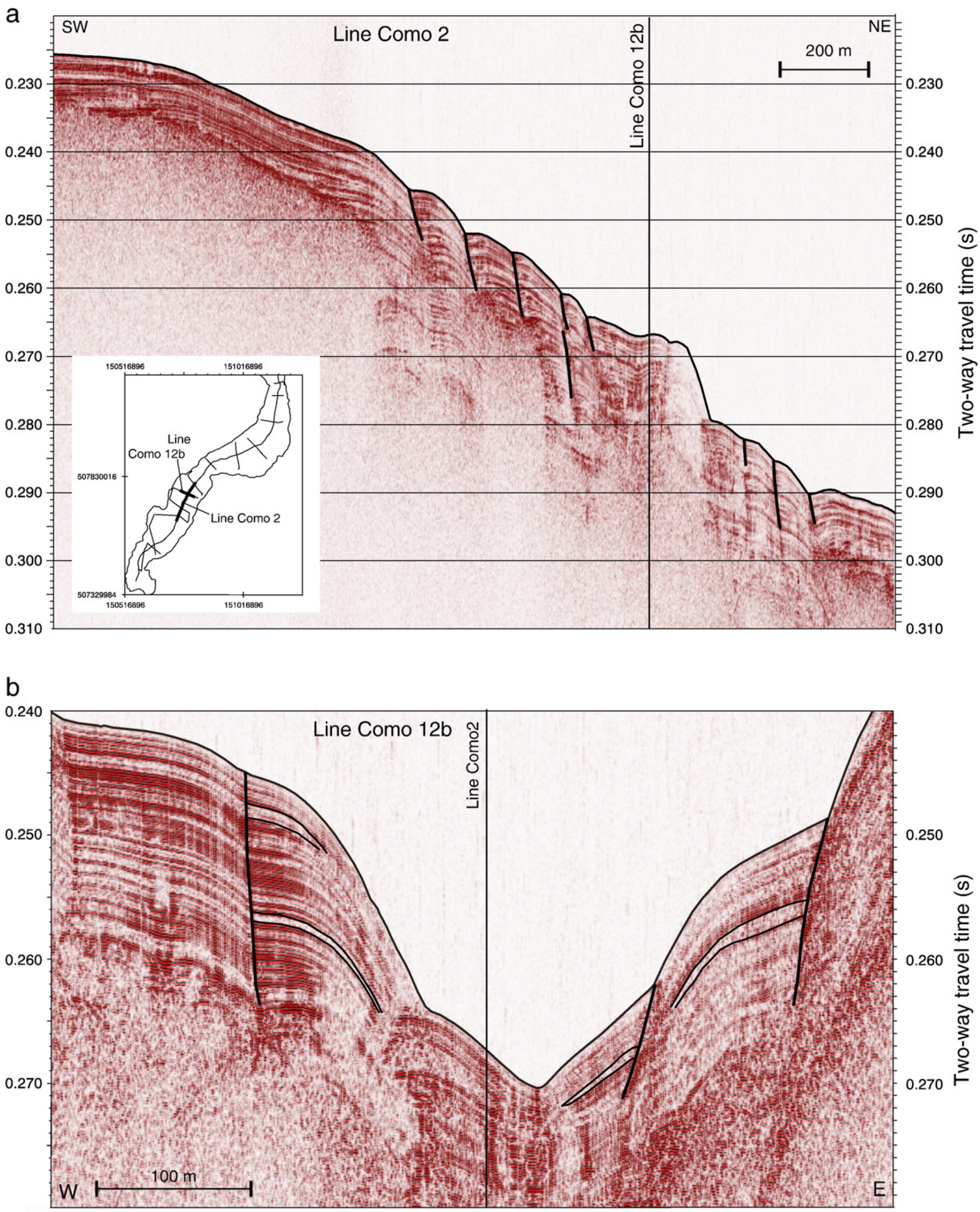


Fig. 8. Seismic sections showing the occurrence of creeping in the Laglio-Como basin where syn-sedimentary growth faults develop along steep slopes (a) and on both sides of an axial depression in the lake floor (b).

