

## Combined continuous electrical tomography and very high resolution seismic surveys to assess continental and marine groundwater mixing

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**ABSTRACT** Salt contamination in the coastlands surrounding Venice Lagoon (Italy) and Laizhou Bay (Shandong Province, China) is generally the result of the complex relationship between fresh, continental groundwaters, paleo-saltwaters in deep aquifers, marine waters, and the seawater encroachment upstream from the river mouths. Saltwater intrusion is also enhanced by the presence of ancient, sandy, buried paleo-channels that act as preferential pathways for groundwater flow and solute transport. The characterization of these hydro-geo-morphological features, considering both the architecture and the pore water quality, is an issue of paramount importance. In this work, after a short overview of the saltwater contamination occurrence that affects the coastlands of Venice Lagoon and Laizhou Bay, we report on the preliminary results of a Very High Resolution Seismic and Continuous Electrical Tomography test carried out in very shallow water (about 1 m) in the Venice Lagoon to test a technique suitable for the better understanding of the surficial-groundwater mixing process. The combined analysis of the two data sets highlights a correlation between lithostratigraphic discontinuities and heterogeneity in the fluid filling the subsurface. The promising results obtained in the Italian site support a prompt use of this integrated methodology on the Chinese study area too.

**Key words:** saltwater intrusion, VHRS, CERT, Venice Lagoon, Laizhou Bay.

### 1. Introduction

The coastal areas are transition zones where the interaction between land and sea processes plays a critical role. More than half of the global population lives in the 60 km wide coastal zone and resources for populations, such as freshwater and food, depend on the critical relationships between land and sea, together with their variations due to both natural and anthropogenic causes. In particular, climate changes and stresses induced by human activities, e.g., pollution, engineering interventions for dams, flood control, canalization, deforestation, urbanization,

agricultural activities, and freshwater withdrawals cause the degradation and the ravage of the habitat.

The coastland surrounding Venice Lagoon, Italy, and Laizhou Bay, Shandong Province, China, are precarious environments subject to both natural changes and anthropogenic pressure. Here, several factors may jeopardize the environment or increase hydrogeological hazards. One of the most important environmental problems is the saltwater intrusion in shallow aquifers (Carbognin *et al.*, 2006; Pousa *et al.*, 2007; Qi and Luo, 2008; Viezzoli *et al.*, 2010).

The saltwater contamination that affects groundwater and surficial soils is an issue of paramount importance considering the ecological, cultural, and socio-economic relevance of these transitional environments. The 3-year project “An integrated monitoring and management approach of hydrologic processes in coastal ecosystems for the understanding of the relationship between continental and marine waters in the Yantai (China) and in Venice (Italy) areas” started in 2008 under the umbrella of the bilateral scientific and technological agreement between the National Research Council of Italy and the Chinese Academy of Sciences. The objective of this project was to investigate the complex relationships between continental and marine groundwaters, in particular the saltwater intrusion, in Laizhou Bay, where the city of Yantai is located, and in Venice Lagoon, and to provide an integrated system for a comprehensive monitoring and understanding of the process. The objectives are planned to be carried out by using in situ measurements, laboratory analyses on water samples, geophysical surveys, and the application of mathematical models for the simulation of the water flow and contaminant transport.

After a short overview of the occurrence of saltwater contamination in the two study areas, we present the result on a test performed in the Venice Lagoon where Very High Resolution Seismic (VHRS) and Continuous Electrical Tomography (CERT) surveys are combined. The goal of this application is the characterization of the lagoon subsoil from the point of view of the deposit architecture and the groundwater quality. In the framework of the bilateral project, the test carried out in Venice was aimed at setting up the integrated methodology in view of an extensive survey along the Yantai coastland.

