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Morphology and geological setting of Iseo Lake (Lombardy) through multibeam bathymetry and high-resolution seismic profiles

Alfredo Bini[1], Daniele Corbari[2,4], Paolo Falletti[2,5], Mauro Fassina[3], Cesare R. Perotti[3] & Andrea Piccin[2]

Keywords: Iseo Lake, bathymetry, high-resolution seismic, geomorphology, last glacial maximum expansion, lacustrine sediments

ABSTRACT

The Regione Lombardia geological mapping program (CARG), in collaboration with the Istituto Nazionale di Oceanografia e Geofisica Sperimentale of Trieste (OGS), realized a geophysical study of Iseo Lake (Sebino).

A multibeam survey and high-resolution single-channel seismic lines allowed the recognition of five physiographic units with different morphologies and evolution: the Oglio prodelta in the northern part of the lake; a central basin with a regular flat floor between –240 and –256 m in depth; the Monte Isola submerged escarpment, bounding the western shores of Monte Isola and emerging at the small islands of San Paolo and Loreto; the Sale Marasino plateau, with a maximum depth of –100 m, between Monte Isola and the eastern shores of the lake; and the southern Sarnico Basin.

In the single-channel seismic profiles crossing the central basin, the uppermost part of the sedimentary infill of Iseo Lake can be subdivided into three sequences, interpreted from top to base as recent lacustrine deposits, glacial deposits recording the last glacial maximum expansion, and lacustrine deposits.

The morphology of the lake was to a large degree shaped prior to the last glacial maximum (LGM) expansion, as erosional action exerted by the LGM glacier was much reduced. The Oglio prodelta, the fan deltas skirting the lake shores and the landslides along the submerged slopes of the lake occurred subsequent to the retreat of the LGM glacier.

RIASSUNTO

Oggetto del presente lavoro è lo studio geofisico del Lago d'Iseo (Sebino), realizzato dalla Regione Lombardia nell'ambito del progetto della nuova Carta Geologica d'Italia (CARG) in collaborazione con l'Istituto Nazionale di Oceanografia e Geofisica Sperimentale di Trieste (OGS). Lo studio è stato realizzato mediante il rilievo batimetrico multibeam dei fondali e l'esecuzione di profili sismici mono- e multicanale ed ha permesso di riconoscere cinque unità fisiografiche, differenziate per caratteri morfologici ed evolutivi: il prodelta dell'Oglio nella parte settentrionale del lago; un bacino centrale con un fondale pianeggiante, a profondità comprese tra –240 e –256 m; la scarpata sommersa di Monte Isola, che limita a Ovest Monte Isola e emerge in corrispondenza delle isole di San Paolo e Loreto; il plateau di Sale Marasino, con una profondità massima di –100 m, tra Monte Isola e la riva orientale del lago; il bacino di Sarnico nella parte meridionale del lago.

Nei profili sismici monocanale ad alta risoluzione sono stati riconosciuti nel bacino centrale almeno tre intervalli deposizionali, che dall'alto al basso comprendono sedimenti lacustri recenti, depositi glaciali attribuibili all'ultima glaciazione e depositi lacustri precedenti allo LGM.

La morfologia del lago è stata in larga misura acquisita prima dell'ultima massima espansione glaciale, poiché l'azione erosiva esercitata dal ghiacciaio LGM appare molto ridotta. La formazione del prodelta dell'Oglio e dei delta conoidi che orlano il lago è successiva al ritiro del ghiacciaio LGM, così come i fenomeni franosi lungo i versanti sommersi.

Introduction

Previous geophysical investigations on southern Alpine lakes were carried out in the 1970s (Finckh 1978). These investigations involved Iseo Lake (Sebino) marginally, reporting only the interpreted bedrock depth, without providing information on the thickness and geometry of sedimentary sequences or on the sedimentary characteristics of the lake deposits. The available bathymetric data for Iseo Lake were collected by the Istituto Idrografico della Marina in the 1960s, in order to support lake navigation, and are not related to the cartographic systems at present in use for land surveys.

In order to fill these gaps, the Struttura Sistema Informativo Territoriale of the Regione Lombardia started a geophysical investigation project in collaboration with the Istituto Nazionale di Oceanografia e Geofisica Sperimentale of Trieste

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[1] Università degli Studi di Milano, Dipartimento di Scienze della Terra "A. Desio", via Mangiagalli 34, 20133 Milano, Italy
[2] Regione Lombardia, D.G. Territorio e Urbanistica, Struttura Sistema Informativo Territoriale, via Sassetti 32/2, 20124 Milano, Italy
[3] Università di Pavia, Dipartimento di Scienze della Terra, via Ferrata 1, 27100 Pavia, Italy
[4] Now: Provincia di Cremona, Settore Territorio, via Dante 134, 26100 Cremona, Italy
[5] Now: ARPA Piemonte, Centro regionale per le Ricerche Territoriali e Geologiche, Corso Unione Sovietica 216, 10134 Torino, Italy

Fig. 1. Reference topographic map of Iseo Lake and surrounding areas. Cartographic reproduction authorized by SWISSTOPO BA056767.

(OGS). Moreover, Iseo Lake is covered mainly by sheet 99 *Iseo* of the 1:50,000 Geological Map of Italy, and subordinately in sheets 78 *Breno* and 98 *Bergamo*. These sheets of the 1:50,000 Geological Map of Italy are currently being completed by the Regione Lombardia geological mapping program (CARG), so yielding significant field data to integrate with the geophysical investigations. To such an extent, in 2002 a bathymetric survey and a geophysical study of Iseo Lake were carried out by the CARG program in collaboration with an OGS group coordinated by Franco Coren. A multibeam survey (February to March 2002) covered the whole extent of the lake, while high-resolution single-channel seismic lines were shot (Piccin & Coren 2002). Further high-resolution multichannel seismic investigations were successfully carried out, in order to gain insight on deeper sediments and structures.

This paper deals with the bathymetric data and single-channel seismic lines, in order to describe the geomorphology of the lake floor and to delineate the sedimentary evolution of the lake and the processes acting since the last glacial expansion.

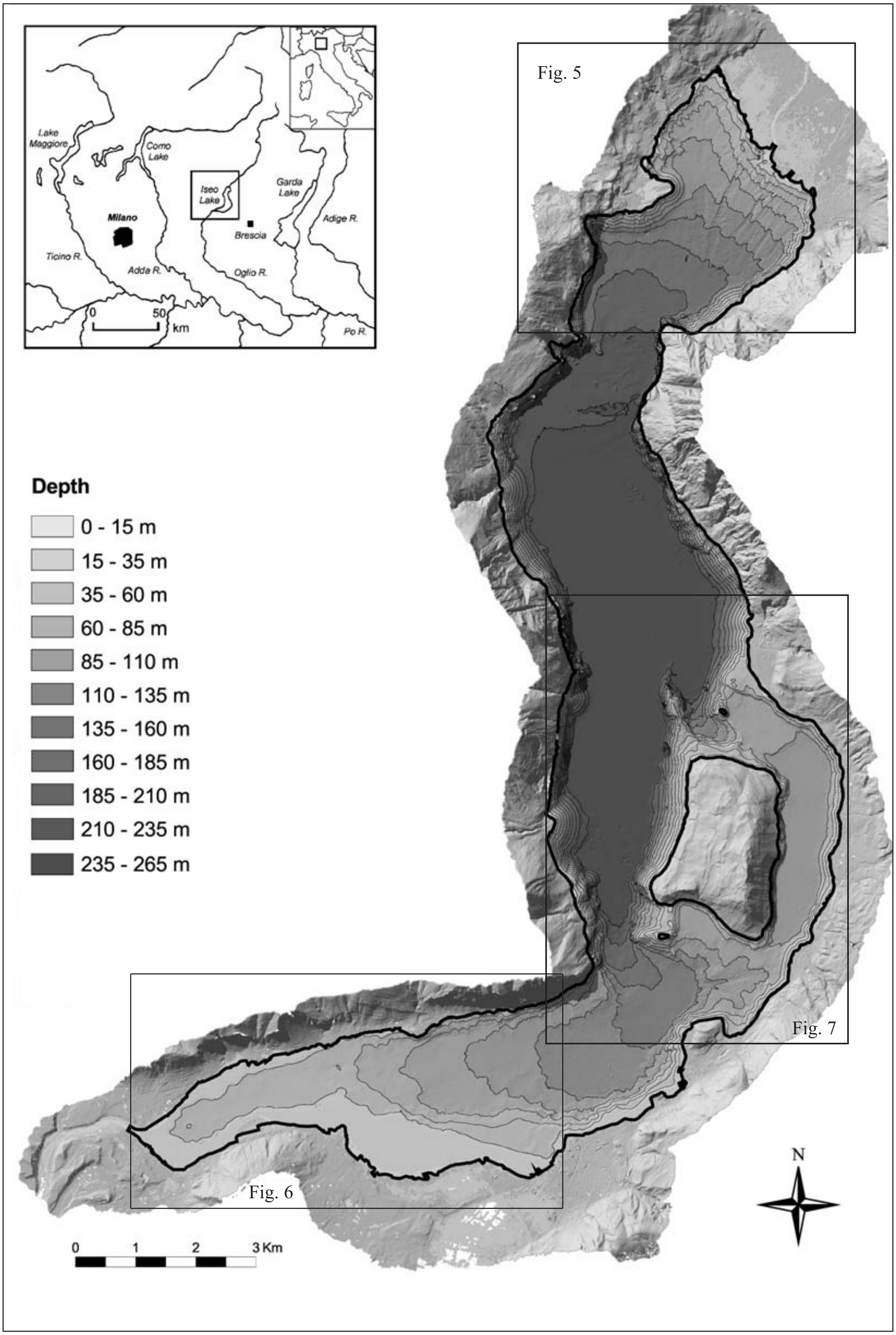

Fig. 2. Image of the digital elevation model, representing the bathymetry of the lake and surrounding areas. Depth in meters below the lake level. The sun's azimuth is N 315° and the sun's elevation above the horizon is 40°.