As for the ^{14}C data, again the thickness of the sandy layer occurring at 10 cm core depth had to be subtracted before calculating a mean background sedimentation rate deduced from the two Cs peaks. This correction gives a mean sedimentation rate of 0.65 cm/yr since 1986 and 0.73 cm/yr between 1963 and 1986. These age constrains in the deepest area of the Como branch, where no significant rivers enter and the hemipelagic input dominates, are in agreement with the mean sedimentation rates of other large glacial lakes in the southern Alps, such as Lake Maggiore (0.58–0.67 cm/yr; Calderoni, 2003) and Lake Lugano (0.70 cm/yr; Lehmann et al., 2002). However, previous ^{137}Cs analyses in other areas of Lake Como yielded slightly higher sedimentation rates: 1.1 cm/yr in the Alto Lario; 1.6 cm/yr in front of the city of Como and 1.0 cm/yr in the Lecco Branch (Chiaudani and Premazzi, 1993).

5.1.3. Mass movements and megaturbidites

The sedimentary infill of the Como branch highlights a wide range of reworked deposits related to sub-aquatic slope failures. Meter-scale listric faults occurring at the slope breaks of the lake floor in the Laglio–Como basin (Fig. 8) are interpreted as growth faults suggesting some creeping in this part of the branch. Two possible slide scars are identified on the steep SW flank of the Bellagio plateau (Fig. 3): the main one extends from ~150 to ~180 m water depth and follows the isobaths over a distance of ~2500 m, while a second one occurs at ~210 m water depth and is approximately 500 m wide. Within the sedimentary fill of the Bellagio plateau, recurrent lens-shaped bodies with low-amplitude to chaotic internal reflections highlight former mass-wasting deposits, suggesting the development of sliding and slumping along the shores of this plateau (black arrows in Fig. 3a). At the foot of the SW slope the hummocky topography and the occurrence of tilted blocks of stratified sediments and lens-shaped bodies with chaotic to transparent internal reflections are interpreted as the accumulation zone of a mixture of slides and slumps originating from the scars upslope. Towards the Argegno basin (Figs. 5 and 6), these deposits abruptly evolve into two large semi-transparent lens-shaped units bearing the typical seismic facies of debris-flow deposits (Prior et al., 1984; Van Rensbergen et al., 1999; Schnellmann et al., 2006). These two debris-flow deposits evolve further downstream from the sill offshore of Argegno into two transparent units filling the pre-existing depressions of the deepest basin (Figs. 5, 6, 7). These several-meter-thick deposits bearing a transparent seismic character but highly reflective bases and developing onlaps along the edges of the deepest basin are interpreted as megaturbidites. Lake Como megaturbidites are similar to the ones documented elsewhere in deep marine and lacustrine basins (Cita et al., 1984; Siegenthaler et al., 1987; Cita and Aloisi, 2000; Rebesco et al., 2000; Rothwell et al., 2000; Schnellmann et al., 2002). The changes of acoustic facies in the Argegno basin described above are thus interpreted to result from the downstream evolution of large debris flows into turbidity currents that wane in the deepest part of the Como branch.

Two major sub-aqueous slope-failure events can therefore be related to the deposition of the two thick seismic units identified in the subsurface of the Como branch. The sediments related to these major events, labelled MT1 (upper one) and MT2 (lower one), can be used as excellent synchronous marker horizons. In the following sections, the volumes, source areas and ages of the deposits MT1 and MT2, and potential triggering factors of the two related events are further discussed.

