First results of Waterborne Geophysical surveys around the Malpasso site (Tuoro sul Trasimeno, Italy) for geological and archeological characterization (velocità e *Q*) che da quello elettromagnetico (conducibilità elettrica) potrebbero essere usati per verificare la relazione di *cross-properties* tra le proprietà sismiche ed elettromagnetiche.

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FIRST RESULTS OF WATERBORNE GEOPHYSICAL SURVEYS AROUND THE MALPASSO SITE (TUORO SUL TRASIMENO, ITALY) FOR GEOLOGICAL AND ARCHEOLOGICAL CHARACTERIZATION

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Introduction. Geological characterization of shallow sediments in water-covered areas is a difficult task with traditional survey techniques. Direct investigations are indeed often neither cost-effective nor reasonably quick and adequate in number to cover the whole surface of a basin and to obtain a reliable correlation of data over a wide area. Geophysical techniques can conversely be very useful to investigate sediments which are entirely located beneath a water-covered area. This could allow for an uniformly spaced, even if indirect, investigation of the interested site. The integration of seismic and non-seismic waterborne surveys can be of great aid in defining related geological properties; the use of non-seismic methods to study shallow inland water is relatively recent but is becoming more and more diffused. Indeed electrical resistivity is very sensitive to fluid phases and clay content, while seismic waves are sensitive to the mechanical properties of the soil skeleton. Therefore a combination and integration of the two methodologies can offer a more complete geological characterization. In this respect we present in this paper preliminary results of waterborne seismic and electrical geophysical surveys on the nothern shore of the Trasimeno Lake in an area around the Malpasso site (Fig. 1).

The Trasimeno lake, located in the Umbria Region of Central Italy, is the broadest lake of the Italian Peninsula, covering about 120 km^2. The extremely low depths, the flat bottom morphology, and the absence of natural outflows and dams along its shorelines caused periodical floods since ancient times, only partially attenuated by creation of an artificial outflows. In contrast to most lakes in Central Italy (Bolsena, Vico, Bracciano, Monterosi, Albano) Trasimeno lake does not fill a volcanic crater, but its origin is related to tectonic processes. In fact, it underwent a complex geological evolution, from a marine gulf in the Early Pliocene, to a subsiding tectonic depression starting in Middle Pleistocene to present (Gasperini *et al.*, 2010).

Given this overall interesting geological setting, the area around the Malpasso site (*Fig. 1*) is also particularly characterized by the presence of an emerging sandstone formation protruding towards the lake and is moreover interesting from the archeological point of view. Several historical reconstructions suggest indeed that within this area, and particularly in the Tuoro plain, the Trasimeno battle (217 a.C.) took place. This battle was one of the most important episodes of the II Punic war and it was fought between the army of the Carthaginian general Hannibal and two Roman legions under the command of the consul Caius Flaminius. New evidences related to historical level fluctuations of the lake and more careful reading of the sources and a critical analysis of previous studies have been significant in respect to a positive identification of this site as a most probable location of the battle (Brizzi and Gambini, 2008). The actual shore line leave only a short passage between the lake itself and the Malpasso (Fig. 1), while the same should be wider in ancient times to allow for the passage of huge armies. In this respect the findings of several dated ceramic materials has shown that for long periods in the Etruscan and Roman times lake levels were usually lower than the present (Cattuto *et al.*, 2011).

With the aims of both reconstructing the geological setting of the area around the Malpasso site and to eventually find some localized remains of the battle we carried out several waterborne geophysical surveys on the area. Adopted methodologies were: magnetic surveys, seismic reflection Chirp Sonar surveys and Continuous Vertical Electric Soundings (CVES) profiles. Within this paper we report some preliminary results along an example profile (Fig. 1) for the last two methodologies underlining the main evidences observed and further planned processing on the data and data integration.

Materials And Methods. Seismic reflection profiles were collected using a Benthos Chirp III system with 4 transducers mounted on board of a small catamaran towed by the boat. Data were collected using a pulse length of 5 ms, a frequency sweep from 2 to 7 kHz, and a digitally sampled at 16 kHz rate. Seismic data were stored in SEGY files, after deconvolution and instantaneous amplitudes computation. Data processing was carried out using SeisPrho (Gasperini and Stanghellini, 2009) and included static correction, filtering and automatic gain control. Vertical resolution of acoustic images is <10 cm; maximum penetration reached, about 10 m.

CVES measurements were obtained by the use of an array of nine electrodes fixed on a floating cable dragged by a boat. The array has two current electrodes, in the cable part closest to the boat, followed by seven potential electrodes. The current electrodes were 16 m apart, while the six couples of potential electrodes in dipole-dipole configuration had exponentially increasing spacing from 0.5 to 16 m. The first potential electrode was 0.5 m from the farthest current electrode. This configuration allowed a maximum depth penetration similar to the seismic one. The towed cable floated on the lake surface thanks to appropriate plastic floaters and was kept stretched by a floating anchor fixed at its end. A multichannel georesistivimeter (Syscal-pro by Iris Instruments in Sysmar update) was used to simultaneously acquire the six potential measurements. The acquisitions were treated with a Laterally Constrained Inversion (LCI) process. The LCI approach was developed to invert vertical electrical sounding data acquired along a profile by Auken and Christiansen (2004), using a pseudo-2D layered parameterization of the investigated geological medium and has been implemented in Matlab environment (Sambuelli *et al.*, 2011). The inversion result of LCI is a set of 1D resistivity models, each of which corresponds to a sounding. All the soundings are inverted simultaneously by minimizing a common objective function, which contains the acquired data, the available a priori information and the constraints. Through the lateral constraints, information from one electro-stratigraphic section are then interconnected with the neighboring ones, producing a smoothly varying 2D section.