## 2. An overview of the processes in the study areas

The coastland surrounding Venice Lagoon is a precarious environment subject to both natural changes and anthropogenic pressure. A number of critical problems affect this lowlying area (Fig. 1a), such as relative land subsidence, periodic flooding during severe winter storms, and saltwater intrusion. The combined effect of sea level rise and land subsidence has enhanced the saltwater contamination and the related soil salinization with serious environmental and socio-economic consequences. The risk of soil desertification and the compromising of agricultural activities are major problems in the farmland bounding southern Venice. Although the area does not experience saline contamination everywhere, a very serious situation has been brought to light in a large portion of the farmland bounding the southern portion of the lagoon. The saltwater contamination extends up to 20 km inland from the coast (e.g., Carbognin *et al.*, 2006). The depth of the fresh/salt-water interface varies from 1 to 30 m below the ground level and exhibits a significant, mainly seasonal, time variation (Fig. 2). The dynamics of the salinization process is especially susceptible to changes in river (Brenta, Bacchiglione, Adige, Gorzone) discharges, to

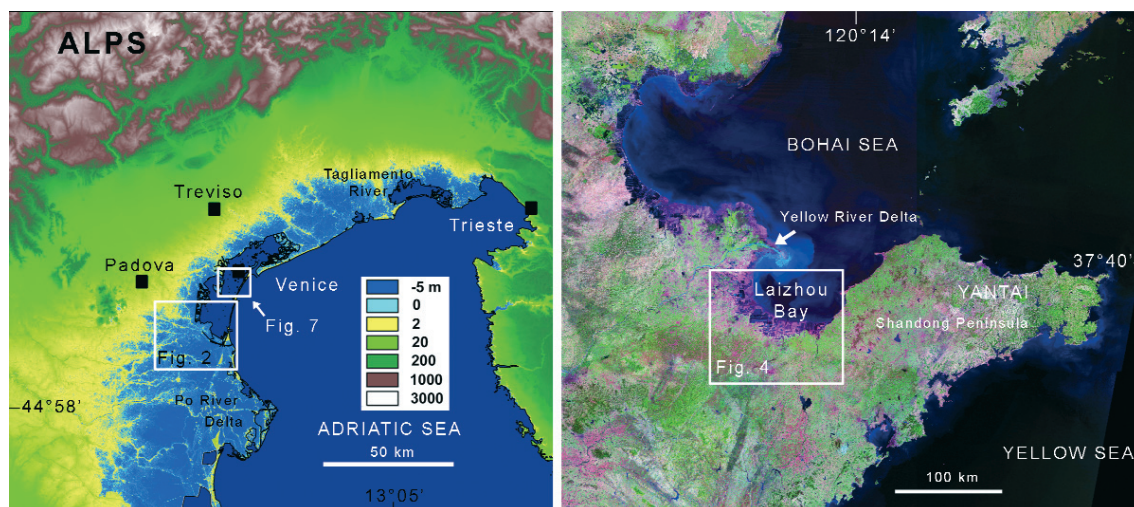


Fig. 1 - a) The northern Adriatic coastland and location of the Venice study area; b) the Shandong Peninsula and location of Laizhou study area.

groundwater and channel levels, which are regulated by several pumping stations managed by the local reclamation authority, and to weather conditions.

In China, twelve coastal provinces, that occupy only 14% of the total Chinese land surface, concentrate, in that area, 50% of the large cities, 40% of the medium cities, and 60% of the gross domestic product. The rapid demographic growth in this narrow zone combined with the fast economic development has imposed a huge pressure on the coastal systems. One major problem connected with the coastland overexploitation is the saltwater contamination of the groundwater resources. This constitutes an extremely dangerous hazard in Shandong, a province that is bounded to the east by a 2930 km long coastline (Fig. 1b) and where groundwater is the main (more than 50%) water resource for industrial, agricultural, and drinking uses. Here, two major problems are related to the groundwater contamination by salt: a) the effects threatening human health (e.g., bone fluorosis, macular teeth) due to fluorine excess in drinkable water, and b) the reduction of agricultural productivity due to soil salinization. The southern coast of Laizhou Bay is one of the areas in China most seriously impacted by seawater intrusion. Saline water contamination is due to modern seawater together with paleo-seawater and brine in shallow Quaternary sediments (Figs. 3 and 4). Based on contamination sources, the southern coast of Laizhou Bay can be divided into four areas (e.g., Meng *et al.*, 2002): i) the part north of Laizhou City where contamination is due to seawater, ii) the Baisha River-Jiaolai River mouth plain area characterized by mixed seawater and saline groundwater intrusion, iii) the Weihe River mouth plain area on the northern Changyi county coast, that experiences mixed seawater and saline groundwater intrusion, and iv) the northern Shouguang plains with a strong saline groundwater contamination.