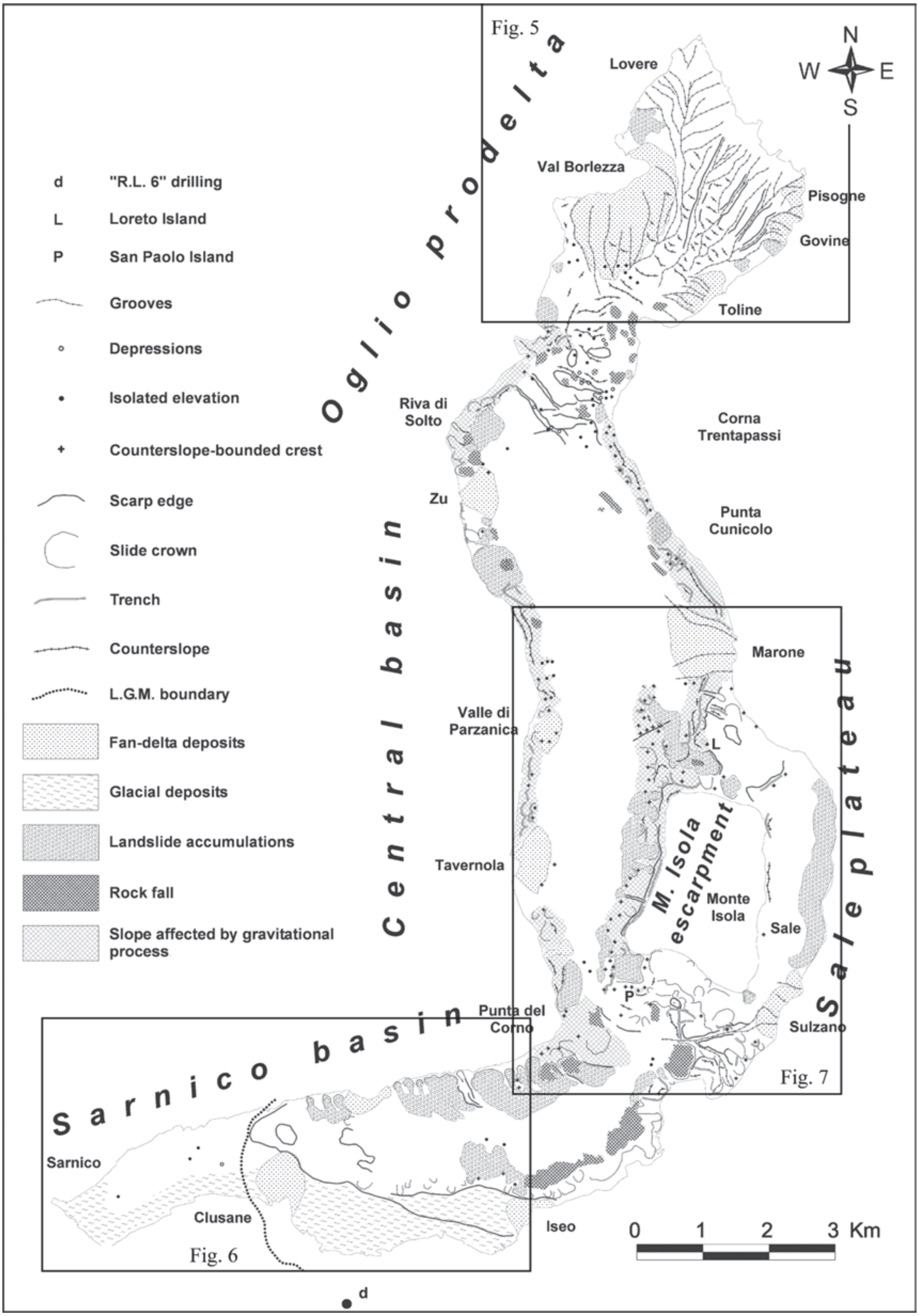

Fig. 3. Geomorphological map of Iseo Lake. The five areas into which Iseo Lake has been subdivided are shown (from N to S: Oglio prodelta, central basin, Sale Marasino plateau, M. Isola escarpment and Sarnico basin).

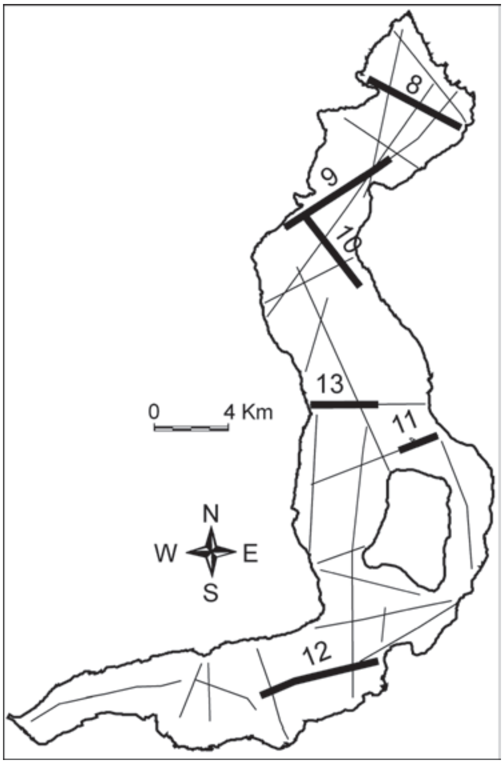

Fig. 4. Index map of the high-resolution single-channel seismic profiles. The seismic sections shown in the following figures are reported according to the figure numbers.

Geographical and geological setting

Iseo Lake is located in central–eastern Lombardy, at the boundary between Bergamo and Brescia provinces (Fig. 1). Iseo Lake covers an area of nearly 60 km^2 (25 km in length), has a maximum depth of 256 m and an average elevation of 185 m a.s.l.. In the central part of the lake, Monte Isola Island has an area of 4 km^2 with a peak elevation more than 420 m above the lake surface.

The structural setting of this area is determined by the complex stacking of south-verging tectonic slices, composed of crystalline basement and a sedimentary succession, upper Permian to Cretaceous in age, pertaining to the Southalpine domain. According to the geological setting, the substratum of the lake consists mainly of Mesozoic carbonate rocks.

The Cenozoic Alpine collisional history is mainly responsible for the structural setting, which is also influenced by inherited Permian and Mesozoic lineaments. The later events of the Alpine evolution led to the emergence of the chain, concluded in the Tortonian and associated with the formation of a structurally-controlled hydrographical pattern.

The origin of the lake is related to Quaternary glaciations superimposed on the Late Miocene fluvial morphology (Bini et al. 1978). Glacial deposits occur on both the edges of the lake. The Franciacorta morenic amphitheatre shoulders the southern shore of the lake and fills the pre-glacial paleo-valley.

Data acquisition and processing

The geophysical and geological investigations were conducted through a detailed morpho-bathymetric survey (Figs. 2 and 3) and single- and multichannel seismic analyses. High-resolution swath bathymetry (multibeam) data were acquired with a Simrad EM3000 Echo Sounder. The EM3000, positioned by differential GPS, is suited to mapping the bottom down to 400 m in fresh water. A frequency of 300 kHz enables the system to be uninfluenced by turbid water. This system was installed aboard the vessel *Libeccio*, provided by the navigation company of Iseo (NAVISEO). Through the Simrad Neptune processing system, the multibeam data allow a morphometric reconstruction of the entire basin with metre-scale resolution (in plane) and decimetric accuracy (in depth).

A conversion was made from the World Geodetic System (WGS84) to the Italian relative coordinates, on which the cartography of the Regione Lombardia is based, in order to generate a digital terrain model combining land and bathymetry of the lake floor (Fig. 2). The resulting digital terrain model needed a further morphological survey on the shores of the lake, completed in 2003 using airborne laser scan survey (LIDAR).

The high-resolution single-channel seismic profiles were shot with a UNIBOOM-like source composed of a Pulsar 2002 (output power 150–300 Joule/shot) and an UWAK 05 transducer that uses broad-band (300–2400 kHz) seismic pulses. The signals were acquired by a single-trace EG&G streamer with differential GPS control, totalling several kilometres of acquired seismic lines (Fig. 4). Seismic data were processed by PARADIGM FOCUS software, in a processing sequence including depth-variant band-pass filtering, recovering of amplitudes with automatic gain control (10 ms window) and a weighted mixing on three tracks (1-5-1).

In addition, ten high-resolution multichannel seismic profiles were successively acquired, in order to provide a better image of the sub-bottom sedimentary and tectonic structures and to delineate the structural setting of the Mesozoic substratum, the interpretation of which is beyond the purposes of the present work.