Both surveys are accurately georeferenced by means of independent GPS acquisition to allow for data integration.

Fig. 1. – Investigated area along the northern shore of the Trasimeno Lake near the Malpasso site. Evidence of the survey line along which the results of geophysical profiles are reported in Fig. 2.

Results and discussions. Both surveys covered the area reported in Fig. 1 in order to obtain a detailed investigation of the surveyed site. We focus here on two almost parallel profiles along a line starting close to the lake northern shore toward the lake center (Fig. 1).

In Fig. 2a the results of the Chirp sonar profile is reported. The lake floor along this profile is almost flat, slightly dipping toward south, and is marked by a weak reflection at about, on average, 3 meter of water depth, partial hidden by the direct wave. We note two main seismic units, a transparent, fine layered upper unit overlaying a lower more reflective unit, showing high-amplitude internal reflectors. The boundary between these units is a dome-shape reflector (U1), which marks a relatively high acoustic impedance contrast. In the first (northern) part of the profile, the presence of gas in the sediment hamper the penetration of the signal down to few decimeters below the lake floor. The observation that the top of gas-bearing deposits is a strong reflector (U0) might indicate early diagenesis due to fluid circulation. The upper unit is punctuated by hyperbolic reflections in the southern, more distal part of the profiles. Observation that these hyperbolas result aligned in correspondence of U0 might suggests a similar origin for such features.

In Fig. 2b the results of the LCI inversion of CVES data approximately acquired along the same profile are reported. The thickness of the low resistivity water layer (average constant resistivity of 7 Ω·m) has been constrained in the inversion thanks to a contemporary acquired bathymetry profile which evidences a lake bottom slightly dipping toward south coherently with the sonar survey. Within the lake sediments it is possible to evidence two low resistivity variations: a reduced increase in resistivity (R1) along an interface which roughly matches the dome-shaped reflector U1 evidenced from the seismic reflection line; this interface can be followed also at the beginning of the profile where the penetration of the seismic signal is hampered by gas bearing sediments. Secondly a slightly more marked decrease in resistivity (R0) is noted towards the lake center with an abrupt change just after the rift of the previous dome. This second resistivity variation appears to be not noted in the seismic reflection line.

Even if these are only preliminary results of the surveys and more accurate and complete comparison over the whole surveyed area, with precise location of each survey line, must be undertaken, it is possible to evidence that both of the surveys have evidenced the presence of a submerged interface within the sediments showing a dome shape that can be related to a more compacted/resistive material probably associable to the ancient shore line. The evidence of lower resistivity sediments in front of this anomaly can support this hypothesis. Moreover electrical surveys mapped this interface for the whole survey area allowing a spatial 2D reconstruction of the this layer; they have also locally evidenced the presence of sandstone formation protruding down the lake bottom near the shore.

Conclusions. Preliminary results of both seismic Chirp Sonar reflection lines and CVES profiles over the survey area have evidenced their potentiality in characterizing the bottom sediments of the area around the Malpasso which is interesting both from the geological and archeological point of views. The results of the two different surveys seem to match in first approximation. However further studies are necessary to allow for an unique reconstruction of the geological setting respectful of both the surveys evidences. In this respect, accurate data

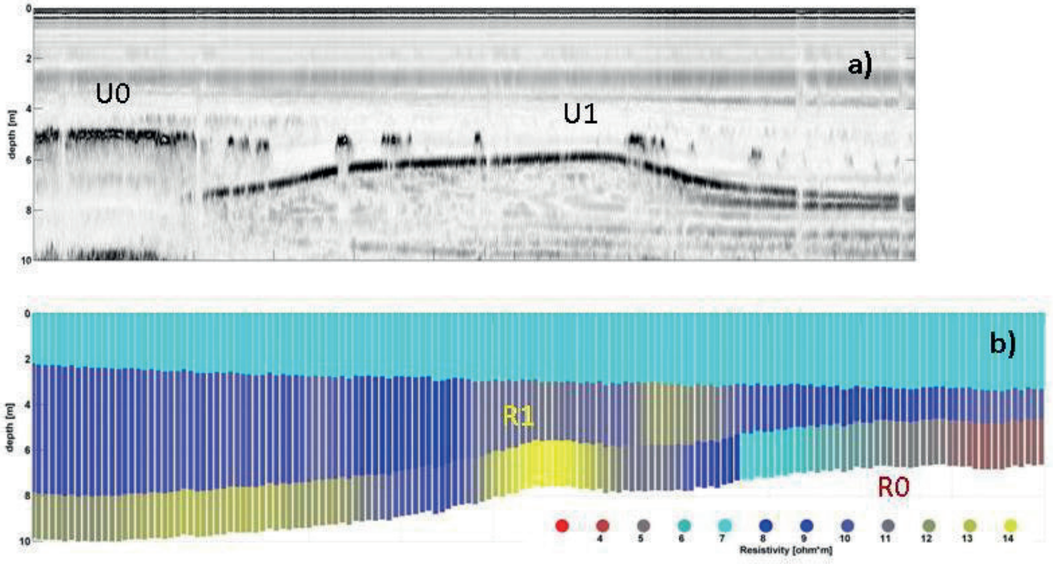

Fig. 2. – Two examples of waterborn geophysical surveys in the investigated area along the survey line of Fig. 1: a) Chirp sonar profile and b) LCI inversion of the CVES survey.

integration must be undertaken; particularly inversions of the CVES data with the a priori constrained interfaces evidenced from the seismic reflection campaigns are planned.

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