Past geomorphological studies have put in evidence the occurrence of exposed or buried geomorphological sandy features in both study areas (Chen *et al.*, 1995; Rizzetto *et al.*, 2003, 2009). In Venice, well developed, sandy paleo-channels crossing the farmland with main directions from inland to the lagoon/sea boundary represent a preferred pathway for saltwater

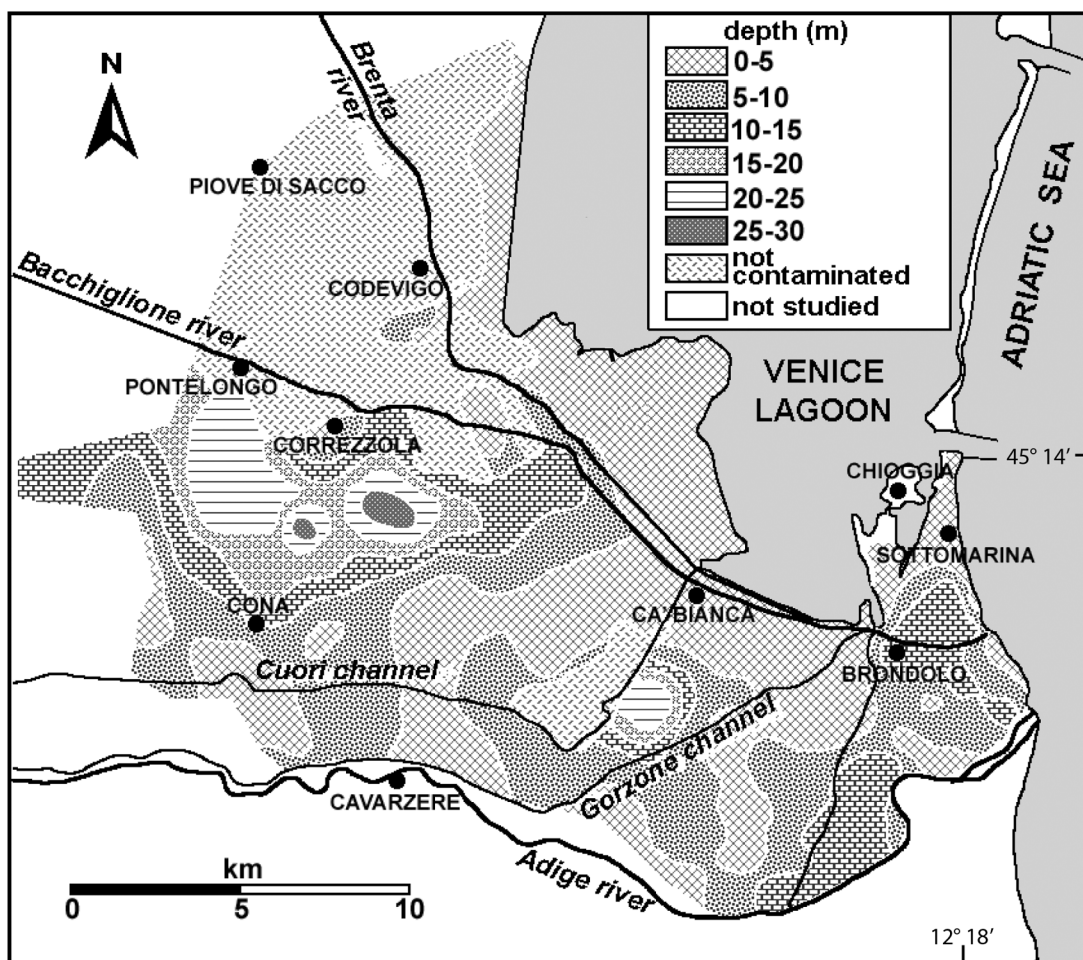


Fig. 2 - Depth of the fresh-salt water interface in the farmland bounding the southern margin of Venice Lagoon (after Carbognin *et al.*, 2006). The location of this area is shown in Fig. 1a.

flow (Han, 2001; Rizzetto *et al.*, 2009; Tosi *et al.*, 2009). In particular, Tosi *et al.* (2009) and Zecchin *et al.* (2009) provided impressive images of the architecture of the lagoon subsoil highlighting the occurrence of several paleochannels entering inland from the lagoon basin. Hydrogeological studies pointed out that these geomorphological features are one of the main reasons for the saltwater contamination process in coastal aquifers due to the high hydraulic conductivity enhancing the groundwater movements (e.g., de Franco *et al.*, 2009; Viezzoli *et al.*, 2010). For this reason, the detection of buried geomorphological features and groundwater characteristics in the lagoon subsoil is essential to understanding the saltwater flow toward the mainland.