5.2. Characterization of the megaturbidites

5.2.1. Volumes of the megaturbidites

On the basis of seismic data, the upper and lower boundaries of MT1 and MT2 were picked where sufficient seismic coverage is available (i.e., between Isola Comacina and Laglio; Fig. 1b) allowing estimation of the minimum volume of these two major deposits over most of the Argegno basin that includes debris flows and thick turbidites (Fig. 9). MT1 has two depocentres occurring on both sides of the sill located offshore of Argegno. Between Isola Comacina and the sill, the debris flow deposit occurs on average at ~5.7 m b.l.f. and has a maximum thickness of 1.8 m. Between the sill and the major morphologic step offshore of Laglio, MT1 is on average at ~5.3 m b.l.f. and has a maximum thickness of 1.6 m. In total, the estimated sediment volume of MT1 reaches $\sim 3.5 \times 10^6$ m^3 (Fig. 9). The older deposit MT2 is thicker and more extensive: its debris-flow deposit occurs ~3 m below MT1 and is relatively thin (up to ~1.6 m thick). It covers the sill and transforms into the megaturbidite located at ~3.6 m below MT1. MT2 has a maximum thickness of 3.2 m in the deeper basin. The estimated sediment volume of MT2 is $\sim 10.5 \times 10^6$ m^3 (Fig. 9). The contour maps of Fig. 9 highlight the influence of two sills on the distributions of both major deposits in the deep basin: while the main sill located offshore Argegno (sill 1 in Figs. 2 and 5) separates the debris flows from the megaturbidites; the minor sill offshore of Brienno (sill 2 in Figs. 2 and 5) only reduces the thickness of the megaturbidites. This specific geometry suggests that sill

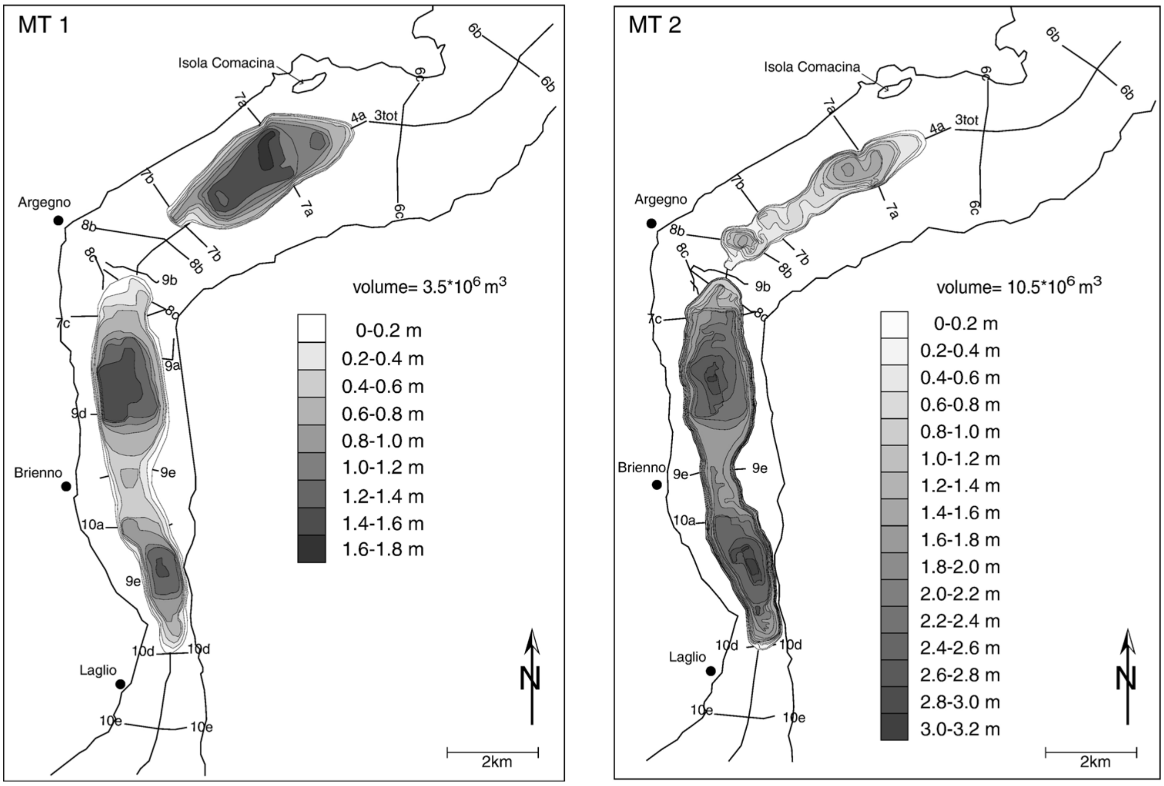


Fig. 9. Isopach maps of MT1 and MT2 in the Argegno basin. Note the lack of MT1 sediments on the top of the sill 1 while the MT2 sediments become thinner in this area. These maps are emphasizing the presence of three depocenters discussed in the text.