Geomorphology

The bathymetry and the digital terrain model (Figs. 2, 5, 6, 7) display the morphology of the lake floor (Fig. 3), which can be divided into several physiographical units, each different in morphology and evolution, as follows (from the north):

- an irregular southward-dipping northern part, from the Oglio delta plain as far as Zu, composed of the Oglio River prodelta;

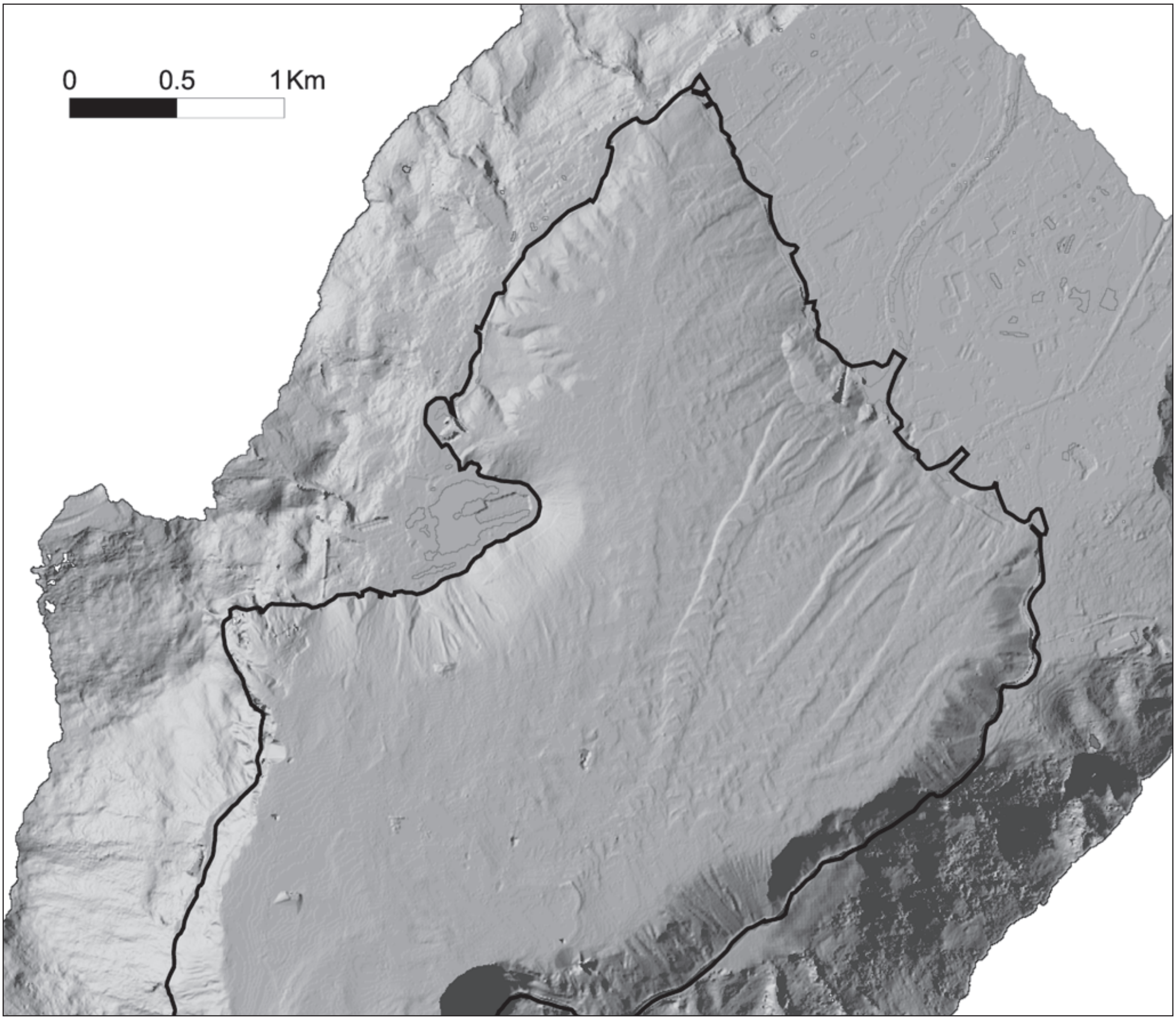

Fig. 5. Image of the digital elevation model, representing the bathymetry of the Oglio prodelta area (sun's azimuth/elevation: N 115°/40°). Several grooves cutting the Oglio prodelta are visible, the more incised of which corresponds to the present Oglio talweg. On the western side of the lake the Borlezza fan-delta is also clearly visible.

- a basin floor plain, on a regularly flat bottom at 240–256 m depth, between the western bank of the lake, the base of the prodelta and the Marone–Monte Isola–Punta del Corno alignment, forming the central basin of the lake;
- a submerged escarpment, stretching from Marone to Punta del Corno, bounding Monte Isola to the west, and emerging with the small islands of San Paolo and Loreto;
- the Sale Marasino plateau with a maximum depth of 100 m and gently southward-sloping, between Monte Isola and the eastern bank of the lake;
- the southern Sarnico basin, irregularly shaped and rising westwards, where the Oglio river exits from the basin.

Oglio prodelta

The Oglio prodelta is formed by a steeper upper part, up to 160 m depth, and a more gently dipping lower part, connecting to the central basin. The steeper upper part shows several longitudinally branched grooves, resembling a fluvial pattern, used by the system to transfer sediments carried by the river towards the central basin (Fig. 5). These grooves disappear at 160 m depth. Six main grooves can be observed (Fig. 8): the first one from the northwest is the least incised and shows an upwardly concave profile along its entire course. The other grooves are more incised and display gorge-like sections.

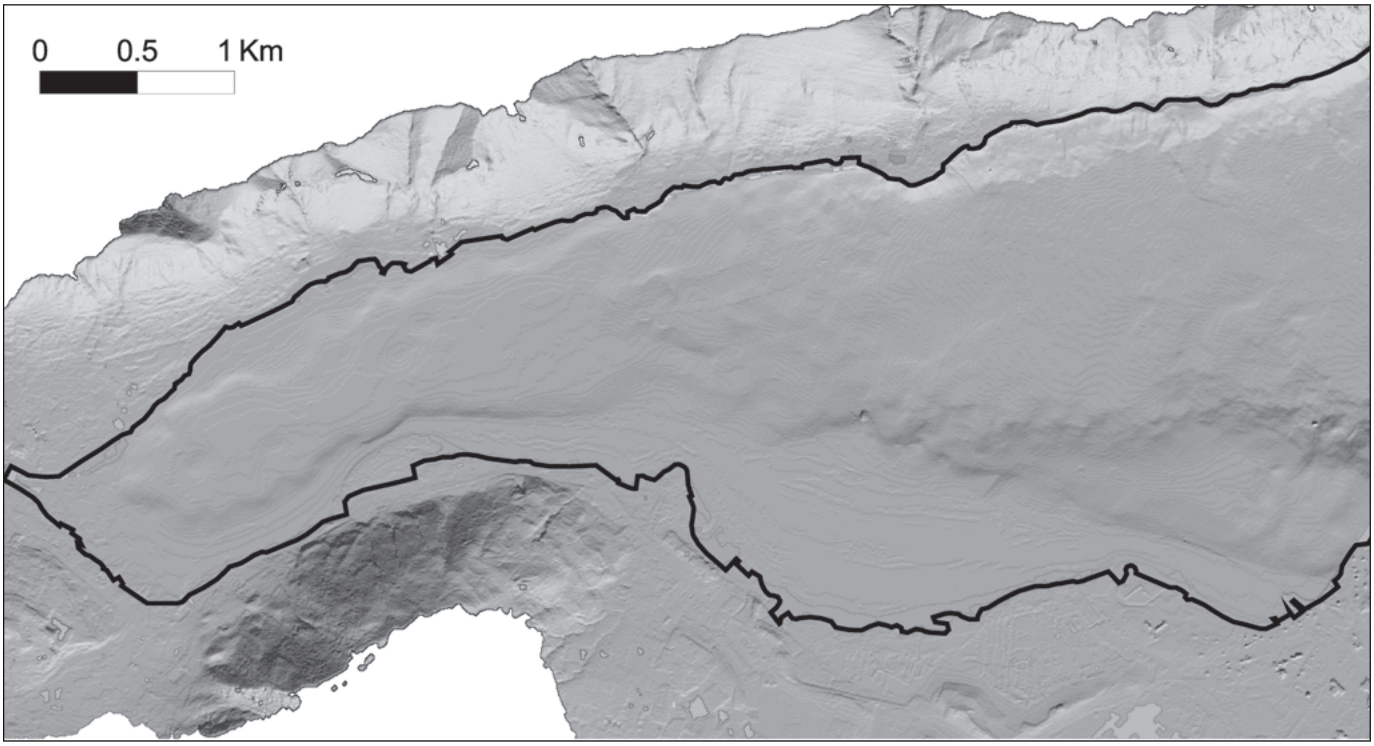

Fig. 6. Image of the digital elevation model representing the bathymetry of the Sarnico basin (sun's azimuth/elevation: N 165°/40°). A central talweg is absent and significant grooves are not visible.

These grooves show an upward-concave profile upstream, turning into a V-shaped morphology in the gorges, and successively, in the middle part of the gorges, they are characterized by a flat-bottom profile. Only the fourth groove from the NW does not originate close to the lake bank, and is wide with a flat bottom. Interfluvial areas are very irregular and characterized by a continuous succession of counter slopes and terraces.

In the single-channel seismic profiles the Oglio prodelta deposits appear to be characterized by two different seismic facies (Fig. 8) which can be hypothetically assigned to fine sediments in the upper part (6–10 m) and coarser sediments in the lower part. Several grooves show a secondary infill, subsequent to the incision (Fig. 8). No grooves may be observed in the deeper part of the Oglio prodelta.

The grooves are related to turbidity currents originating from the Oglio River. In the single-channel seismic profiles (Figs. 9 and 10), terraces and counter slopes in the interfluvial areas seem to be related to gravitational movement of water-saturated sediments on the prodelta slope. The southern, less steep part of the prodelta is very irregular, due to the occurrence of counter slopes, depressions and landslide accumulations from both the eastern and western slopes. To the east (Corna Trentapassi) the landslides are mainly subaerial falls (the last one occurred in the first decade of the 19th century), and subordinately slides. To the west they are mainly minor slides of the large deep-seated gravitational slope deformations affecting both the emerged and submerged slopes (trenches and counter slopes), as well as rock falls. In the steeper part, near Lovere, an accumulation of submerged landslides may be recognized, related to deep-seated gravitational slope deformation.

Several fans edge the lake at the mouth of the subaerial valleys. The main accumulation occurs at the mouth of the Borlezza stream, prograding onto the Oglio prodelta. Other accumulations can be recognized on the eastern shores at Pisogne and Toline. Turbidity current grooves are present only along the Borlezza and Pisogne fans.

The Borlezza fan has been artificially extended with a subaerial landfill, allowing the enlargement of industrial areas. Soil movement measurements taken from satellite interferometric radar (SAR-PS technique), recently acquired by Regione Lombardia, indicate that these zones are in strong subsidence.

Central basin

Deeply bordered by almost vertical cliffs, the central basin is almost completely flat (Fig. 7), while attaining the maximum depth of the lake (256 m).