### 3. Continuous electrical tomography and very high resolution seismic surveys

It is known that the application of combined seismic and electrical measurements is a

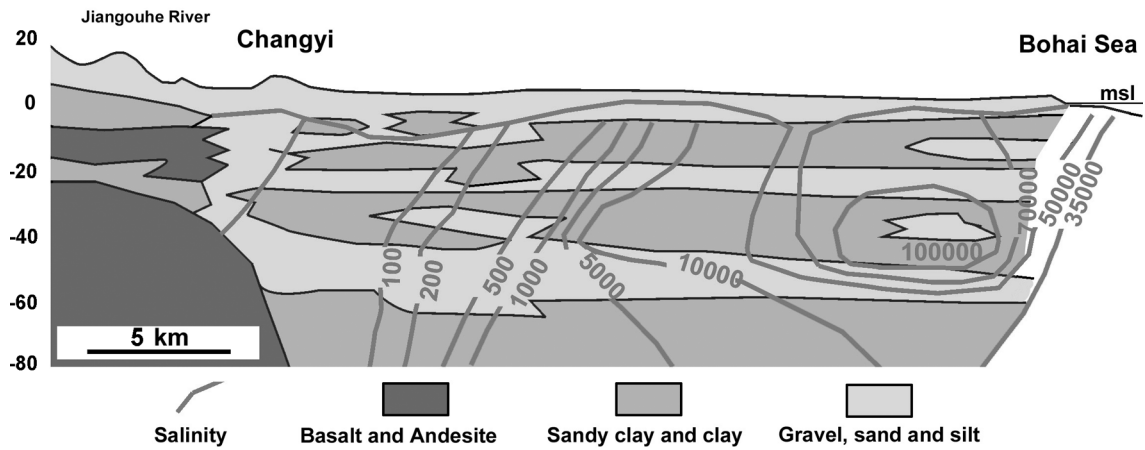


Fig. 3 - Sketch of the subsoil architecture and Cl<sup>-</sup> concentration (mg/l) in a vertical section crossing the Shandong coastland (after Xue *et al.*, 2000). The section location is shown in Fig. 4 (A-A').

methodology suitable for hydrogeologic characterizations (e.g., Taylor and Cherkauer, 1984). Nevertheless, its application in lagoons is not common. A VHRS system has been implemented for surveys in water depths of about 1 m and widely used in Venice Lagoon over the last few years (Baradello and Carcione, 2008; Tosi *et al.*, 2009; Zecchin *et al.*, 2009). A few CERT surveys have been also carried out in the lagoon (Allen and Merrick, 2007) and river mouths (de Franco *et al.*, 2009). However, these two techniques have never been used simultaneously in very shallow water depth (about 1 m).