1 played a key role in the development of the debris flows into turbidity currents, while sill 2 essentially induced some focusing of the turbidity currents. This also indicates that during both events, the flows had a higher energy above sill 1 than above sill 2. It is therefore postulated that during these two major events, large slope failure occurring in the NE part of the Como branch resulted in the formation of a debris flow, that evolved downstream (i.e., towards the SW) into a turbidity current, as the mass flow underwent a hydraulic jump when crossing sill 1. Such large turbidity currents can strongly erode before becoming depositional (Sturm and Matter, 1978; Mulder and Cochonat, 1996), as it is seen in the Lake Como seismic data. This temporal and spatial separation of two flow processes, together with the inherited morphobathymetry leads to three distinct depocenters (Fig. 9).

5.2.2. Source area of the megaturbidites

The source areas must be located within the lacustrine basin because investigations in the catchment surrounding the lake did not encounter evidence of failure areas (Fanetti, 2004). Since turbidites occur downstream from debris-flow deposits (Kassem and Imram, 2001) the source areas of megaturbidites MT1 and MT2 must be located in the NE part of the Como branch. Furthermore, the occurrence of creeping in the southern part of the branch excludes catastrophic mass movements coming from that area. Because the NE part of the Como branch is separated from the rest of the lake by the Bellagio plateau (Figs. 1 and 2), no gravity-driven sediment flows originating from the other branches of the lake (i.e., Alto Lario and Lecco branches) can reach the Como branch. Based on our seismic and bathymetric data set presented above, the sediment source area for MT1 and MT2 is thus the SW slope of the Bellagio plateau where two recent, large slide scars are observed (Fig. 3).

A mean sediment thickness of ~18 m presently covers the acoustic substratum along the SW edge of the Bellagio plateau (Fig. 3). Assuming that such a sedimentary cover was initially draping the steep SW slope of the plateau prior to the development of the scars and that the base of the slides was just above the basement, the minimum volume of the missing sediments can be roughly estimated between 14×10^6 and 20×10^6 m^3 based on element geometries from the multibeam data (Fig. 3c). Taking into account (i) that part of these reworked sediments is accumulated at the foot of the slope (accumulation zone in Figs. 2a and 3d), (ii) that the porosity of the initial sediments was different to the one of the deposits, and (iii) that the debris flows were erosive and probably reworked additional sediments in the Argegno basin, these estimations of removed sediments along the slope of the Bellagio plateau are in the range of the total volume of MT1 and MT2 accumulated in most of the deep basin (i.e., $\sim 14 \times 10^6$ m^3).

5.2.3. Age of the megaturbidite events

Available sedimentation rates ranging from 0.65 to 0.73 cm/yr (core CO-14) and from 0.42 to 0.59 cm/yr (core CO-17), allow a mean sedimentation rate of ~0.6 cm/yr to be estimated for this deep basin. Assuming that the background sedimentation in the distal part of the Argegno basin (i.e., at CO-14 coring site; Fig. 5) remained relatively constant in the recent past, the age of MT1 and MT2 can be roughly estimated by the extrapolation of this basin's mean sedimentation rate. These calculations suggest that the top of MT1 located at 520 cm b.l.f occurred ~870 years ago (AD ~1130); while the top of MT2 lying 360 cm below the base of MT1 would be ~600 years older (AD ~530). Both megaturbidites from the Como branch thus probably occurred during historical times in the 12th and the 6th century.

5.3. Trigger mechanisms

Mass movements generally occur when applied shear stresses increase beyond the critical shear strength of sediments. In underwater sedimentary environments, high sedimentation rates building up excess pore pressure and underconsolidation (weak layers), sea (lake) level fluctuations, seismic loading due to earthquakes, storm-wave loading, bubble-phase gas charging and biological processes, such as bioturbation, either increase the applied shear stress or reduce the critical shear strength of sediments, promoting mass movements (Rothwell et al., 2000; Canals et al., 2004). In particular, based on available data in the Como branch and on former studies in the Alpine area, the following potential trigger mechanisms could be addressed: overloading due to high sedimentation rates and steep slopes, lake-level fluctuations and ground acceleration during earthquakes.