The central basin is connected to the Oglio prodelta through a gently dipping surface. To the south, the central

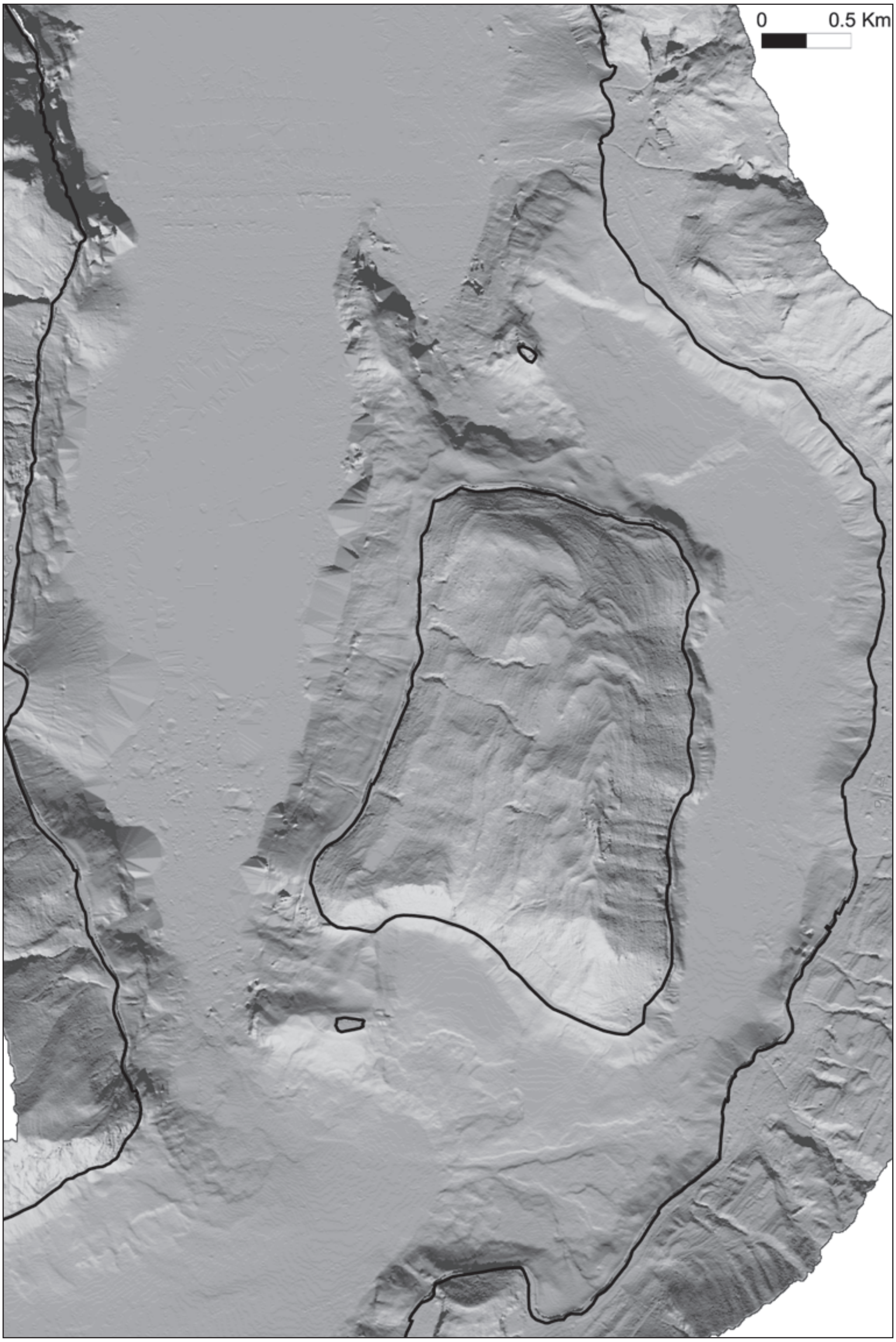

Fig. 7. Image of the digital elevation model, representing the bathymetry of the Monte Isola area, with the southern sector of the central basin and the Sale Marasino plateau (sun's azimuth/elevation: N 185°/40°). The small islands of S. Paolo and Loreto, respectively to the south and north of Monte Isola, are shown. The submerged ridge running north of M. Isola is greatly affected by counter slopes, isolated reliefs (including Loreto Island), rectilinear and semicircular trenches, downslided rocky blocks and slide accumulations. The escarpment to the west of Monte Isola southwards as far as San Paolo Island is affected by crowns of submerged landslides and accumulations. Several wide grooves with undefined talweg, with concave bottoms, can be related to turbidity currents originating from the Sulzano prodelta.

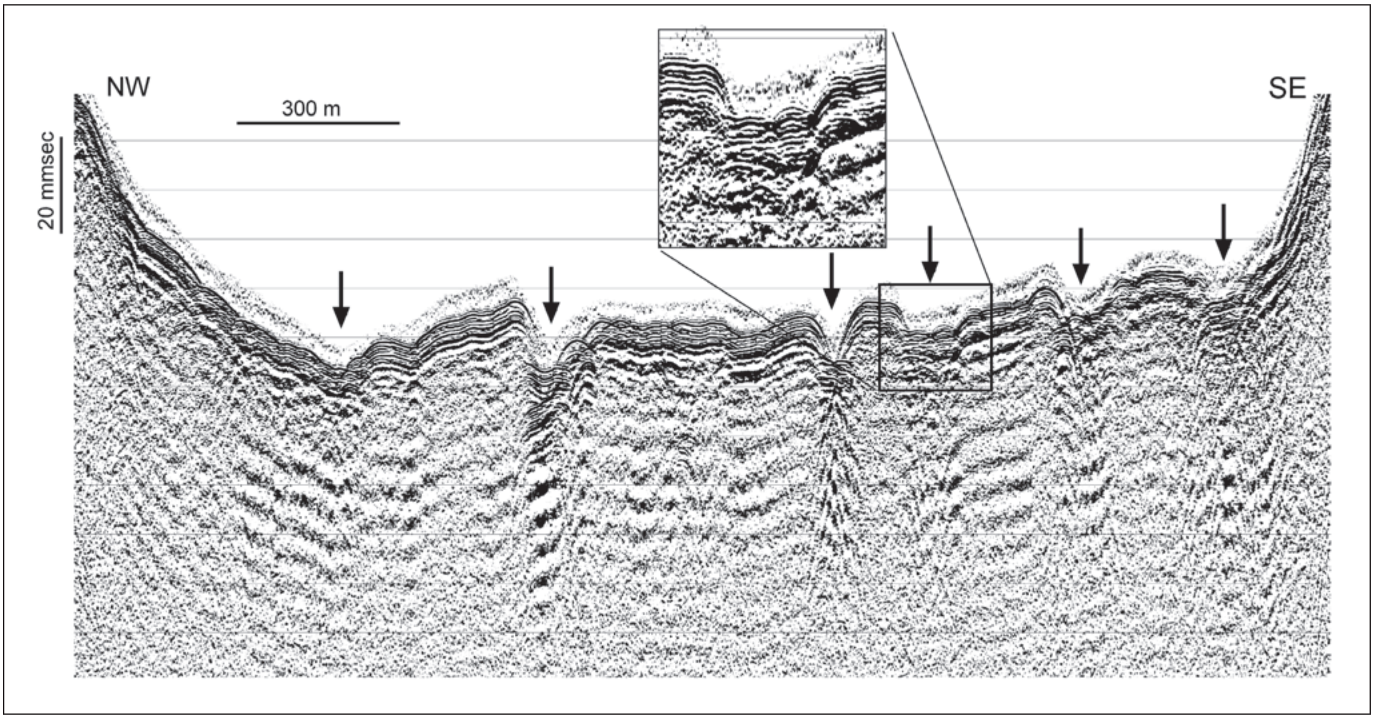

Fig. 8. Single-channel seismic profile crossing the Oglio prodelta (see Fig. 4 for location). The arrows indicate the main grooves that cut the lake floor. The zoom shows an example of secondary infill, subsequent to the incision, that characterizes some grooves.

basin is bounded by a northward-sloping surface, always steeper than the slope at the northern boundary. This surface reaches the maximum inclination along the Monte Isola submerged escarpment.

Several landslides and rock falls can be recognized, mainly from the slopes between Zu and Tavernola. A wide landslide scar affects the slopes to the south of Zu. North of Marone, several landslide crowns with terraces and counter slopes cut the western slope of Punta Cunicolo.

Along the slopes, several sediment accumulations can be recognized at the mouths of subaerial valleys. Most of these accumulations have no subaerial evidence, and no emerged delta plains can be identified. Only the Tavernola fan and the Marone fan are associated with a proper fan-delta with emerged delta plain and prodelta. The Tavernola fan is about 250 m long and 250 m wide, and seems to comprise a more recent part, forming the partially emerged fan delta, and a lower part forming a NE–SW ridge in front of the prodelta. The Marone fan is less evident, corresponds with the Monte Isola escarpment, and is cut to the north by the Punta Cunicolo landslides.

Monte Isola escarpment

The escarpment bounding the west of Monte Isola and running submerged from Marone (eastern shore) to Punta del Corno (western shore), culminating on San Paolo (south of Monte Isola) and Loreto (north of Monte Isola) islands, connects the central basin, with a water depth of 250 m, to the Sale Marasino plateau at 79 m depth, over a 400–500 m distance (Fig. 7).

To the north, the connection between Monte Isola and the lake bank takes place through a wide and almost flat terrace (-79 m), showing an almost rectilinear escarpment with a 20 m difference in level, representing the westwards termination of the Monte Isola escarpment (Fig. 7). The -79 m terrace partly shoulders the Marone fan delta. The single-channel seismic profiles crossing in this area show evidence of ongoing tectonic activity (Fig. 11). Between Loreto Island and Monte Isola the escarpment and the terrace are incised by a wide valley with a course characterized by variable slopes but never subvertical, being unassociated with any streams on the lake shore. This valley cuts a semiarcuate landslide crown into the terrace.