The VHRS system (Fig. 5) consists of an impulsive energy source (boomer) and an electro-

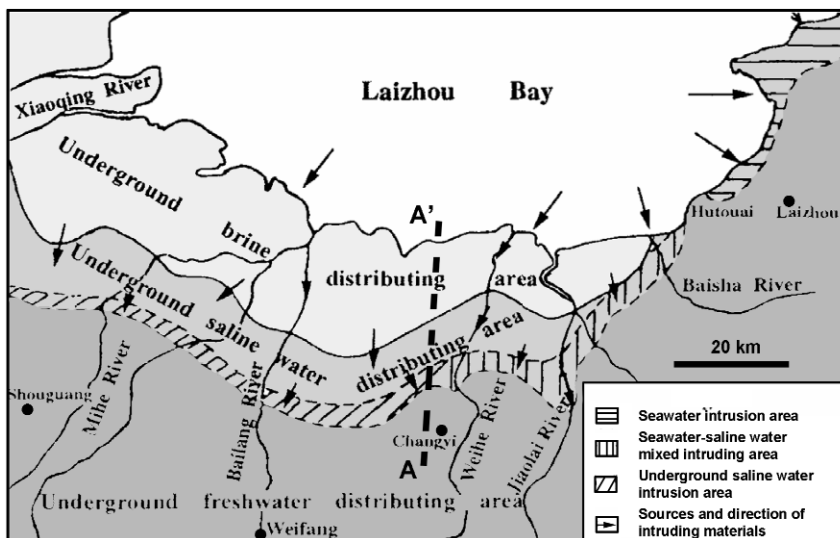


Fig. 4 - Regionalization of the different types of saltwater contamination in the southern coast of the Laizhou Bay (after Meng *et al.*, 2002).

