Sub-bottom and GPR surveys over two puzzling lakes within the Ivrea Morainic Amphitheatre (NW Italy)

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Con la collaborazione di:
M. Bobbio e P. Giurco

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L. Sambuelli [1] , S. Piro [2] , A. Fiorucci [1] , C. Comina [3] , C. Colombero [3] .

[1]DIATI - Politecnico Di Torino - I, [2]ITABC - CNR - Roma - I, [3]DST - Università di Torino - I

Introduction

Lake sediments, including those of the peri-alpine and pro-glacial lakes, are well known records of the past climate and environments (e.g. Carrivick and Tweed, 2013). Extensive studies have been devoted to the evaluation of sedimentation rates and correlated climatic conditions as an important factor controlling the preservation of inland waters. This is even more relevant over lakes with no inflows, where the only factors governing sedimentation rates are related to the external environment. Several literature papers (Table 1) report on quite uniform sedimentation rates, ranging between 0.3 and 0.9 mm/yr.

Table 1 – Sedimentation velocity in some lakes as referred to in literature.

Paper	Site	Elevation [m a.s.l.]	Average sed vel [mm/yr]	Core length [m]	Inflow
Simonneau et al., 2014 *[Quat. Sc. Rev.]*	Lake Blanc Huez, W French Alps	2550	0.3	3.4	No
Menounos, 1997 *[The Holocene]*	Sky Pond, Colorado, USA	3000	0.3	3.8	No
Lami et al., 2000 *[J. of Limnol.]*	Candia Lake, NW Italy	226	0.3 – 2	1.1	No
Punning et al., 2003 *[J. Paleolimn.]*	Viitna Linajarv, N Estonia	75	0.9	9.5	No
Punning et al., 2003 *[J. Paleolimn.]*	Viitna Pikkjarv, N Estonia	75	0.35	4	No
Facchinelli et al., 2005 *[RMZ Mat. and Geoenv.]*	Sirio Lake, NW Italy	266	0.5 (1)	1.7	No
Finsinger et al., 2006 *[Quat. Sc. Rev.]*	Avigliana Lago Piccolo, NW Italy	353	0.5 (2)	14.92	No
Finsinger et al., 2014 *[Jour. of Limnol.]*	Avigliana Lago Grande, NW Italy	353	0.6	3	No
(1) in the last 2000 years	(2) down to 8.3 m				

Determining nature and thickness of lake sediments is therefore particularly relevant for an accurate reconstruction of the geological setting, the paleo-climatic record and the eventual colmatation risk. With this aim, given the high costs and technical challenges of direct sediment coring, geophysical surveys can be seen as a valuable tool either to locate significant cores or to extend existing core information. Within the frame of a long-lasting research concerning waterborne geophysical surveys over inland waters, several lakes of glacial origin, located at the foot of Northwestern Italian Alps, have been investigated. Here glacier's retreat (about 15 kyr BP, according to Vescovi et al., 2007) left well recognizable frontal and lateral morainic structures, basal erosion surfaces and depressions in the bedrock. The topographic constraints and permeability contrasts generated by both these positive and negative glacial forms promoted localized water accumulation and the consequent origin of several glacial lakes. One of the largest and best known Alpine complex of glacial forms, which is still hosting many glacial lakes, is the Ivrea Morainic Amphitheatre (IMA, Gianotti et. al., 2015). Two of the IMA lakes have been extensively studied: the Candia Lake (45°19'27.90"N, 7°54'40.85"E) and the Sirio Lake (45°29'12.08"N, 7°53'1.56"E). The Candia Lake originated in a proglacial position, located in the IMA frontal sector, at the southwestern internal edge of one of its outer and more extended morainic arcs. It currently lies on a suspended fluvial terrace, approximately 4-8 m above the present Dora Baltea River alluvial plain.

Table 2 – Main characteristics of Sirio and Candia lakes.