5.3.1. Overloading

Slope failure along the steep SW slopes of Bellagio plateau due to overloading would be favoured by relatively high sedimentation rates along this flank of the plateau. Available recent sedimentation rates in the lake are rather high in the deep basins of Lake Como: 0.6 cm/yr on average in the deepest part of the Como branch (this study) and 1.0 cm/yr in the Lecco branch (Chiaudani and Premazzi, 1993). However, lithologies and available ^{137}Cs and ^{14}C analyses on several short cores retrieved on the Bellagio plateau (Fanetti, 2004) suggest much smaller recent sedimentation rates (ranging from 0.27 to 0.02 cm/yr) as well as the occurrence of sedimentary hiatuses and erosion surfaces. Since the Bellagio plateau plays an important role on the hydrodynamics of Lake Como by influencing the water exchange between the Lecco and Como branches, such contrasting sedimentation rates between the plateau and the deep basins probably result from the influence of currents that prevent hemipelagic sediment accumulations on the Bellagio plateau. These currents, however, focus these particles in the narrow deep basins of the Como branch. As a result, such currents may have favoured high accumulation rates of hemipelagic sediments along the steep slopes of the Bellagio plateau that became prone to slope failure.

5.3.2. Lake level fluctuations

Under hydrostatic conditions, lake level fluctuations do not alter the stability of sub-aqueous slopes, because effective pressure is independent of water depth. If impermeable layers occur, however, a change in lake level and thus a change in confining pressure may induce pore-fluid overpressure at that depth (Hampton et al., 1996). This would decrease effective pressure and shear strength, so that slope stability can be reduced significantly. Such a weak layer potentially could develop in a gliding plane of a sub-aqueous slide.

In perialpine lakes, lake-level fluctuations can be caused by changes in the hydrologic budget that match observed glacier fluctuations in their catchments. The general trend shown by historical data suggests that glacier advances during the Little Ice Age (LIA) coincided with cooler winters and wetter summers in the Alps favouring both glacier advances and higher lake levels (Holzhauser et al., 2005). According to Magny (2004) and Holzhauser et al. (2005) significant glacier advances in Swiss Alps prior to the LIA were clustering at 500–600 AD and 1100–1200 AD and matching episodes of high lake levels in Central Europe. In our study area no geological data of Holocene lake-level fluctuations are available in the literature. Variations of varve thicknesses in the proglacial Lake Silvaplana (Leeman and Niessen, 1994) suggest, however, reduced glaciers from 100 to 650 AD and a major glacier advance between 650 and 1200 AD in the northern part of the Bernina Massif (Engadine valley, Switzerland) located close to the northern limit of Adda catchment area (Fig. 1a). Since Lake Como drains the meltwaters of several glaciers from the southern part of the Bernina, Ferré, Disgrazia and Ortles massifs via the Adda River, similar glacier fluctuations may have also occurred in our study area (Pelfini, 1999) and may have favoured fluctuations in the level of Lake Como at the times when MT1 and MT2 were triggered.

5.3.3. Earthquake shaking

Large sub-aqueous landslides and megaturbidites triggered by strong local earthquakes in lacustrine environments have been documented in mountain ranges with either high or low historical seismicity (Siegenthaler et al., 1987; Beck et al., 1996; Chapron et al., 1999; Shiki et al., 2000; Schnellmann et al., 2002). The best argument to assess a seismic trigger is the correlation of such sedimentary events with a well-documented historical earthquake (Arnaud et al., 2002; Monecke et al., 2004; Nomade et al., 2005). Earthquake-triggered slides in lakes can also have a regional extension and be synchronously occurring in lacustrine sub-basins or nearby lakes (Schnellmann et al., 2002; Monecke et al., 2004).

The Lake Como area is characterized by low seismicity (Guidoboni, 1986). Earthquakes with estimated magnitude in the range of 6.0 to 6.5 have, however, generated catastrophic effects in the Po plain in 1117 and 1222 AD (Michetti, 2005). In particular, the well-documented Brescia earthquake (see Fig. 1a for location) on 25 December 1222 had an estimated magnitude of 6.2 and was located ~90 km from Bellagio (Serva, 1990 for a review). During this event, an intensity of V was estimated by Guidoboni and Ferrari (2000) in the city of Como. Monecke et al. (2004) have shown that organic-and carbonate-rich lake sediments start to be affected by earthquakes when ground shaking is reaching intensities of VI to VII. We postulate that the sub-aqueous landslides in Lake Como are possibly caused by a combination of some of the trigger mechanisms listed above, so that it is not possible to assume a quantitative threshold in minimal earthquake strength. Earthquakes, however, can act as the final external trigger and the 1222 AD Brescia event could thus be a potential trigger for the event that caused the MT1 deposit.