From Monte Isola to the north runs a submerged ridge with very steep slopes (Fig. 7). This sector of the escarpment is strongly affected by counter slopes, isolated reliefs (including Loreto Island), rectilinear and semicircular trenches, fallen rocky blocks and slide accumulations. This means that the whole sector is collapsing, leading also to the formation of a graben filled by fine sediments (Fig. 11).

A similar morphology can be recognized on the Monte Isola escarpment to the west of Monte Isola, southwards as far as San Paolo Island (Fig. 7). Crowns of submerged landslides and accumulations are more evident. Some accumulations are related to subaerial flows and slides, as a debris flow furrow, extending underwater and ending in a detrital fan.

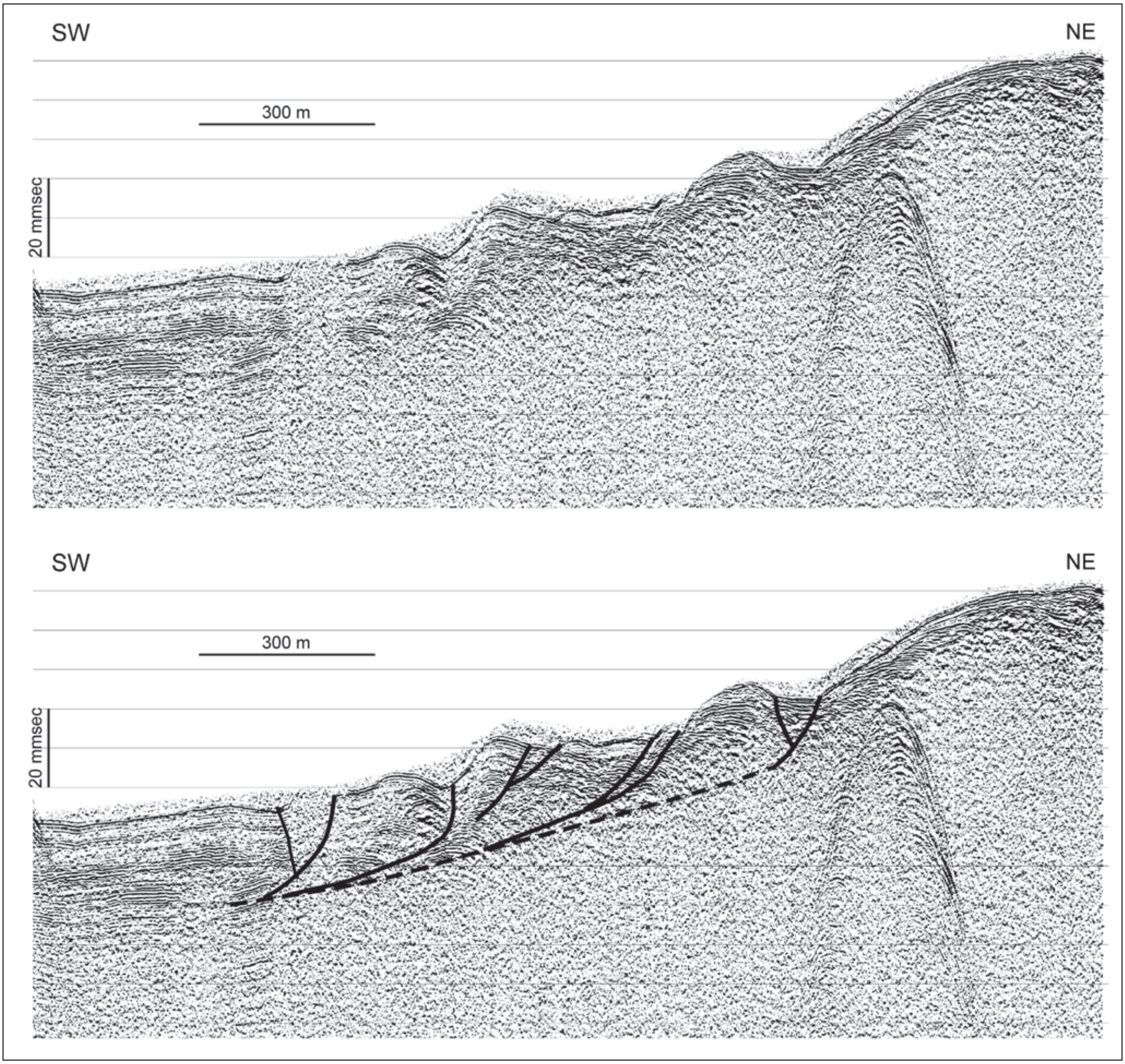

Fig. 9. Single-channel seismic profile along the Oglio prodelta, showing the active gravitational sliding processes affecting the slope. Several normal faults, detachment surfaces, reverse slope areas and rotated blocks are visible. See Fig. 4 for location.

To the south and southwest of San Paolo Island, the escarpment, still affected by mass collapse, is cut by a large valley connecting the central basin to the Sarnico basin (Fig. 7). To the southwest the escarpment continues beyond the valley with the same characteristics, ending immediately on the lake bank. The wide northwards-sloping valley from the Sarnico basin narrows northwards while incising the escarpment, and shows along the talweg a bottom profile with steps separated by sloping surfaces.

Sale Marasino plateau

The Sale Marasino plateau, between Monte Isola and the eastern shore of the lake, gently dips southwards (Fig. 7). The

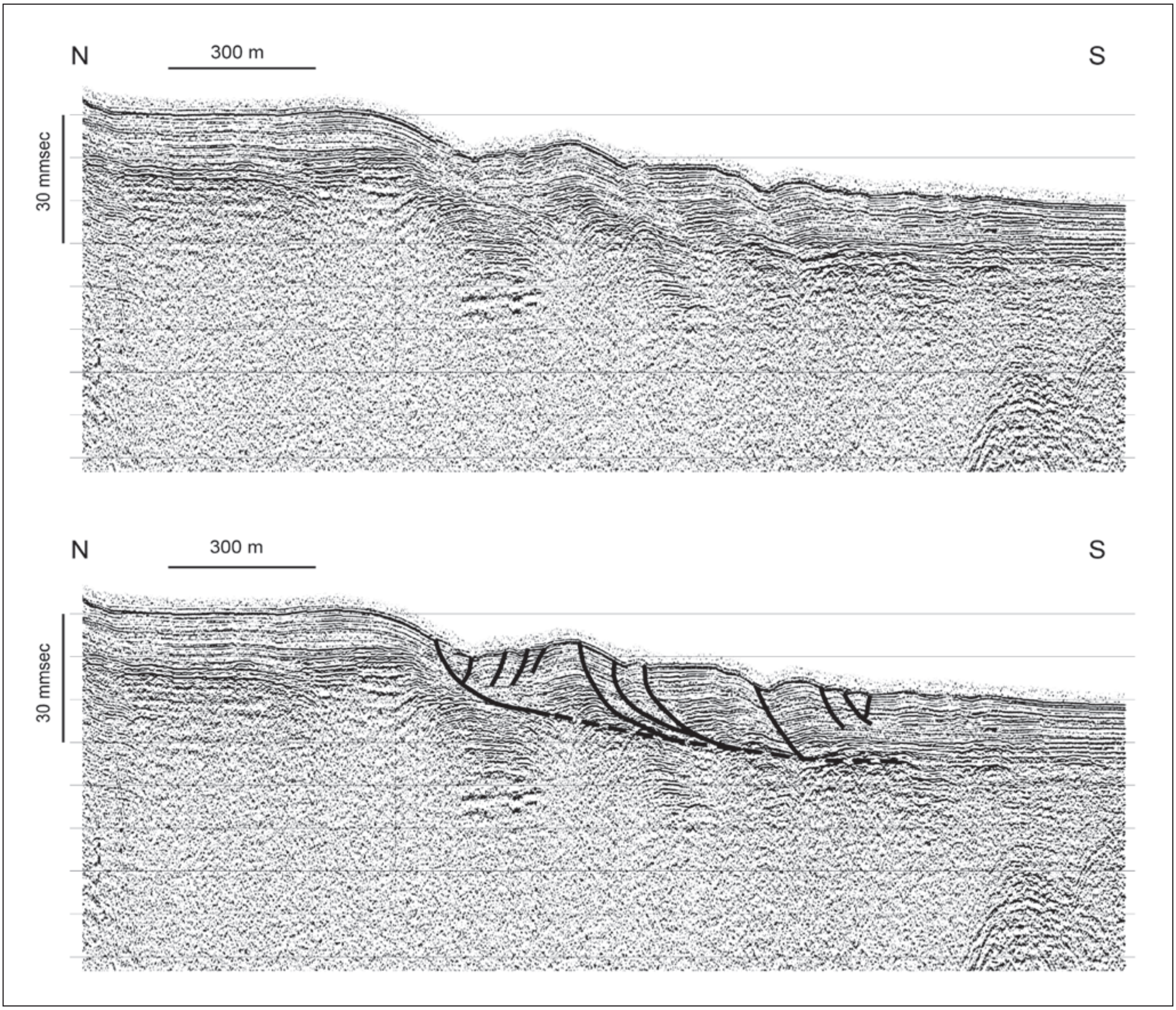

Fig. 10. Single-channel seismic profile crossing the lower part of the Oglio prodelta, at the transition with the central basin (see Fig. 4 for location), showing the gravitational processes affecting the greater part of the area.

depth of this plateau is less than the central basin, attaining a maximum depth of 99.5 m, so being 150 m shallower than the central basin. The floor is almost flat, while the isobaths on the eastern side outline gentle detrital fans originating from several landslides on the Sale Marasino slopes. To the south, two prodeltas and associated emerged delta plains are recognizable (Fig. 7).

The southern connection with the Sarnico basin takes place through a wide semiarcuate escarpment with different morphology and a lower height than the Monte Isola escarpment. This area is still affected by slide crowns and accumulations, terraces and counter slopes. The most evident morphological features are several wide grooves with undefined talweg, related to small-scale sediment flows, with a well-defined gorge groove and a concave bottom. These features can be related to turbidity currents originating from the Sulzano prodelta (Fig. 7).