Name	Sirio	Candia
Basin	Dora Baltea - Po	Dora Baltea - Po
Origin	Glacial erosion	Proglacial
Mean elevation	266 m	226 m
Volume	5.25 Mm^3	7.2 Mm^3
Maximum depth	43.5 m	7.5 m
Mean depth	18 m	4.7 m
Maximum length	0.9 km	2.11 km
Maximum width	0.45 km	0.85 km
Perimeter	3.3 km	5.8 km
Surface	0.3 km^2	1.5 km^2
Catchment area	1.4 km^2	8.9 km^2

The Sirio Lake is located northern the Candia Lake, in a more internal IMA position, and entirely lies on the granulitic rocks of the Ivrea-Verbano zone, which were intensely eroded by the glacier mass. Despite the different origin, the two lakes show some similar characteristics (Table 2) and both have no, or very scarce, inflows and outflows. Paleoclimatic studies, involving continuous drilling of the lakebed sediments, have been performed on both lakes. Facchinelli et al. (2005) estimated a mean sedimentation rate of 0.5 mm/yr for the last 2 kyr BP on a 1.7 m long sediment core sampled in the Sirio Lake. According to Lami et al. (2000), the bottom of a 1.1 m long core of the Candia Lake dates back to nearly 2 kyr BP, with a resulting similar sedimentation rate. An extensive waterborne Continuous Vertical Electric Sounding (CVES) investigation, aimed at the reconstruction of the Candia lakebed sediment nature and geometry, found a 10-to-15 m thick pack of sediments showing an average electrical resistivity of 30 Ωm, nearly throughout the whole lake bottom, and thus interpreted as fine-grained saturated lacustrine sediments (Colombero et al., 2014). In this work our attention is focused on the Sub-bottom and GPR surveys recently acquired on the two lakes. Results of the new surveys arise a puzzling situation with respect to sediment nature and related thickness.

Experimental evidences

We performed the Sub-bottom surveys with a Syquest Bathy-2010PC Chirp profiler driving two TR-109 3.5-kHz transducers or a Stratabox Line-in-Cone 10-kHz transducer. On the Sirio Lake, 11 profiles were acquired, for a total investigated length of about 3.3 km. On the Candia Lake, we acquired 30 Sub-bottom profiles, for a total length of about 13 km and, contemporarily, 9.5 km of GPR data were recorded with a 40-MHz Subecho antenna and a K2 IDS control unit. All the acoustic and GPR profiles were tracked with GPR devices, georeferencing each ping or trace with a metric precision. Standard processing techniques were applied on the raw datasets. On the Sirio Lake, all the raw sub-bottom profiles showed one or more multiples of the rock basement, acting as an acoustic mirror (Figure 1a). Only after further processing, involving time and spatial filtering and autocorrelation, a quite uniform thin carpet of lake sediments could be observed along some profiles (Figure 1b). These sediments show an average thickness of about 2.5 m, which increases to approximately 4 m in a few short profile segments. Similar results are observed on the raw profiles of the Candia Lake, where multiples are even more visible because of the shallower water depth (Figure 2a). Also in this case, after processing, a thin (1÷1.5 m) layer of sediments just below the water-sediment interface which acts as an acoustic mirror is highlighted (Figure 2b). This layer is also visible somewhere within the GPR profiles (Figure 3) where water depths are lower than about 3 m.