No historical event from the Italian seismic catalogue matches the occurrence of MT2 in the Como branch. However, 60 km NNE from Bellagio, in the basin fill of proglacial Lake Sils (Switzerland) located along the historically active Engadine Fault (Schmid et al., 1990), Blass et al. (2005) documented a MT with an estimated volume of 6.5×10^{6} m^{3} that was deposited around 700 AD. No clear triggering mechanism has been proposed for this major event affecting the prodelta of Lake Sils. Because some Engadine earthquakes, however, also affect the Lake Como area, and taking into account the dating uncertainties in both lakes, we suggest these two large MT may have been triggered by the same ground acceleration associated with an earthquake in the early 6th century.

6. Conclusion and perspectives

The combination of multibeam bathymetry, high-resolution seismic profiling and short gravity cores in the deepest sub-basin of Lake Como highlight that recent sedimentation in the Como branch consists of alternating hemipelagic and mass-wasting deposits. In this fjord-like basin, the ponding and draping geometry of background sedimentation, together with low sedimentation rates in the Bellagio plateau but high sedimentation rates in the Argegno basin, suggest that hemipelagic sedimentation is significantly influenced by internal currents within the lake between the Lecco and Como branches. These currents focus the settling of clastic particles in the deepest part of the narrow Como branch (>400 m water depth) where a mean sedimentation rate of ~0.6 cm/yr is deduced from ^{137}Cs and AMS ^{14}C results. These currents may also have favoured high accumulation rates of hemipelagic sediments along the steep (18°) SW slopes of the Bellagio plateau. Today, this slope of the plateau is characterized by (i) two large sub-recent slide scars at ~150 m and ~210 m water depth, and (ii) a mix of recent slides and slumps accumulating at the foot of the slope.

The basin fill of the Como branch has been locally affected by a wide range of gravity-reworking phenomena along the steep slopes: some creeping occurs between the towns of Laglio and Como, while former slides and slumps are frequent in the infill of the Bellagio plateau. In the deep and narrow Argegno basin the deposits of two big sub-lacustrine landslides (MT1 and MT2) could be identified. The calculated volumes for the MT1 and MT2 are 3.5×10^6 m^3 and 10.5×10^6 m^3 respectively and they were distributed over a basinal length of 5.5 km. Based on our dataset, we suggest that the deposition of these sediments was probably triggered in the mid 12th (MT1) and early 6th (MT2) centuries and are related to the collapse of the steep SW slopes of the Bellagio plateau leading to the formation of debris flows that eventually develop into turbidity currents offshore Argegno.

The potential triggering mechanisms of these two large slope failures most probably resulted from a combination of overloading of the steep slope with earthquake shaking and/or rapid lake level fluctuations due to Holocene climate changes. Such large subaqueous slope failures may also represent a significant natural hazard in Lake Como because smaller but similar events in the Alps have induced large tsunami waves (Schnellmann et al., 2002) and violent seiche effects (Siegenthaler et al., 1987; Siegenthaler and Sturm, 1991; Chapron et al., 2004). Hence, future large slope failure in the Como branch may induce dangerous waves along the highly populated lake shore and especially near the town of Como where the lake floor shallows gently.

However, future investigations are required to constrain the history of the MT1 and MT2 events, their triggering and the potential risk of similar events for the populated lake shores. In particular, the age of these megaturbidites and the stability of the sediments prone to slope failure in Lake Como could be documented by long coring at key sites in the branches of Como and Lecco. The integration of geotechnical characterization of Holocene sediments with the detailed multibeam bathymetry of Lake Como will allow disentangling the main trigger mechanisms of these large slope failures. Modelling of sediment displacement also would provide the database to evaluate the generation and reflection of potentially dangerous tsunami waves in the deep but narrow basins of Lake Como.

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