Sarnico basin

The Sarnico basin forms the southward continuation of the wide valley which cuts the Monte Isola escarpment. This valley has a concave profile, a constant dip to the northeast and a

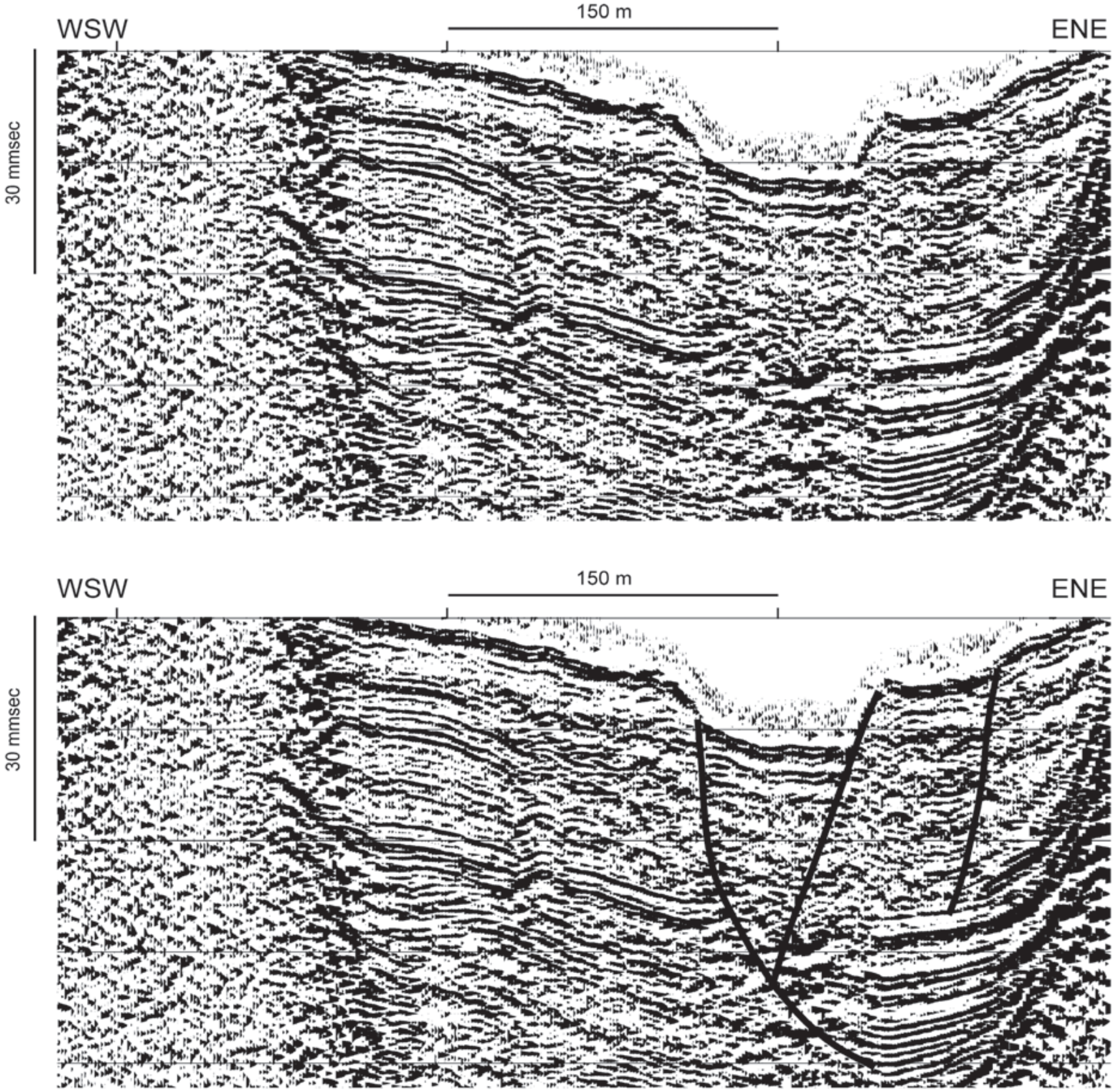

Fig. 11. Single-channel seismic profile showing the graben located on the ridge to the north of Monte Isola (see Fig. 4 for location). The normal faults delimiting the graben are active as they displace the lake floor and have a roughly N–S direction.

maximum width (1.5 km) in front of Iseo. A proper central talweg is absent and significant grooves are not recognizable (Fig. 6). The seismic characteristics of the slopes appear to be related to sediments and not to Mesozoic rocks. To the southwest, in front of Clusane, the basinal slopes are steeper and end abruptly on a 15 m wide plateau, with the emissary at its end. The end of the valley and the beginning of the plateau coincide with the last glacial maximum expansion. This plateau is possibly related to the deposits of glacial streams in a marginal glacial lake located near Sarnico at the front of the retreating glacier. On the escarpment, the multibeam data (Fig. 6) show elongated buried relief (Fig. 12) which may be interpreted as relict glacial morphologies (terminal moraines? see also the single-channel seismic profile of Fig. 12). The concave profile, without talweg, of this valley could thus be related to glacial erosion, resulting in the nearly U-shaped morphology.

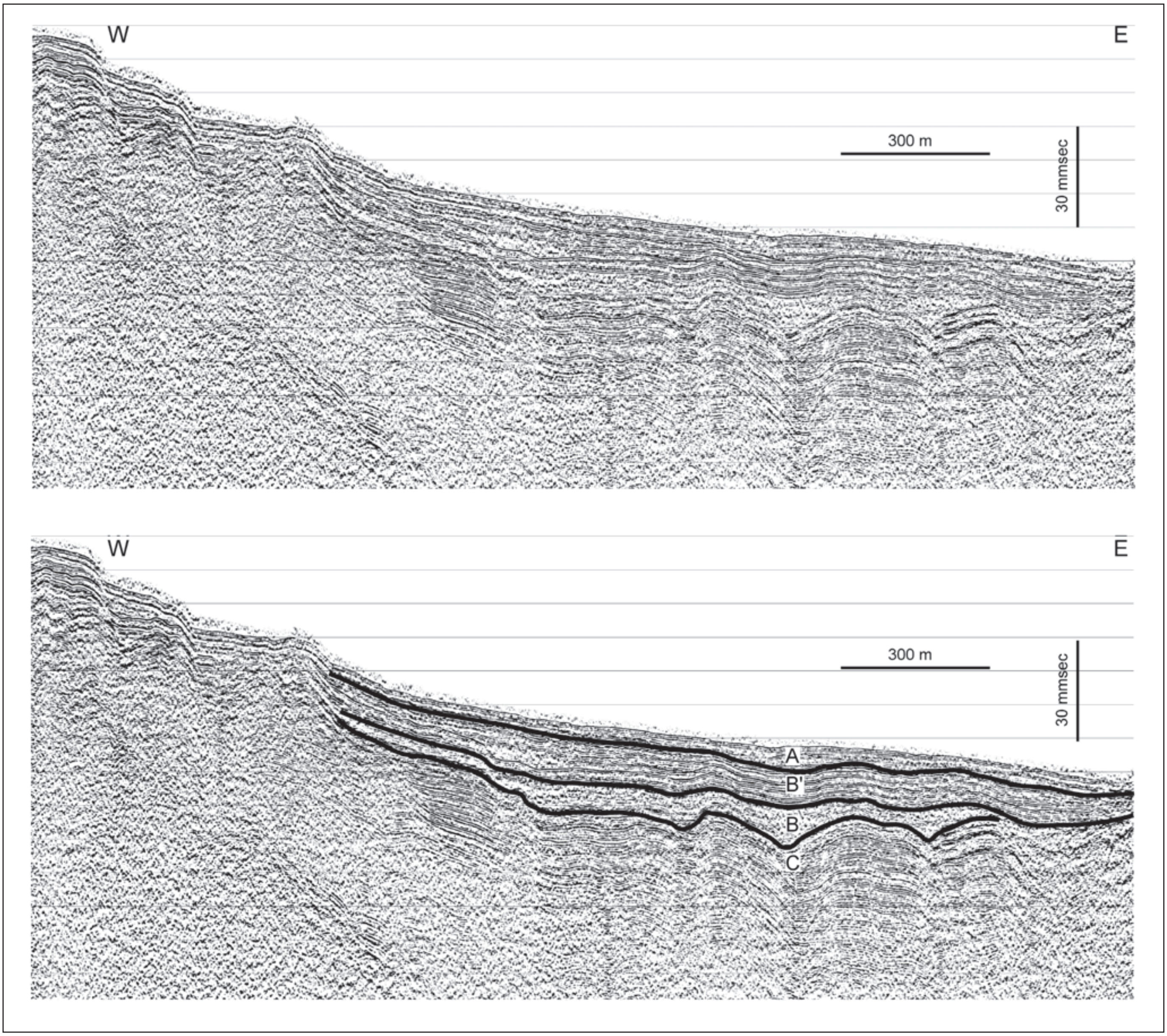

Fig. 12. Single-channel seismic profile crossing the Sarnico basin (see Fig. 4 for location). In this area sequences A and B drape a pre-existing topography linked to gravitative movements and glacial shaping. Sequence B', an interval with subparallel and continuous reflections, is unconformity-bounded at the top by Sequence A.

Sediment characterization

Based on reflection characteristics and geometries in the single-channel seismic profiles, and supported by the multichannel lines which show the whole post-Mesozoic succession, three sequences can be recognized in the uppermost part (120 ms t.w.t.) of the sedimentary infill of the lake, with reference mainly to the central basin. There is a physical correlation only between the Oglio Prodelta and basin areas, while the correlations between the Sarnico area and the Sale Marasino Plateau are based only on the seismic facies and relative stratigraphic position and are probably time-equivalent. The recognized sequences are described as follows; from the lake floor downwards (Fig. 13).