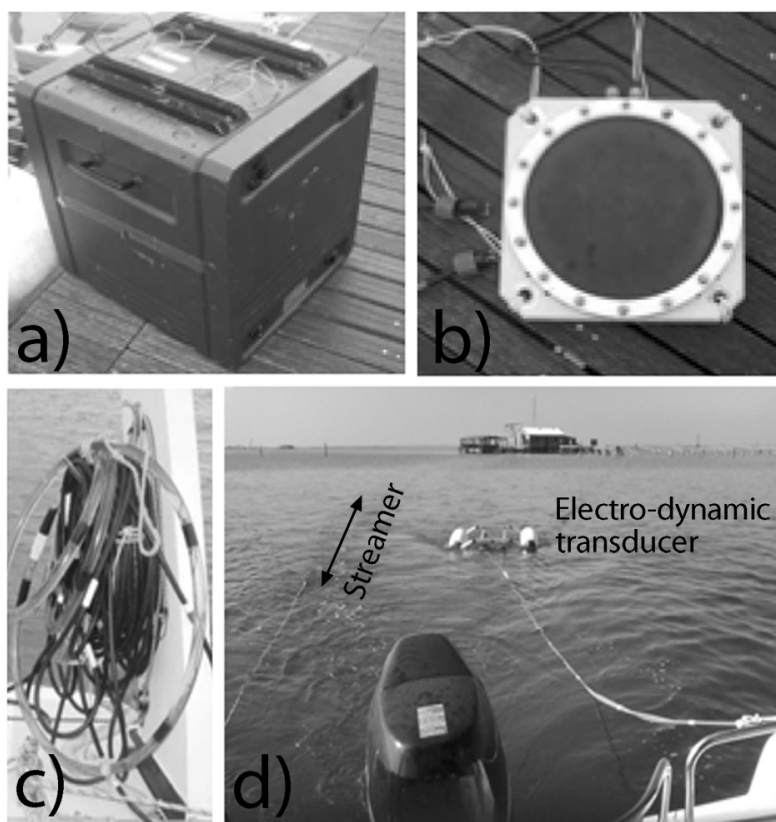


Fig. 5 - The VHRS acquisition system: a) the impulsive energy source (boomer); b) the electro-dynamic transducer (plate), c) the streamer, d) the geometry of the system optimized to operate in less than a 1 m water depths.

dynamic transducer (UWAK05) mounted on a catamaran frame. A pre-amplified oil-filled streamer composed of eight piezoelectric elements connected in series with a 2.8 m active array section were used to collect the signals. The geometry of the system was optimized to operate in less than a 1 m water depth, with the best acquisition obtained when the streamer was deployed parallel to the boomer, towed with a 2 m lateral offset, and kept as shallow as possible (about 0.3 m beneath the water surface).

CERT surveys are carried out by means of a geo-resistivimeter configured to work in continuous survey acquisition. The system is composed of an 80 m long floating marine multipolar cable with 16 graphite electrodes towed by a boat and connected to an IRIS Syscal Pro 72 Switch geo-resistivimeter characterized by a multi-channel capability (Fig. 6).

Positioning records for both surveys are collected using an integrated DGPS navigation system. We tested the coupled CERT-VHRS in the shallows (about a 1 m depth) of Venice Lagoon in July 2009 (Fig. 7).

#### 4. Result and discussion

Although, at the moment, only preliminary interpretations are available, these results and



Fig. 6 - The CERT system: a) the floating marine multipolar cables with graphite electrodes, b) the energy source, c) the IRIS Syscal Pro 72 Switch georesistivity meter.

possible feed-backs should be useful to improve this methodology and plan new tests in the Yantai coastland too. From a general point of view, the VHRS survey reveals the architecture of the subsoil while CERT shows their lateral and vertical resistivity variations.

The VHRS survey reveals the presence of several buried geomorphological features in the

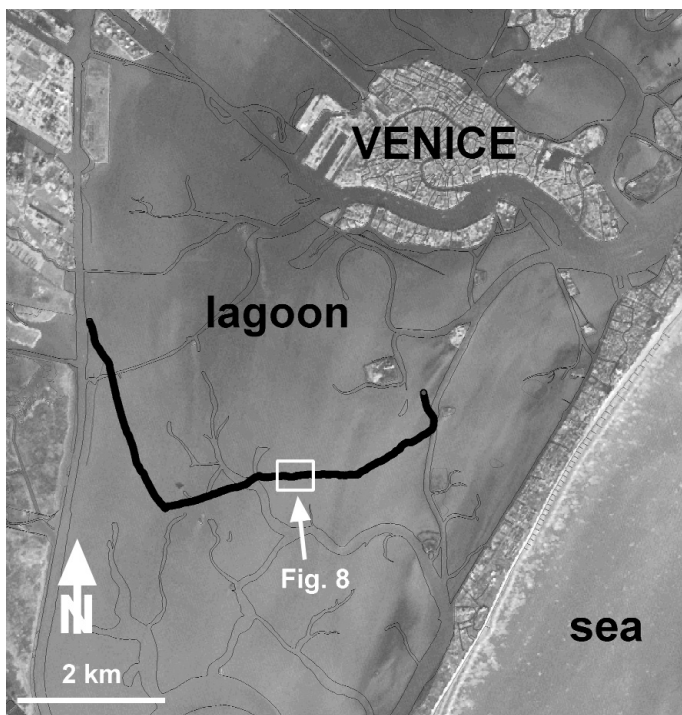


Fig. 7 - Position of the CERT-VHRS survey test performed in the shallows of Venice Lagoon. The location of the area is provided in Fig. 1a.