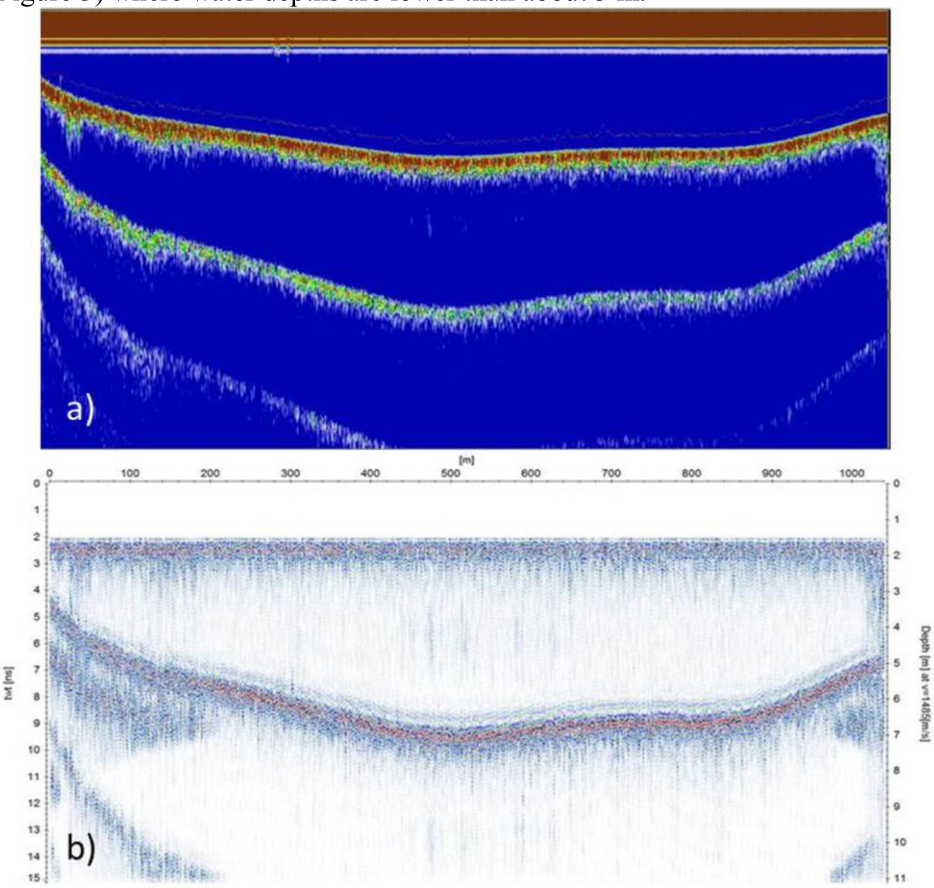

Figure 1 – Candia subbottom profile: a) raw data and b) processed.

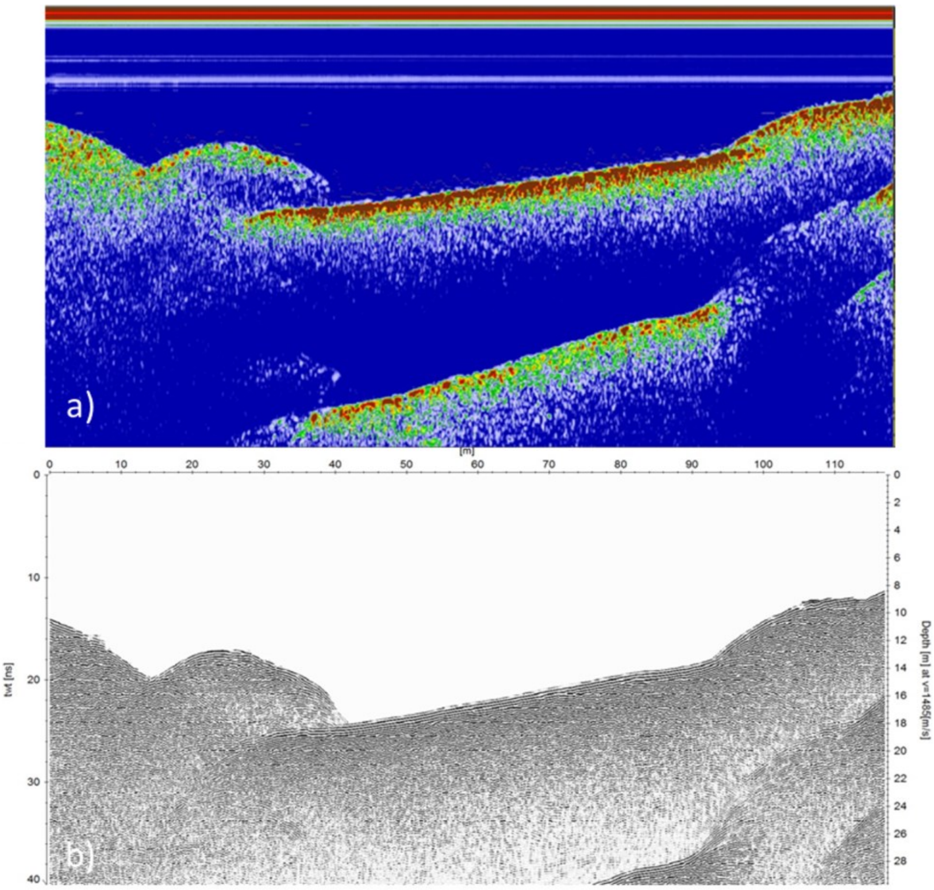

Figure 2 – Sirio subbottom profile: a) raw data and b) processed.