<u>Sequence A:</u> The uppermost interval, 5–15 ms in thickness, shows high to moderate reflectivity, with highly continuous and subparallel reflections, which is consistent over almost the entire Iseo Lake. Local changes in amplitude are interpreted as related to the occurrence of gas. In the Oglio

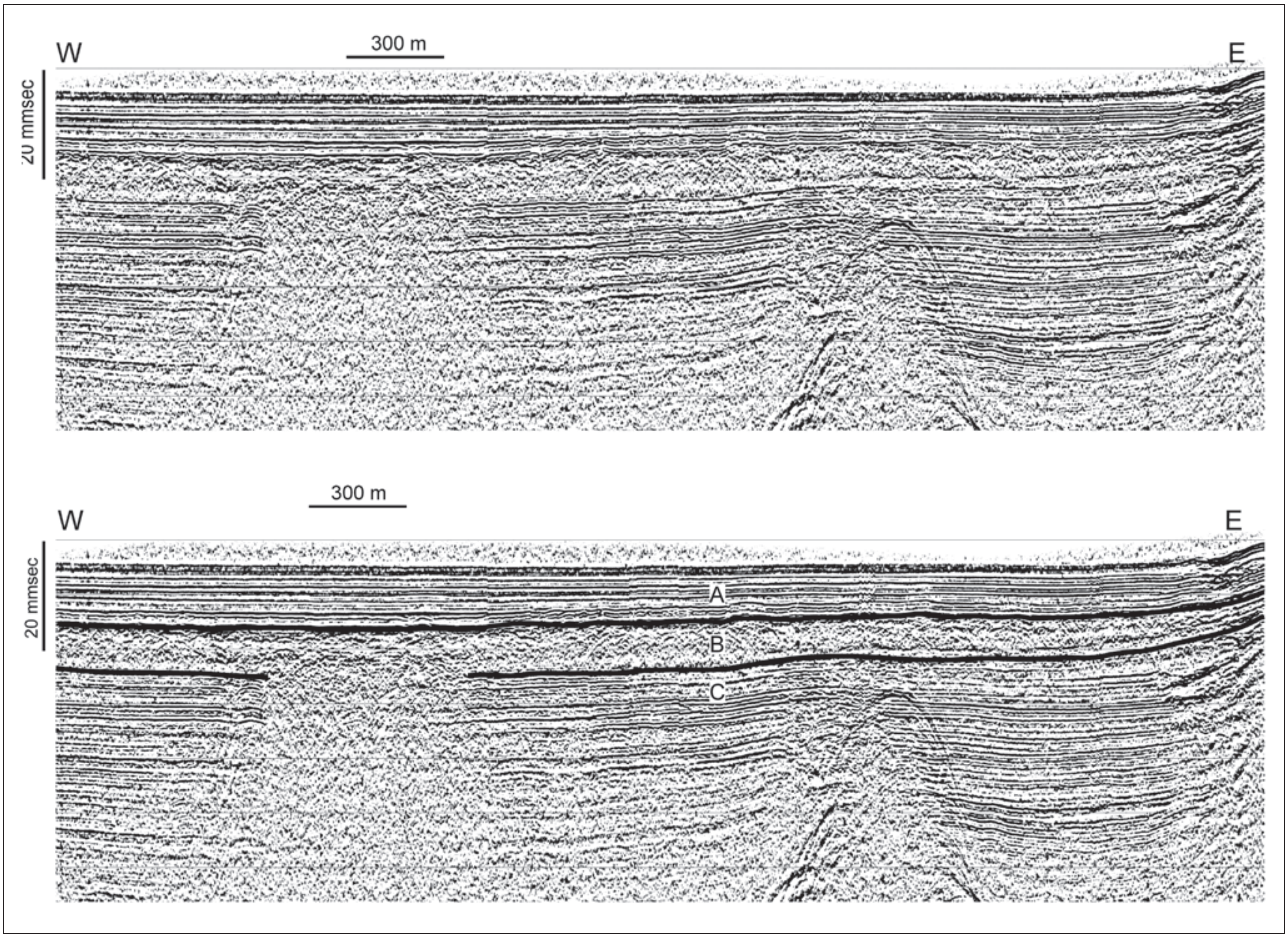

Fig. 13. Single-channel seismic profile crossing the central basin (see Fig. 4 for location). The recognized sequences A, B and C are shown. Sequence A represents recent lacustrine deposits. Sequence B records the last glacial maximum expansion, while Sequence C is interpreted as the deposits prior to the LGM, including prevailing lacustrine deposits, detrital sediments and possibly glacio-lacustrine sediments.

prodelta this sequence shows different characteristics in the lower part (under 6–10 ms of probable fine-grained sediments), displaying broken geometries, related to a very irregular depositional topography, and high-amplitude reflections, presumably indicating coarser layers (Fig. 8).

Sequence B: The middle interval, 5–20 ms in thickness, corresponds to a low-reflectivity to transparent sequence, and is recognizable only in the central and southern part of the lake. Disturbed reflections with broken continuity in the upper part of the sequence seem to be connected to gas occurrence.

Sequence C: The lower interval, detected down to a maximum of 120 ms from the lake floor, displays moderate- to low-amplitude reflections with good continuity. Like Sequence B, Sequence C is recognizable only in the central and southern part of Iseo Lake.

In the Sarnico basin, sequences A and B show different characteristics and geometries, draping a pre-existing topography linked to gravitational movements and glacial shaping. Sequence B, an interval with subparallel and continuous reflections (B' in Fig. 12) is unconformity-bounded at the top by Sequence A.

In the Sale Marasino plateau, Sequence A is underlain by a coarse interval, showing exclusively high-amplitude irregular reflectors and different from Sequence B. Figure 14 shows the stratigraphic relationships of the described sequences in the Oglio prodelta and central basin area.

In the depocentral sector of the lake (central basin), sediments of sequences A, B and C are bounded by regularly parallel reflectors, without erosional surfaces. According to their seismic characteristics, these sediments seem to be different from those interpreted as glacial in other Alpine lakes (Lake

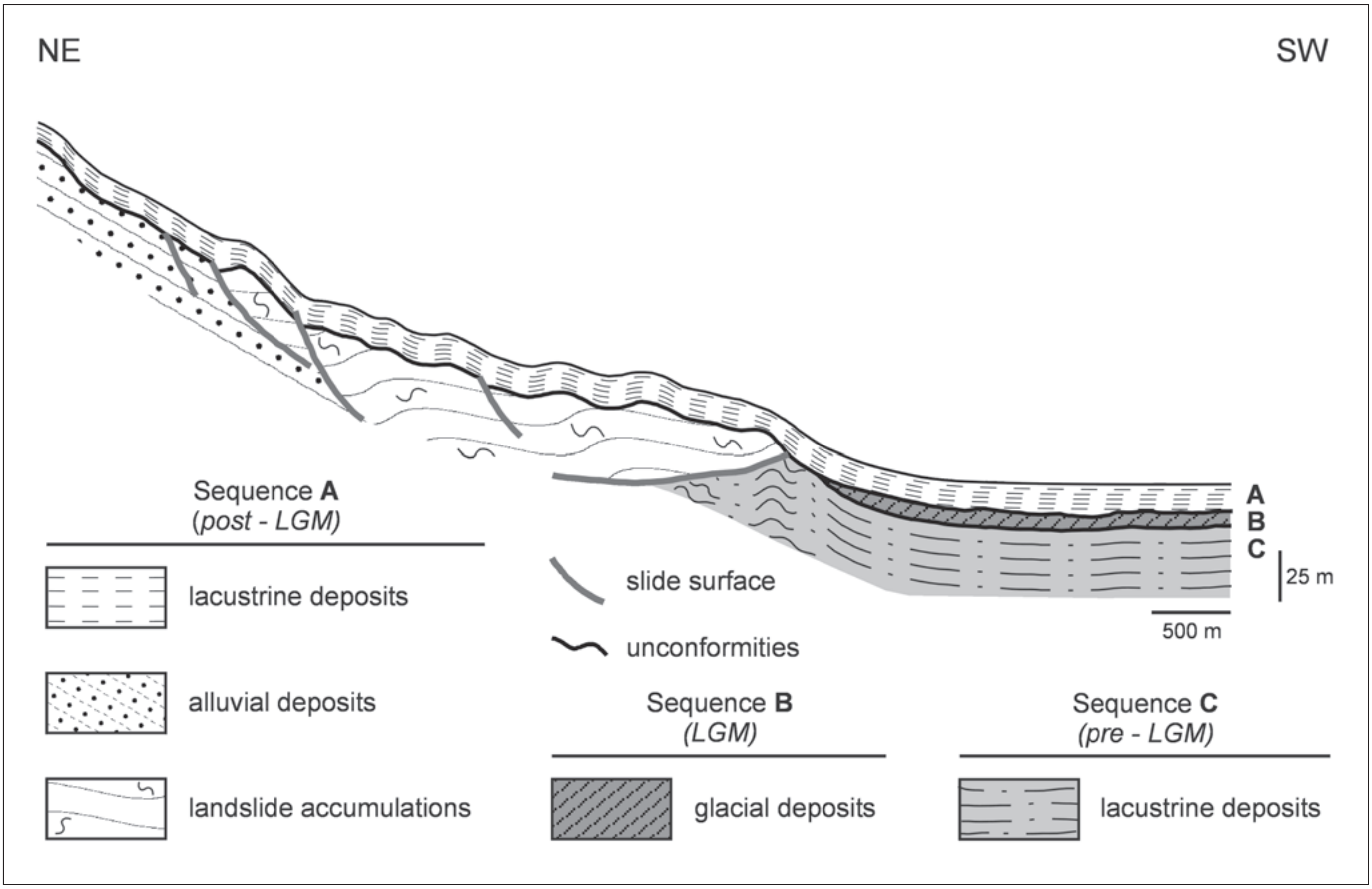

Fig. 14. Stratigraphic relationships between the recognized sequences in the northern part of Iseo Lake, at the transition from the southern sector of the Oglio prodelta to the central basin.