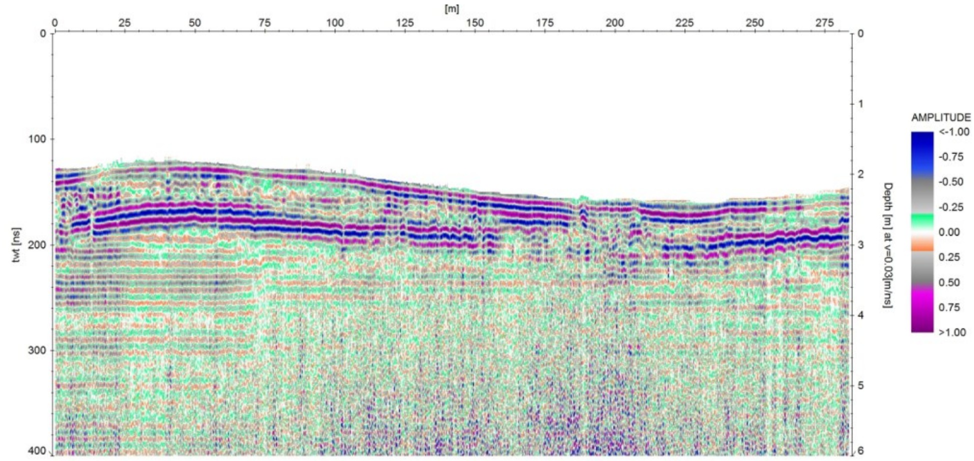

Figure 3 – GPR profile on Candia Lake.

Discussions

Considering the similar sedimentation rates estimated on core samples of both lakes for the last 2 kyr BP, and the sediment thickness reconstructed from the presented geophysical surveys a puzzling situation appears. In particular, the reconstructed lacustrine sediment thicknesses (2.5-3 m for Sirio Lake and 1.5-2 m for Candia Lake, on average) appear to be non-coherent with the measured sedimentation rates.

For Sirio Lake, it is not clear which kind of climatic evolution could have generated 1.7 m of sediments in the last 2 kyr, compared to only 1-1.3m in the preceding 13 kyr. Considering the total lacustrine thickness as the result of 15 kyr of sedimentation, a very low mean sedimentation rate (approximately 0.2 mm/yr, less than half the rate estimated by Facchinelli et al., 2005) would be obtained. Such a low value could be only partially explained with the absence of an inflow and the scarce sediment supply from the lake surroundings, which are totally composed of granulitic rock with very thin and loose terrigenous covers.

For Candia Lake, the sediment thickness observed by the past CVES surveys (10-15 m) could be motivated by the sedimentation rate observed by Lami et al. (2000). However, considering the acoustic results, it is not clear the nature of sediments having a resistivity of about 30 Ωm and acting as an acoustic mirror. At present, the most probable interpretation is the presence of a thin but widespread shallow layer of high-porosity lacustrine sediments hosting gases released from the decomposition of organic matter. This latter was found to be particularly abundant (12-37% of sample dry weight) in the topmost sediments sampled by Lami et al. (2000). These quantities, together with the anoxic conditions of the lake bottom and the absence of seasonal water mixing or inflow circulation, could probably support the hypothesis of gas formation in the shallower lacustrine sediments, approximately at 1.5-2 m from the lake bottom, inhibiting the acoustic penetration. Conversely, another explanation to electrical and acoustic results would be to consider these acoustic impenetrable sediments not as lacustrine deposits but as sub-glacial silts, settled before the glacier retreat and consolidated by the ice weight. However, in this case, analogously to Sirio Lake, a marked change in the sedimentation rate would be implied. In particular, lacustrine sediments would be represented by the thin layer of sediments observed at the top of the lake bottom. This sediment pack (1.5-2 m) would have deposited in the last 15 kyr, with the shallowest meter deposited only in the last 2 kyr (considering the sedimentation rate estimated by Lami et al., 2000), and thus with deeper 0.5-1 m representing the previous 13 kyr of sedimentation.

Motivations for this variation do not appear to be explained by literature evidences on particular climatic transition at that time. Literature data on sedimentation velocity in lakes without inflow (Table 1) do not justify either such low sedimentation rates in the period from 2 kyr to 15 kyr or such an eventual dramatic change in sedimentation rate. In addition, the observations made on these two lakes are not common to all the lakes within the IMA. Sub-bottom profiles acquired on a third IMA lake (Viverone Lake, located between Candia and Sirio lakes, at a distance of approximately 20 km from both) gave a clear imaging of acoustically transparent lacustrine sediments, up to 30-m tick. Unfortunately, no literature information on drill cores and sedimentation rates on the Viverone Lake was found for a critical comparison with the two investigated lakes. Further studies are therefore needed to understand if the sediment nature and thickness observed by the presented surveys confute the sedimentation rate estimated on the Sirio Lake and highlight the widespread presence of water and gas saturated sediments on the bottom of the Candia Lake or are indeed potential indicators of a particular climatic transition.

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