Annecy, Beck et al. 1996, Van Rensbergen et al. 1998; Lake Le Bourget, Van Rensbergen et al. 1999; Lake Geneva, Morend et al. 2002, Vernet 1974; Zurich Lake, Hsu & Kelts 1984). Paleobotanical and paleomagnetic investigations, as well as geochronology, on cores from other Alpine lakes allow us to relate sediments of comparable thickness to the last glaciation and successive time intervals. The only available drilling in the Iseo area is the ”R.L. 6” drilling at Cremignane d’Iseo, some 100 m to the south of the southern shore of the lake. In the ”R.L. 6” drilling, middle and upper Pleistocene sediments comprise the upper 50 m of the core (unpublished paleomagnetic data). This element, and the lack of till and erosional surfaces in the lake sediments, seems to indicate peculiar dynamics and morphology of the Oglio glacier during the last glaciation.

Unlike other glaciers on the southern side of the Alps, field data (Bini & Zuccoli 2004; unpublished CARG program data) indicate that the Oglio glacier in this area of the Camonica Valley had a reduced thickness and a low topographic gradient of 10‰ and locally less. At Pisogne the Oglio glacier was 600 m thick, while for example the Adda glacier at the northern part of Lake Como was about 2000 m thick. The thickness of the Oglio glacier was less than 200 m in the middle part of the lake, and presumably less than 100 m in front of Iseo, in the Sarnico basin. In contrast with the large amounts of till deposited during the LGM in other valleys on the southern side of the Alps, the Oglio glacier left few deposits and inconspicuous morphologies. During the LGM the Oglio glacier did not reach Sarnico (Fig. 15) and infringed land somewhere between Clusane and Iseo. These data suggest the occurrence of a floating glacier from the Corna Trentapassi narrow as far as S. Paolo Island, encroaching the floor in the Sarnico basin to the south of S. Paolo Island and with a minor branch in the Sale Marasino channel. The glacier appears to act as a tidewater glacier, with low surface gradient and frequent fluctuations of the ice-front, characterized by slow advance phases and rapid or almost ”catastrophic” retreats (Lonne & Syvitski 1997). The fluctuations of the Oglio glacier, confined between the narrows of Corna Trentapassi and Monte Isola, may have been somehow hampered. This model explains the lack of ablation till, the lack of glacial erosional features and the very reduced supraglacial debris left by the LGM glacier.

Fig. 15. The probable last glacial maximum expansion in the Iseo area, reconstructed from CARG field data. The LGM glacier did not reach the southern shore of the lake and was possibly floating south of the Corna Trentapassi narrows. Cartographic reproduction authorized by SWISSTOPO BA056767.

The seismic facies of Sequence B is homogeneously characterized by the lack of reflections, so being different from the seismic characteristics of normal lacustrine sediments (Van Rensbergen et al. 1999). The ubiquity of Sequence B over the lake does not fit its interpretation as turbidity current and\or landslide accumulation. Thus the most consistent interpretation for Sequence B is as an unconsolidated massive diamicton, yet without an erosional lower boundary. Similar sequences in other Alpine lakes are related to subglacial lacustrine sedimentation (Lake Annecy, Beck et al. 1996, Van Rensbergen et al. 1998; Lake Le Bourget, Van Rensbergen et al. 1999; Zurich Lake, Hsu & Kelts 1984). In these lakes the subglacial sedimentation is interpreted as recording the melt of stagnant blocks of dead ice, while in Iseo Lake, ice is believed to have been in continuity with the glacier. The lack of evidence of retreat could be related to a rapid retreat of the tidewater glacier. A rapid deglaciation is also argued for Lake Zurich (Hsu & Kelts 1984), Lake Annecy (Beck et al. 1996), Lake Geneva (Moscariello et al. 1998) and Lake Le Bourget (Van Rensbergen et al. 1999).

Therefore, Sequence B records the last glacial maximum expansion while Sequence A corresponds to the lacustrine sedimentation successive to the retreat of the LGM glacier. On the southern side of the Alps, Lake Como was completely

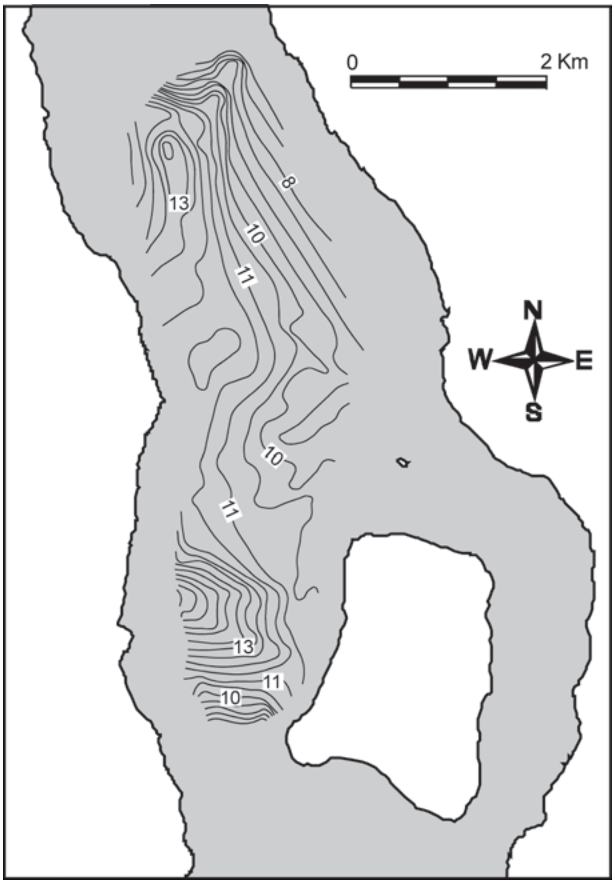

Fig. 16. Isopach map of Sequence A, showing the top of the LGM deposits in meters below the lake floor. The maximum thickness of this sequence is reached in the western part of the central basin and is more than 15 m. Sequence A represents recent lacustrine deposits post-dating the last glacial maximum expansion.

deglaciated and had terrestrial vegetation on the slopes at 15,500 years BP (Bini et al. 1997). At 13,490 BP the Valtellina was also completely deglaciated, and at 12,320 BP a dense forest of birch and pine trees was already growing (Pini 2002; Zoller et al. 1977). According to Niessen & Kelts (1989) Lake Lugano was completely deglaciated at 12,800 BP and, relating to correlations between Lake Lugano and Lake Zurich, the deglaciation would have been synchronous over all the Alpine lakes. Indeed, Lake Lugano displays a peculiar history: Strini & Bini (1998) demonstrated the occurrence of a huge block of dead ice in the Menaggio Valley (between Lugano and Como lakes) long after the retreat of the Adda glacier from Lake Como, as documented by the aforementioned U/Th and radiocarbon ages, while a 13,070 BP radiocarbon age on wood from sediments of Lake Lugano indicates that at that time the glacier had already retreated from the lake.

According to these data, and taking account of the lake morphology, the retreat of the LGM glacier from Iseo Lake should have taken place at 16,000 BP or before. Sequence A thus encompasses the latest Upper Pleistocene and the Holocene. With an estimated average thickness for Sequence A of 15–20 m (10–15 ms twt), a sedimentation rate of about 0.1 cm/a can be inferred. This value is consistent with sedimentation rates known for lakes in the literature (Einsele 1992, and references therein), including lakes with significant clastic supply, and is comparable with sedimentation rates for recent sediments in Lake Neuchatel (Gorin et al. 2003), Lake Geneva (Baster et al. 2003) and Lake Annecy (Beck et al. 1996).

Sequence C represents the deposits prior to the LGM, including prevailing lacustrine deposits, detrital sediments and possibly glacio-lacustrine sediments.

The seismic facies with subparallel and continuous reflections, interposed between sequences A and B in the Sarnico basin (Fig. 12), may be related to glacio-lacustrine deposition in a margino-glacial environment, related to the extension of the LGM glacier, which did not reach the southwestern end of the lake.

Conclusions

High-resolution geophysical investigations and field geological data from the Regione Lombardia geological mapping program (CARG) allow us to draw the following conclusions.

In the uppermost part of the sedimentary infill of the lake, in the central basin, three sequences can be recognized, interpreted respectively as recent lacustrine deposits (Sequence A), glacial deposits (Sequence B), and lacustrine deposits prior to the LGM (Sequence C). Sequence B would record the last maximum expansion of the glacier. The top of Sequence B is found at 10–20 m depth below the lake floor (Fig. 16), indicating a sedimentation rate of about 0.1 cm/a, comparable to other known situations.

The morphology of the lake is prevalently antecedent to the last glacial maximum expansion.

In the Sarnico basin (Fig. 12), the seismic profiles show that the last glacial maximum tills, underlying the lacustrine deposits, drape a pre-existing U-shaped morphology, connected with previous glaciations that were more significant than the LGM in the study area. The Sarnico basin is the only area in the lake where glacial morphologies can be recognized.

Some features may be considered as inherited from the preglacial period: as an example, the northwards narrowing (against the flow of the basin) of the submerged valley located to the southwest of the Monte Isola escarpment allows us to exclude a glacial origin for this valley, indicating instead a possibly preglacial fluvial erosion.

In contrast to these preglacial structures, the Oglio prodelta, the fan-deltas and the landslides along the submerged slopes of the lake formed during postglacial evolution, subsequent to the retreat of the LGM glacier.

In analogy with similar situations in other Southalpine areas (Bini et al. 1998; Bini et al. 2001), most of the geomorphological features would form in a relatively short time following the retreat of the glacier, which left conspicuous volumes of unstable sediments on the unvegetated slopes, soon to be dismantled by debris-flows and landslides. At present, only the Oglio River and the streams with significant flow rates, discharging from valleys where remarkable amounts of sediment are available for erosion, produce turbidity currents. The largest of these active fan-deltas is the Borlezza fan, at the mouth of the Borlezza gorge, which, according to field data, was filled in every glaciation and successively emptied by erosion.

Landslides, slumps and deep-seated gravitational slope deformations are frequent and generally still active on the Oglio prodelta, on the lake slopes and on the Monte Isola escarpment. Landslide accumulations are partially remobilized in front of Lovere and to the south of Punta del Corno. The graben observed in the high-resolution seismic profiles to the north of Monte Isola (Fig. 11) highlights ongoing gravitational tectonic activity.

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