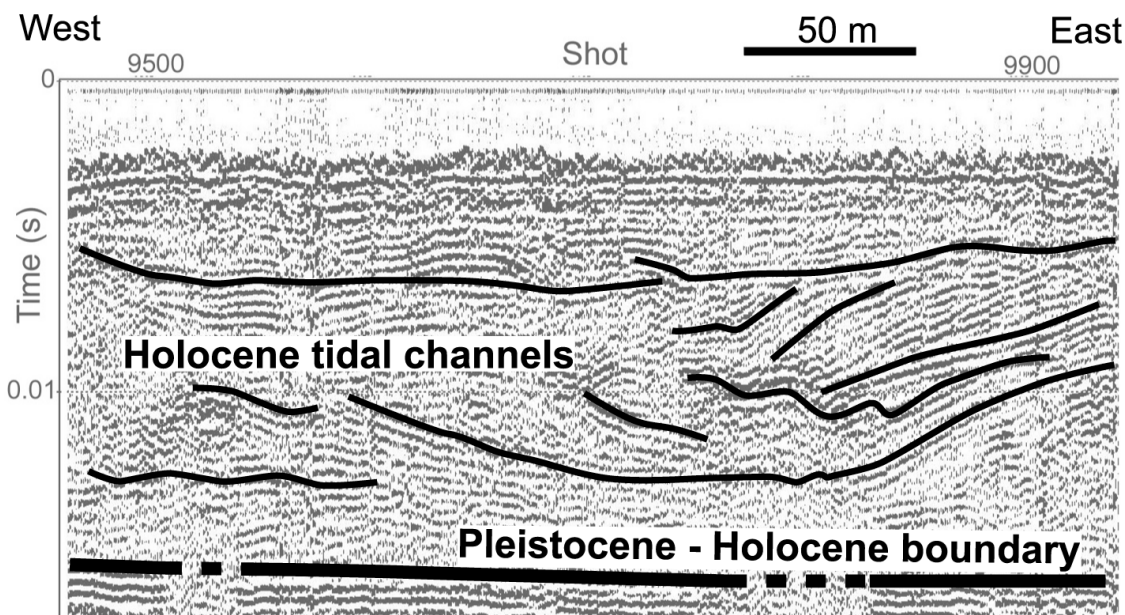


Fig. 8 - Example of VHRS section showing a buried paleo-channel in the Holocene deposits. Water depth is about 1 m. The location of the section is shown in Fig. 7.

shallow subsurface. An example of a detected ancient channel is shown in Fig. 8. Fig. 9 shows an example of CERT-VHRS profiles. Some abrupt resistivity changes in the nearby geomorphological structures or transparent seismic reflector occurrences are detected. The resistivity profile shows appreciable variations below a 10 m depth. At this depth, the seismic section is characterized by strong and discontinuous reflectors disrupted in places by transparent seismic faces. The figure highlights a good spatial correlation between the resistivity variability and the seismic transparent faces, but sign of the electrical resistivity variation is not the same along the section: the resistivity increases at the beginning and at the end of the section, while it decreases in the central portion. Resistivity anomalies can be related to salinity variations in the ground water and/or gas occurrence. To date we are not able to distinguish which process the resistivity changes detected by CERT are related to. Actually, resistivity of about 0.2 Ohm-m is typical of sea water, while higher values (about 2 Ohm-m) are indicative of brackish waters but also salt water and gas. Moreover, the seismic profile shows gas plumes rising from the Pleistocene layers where the electrical section highlights increasing resistivity values. Conversely, the resistivity increase in the first and last parts of the investigated section is, therefore, compatible with the expected salinity decrease with depth. The relative low resistivity at the center of the profile might reflect a depositional feature, for example the presence of a paleo-tidal channel with a salinity value slightly higher than that measured in the surrounding formations.

## 5. Conclusive remarks

This work is aimed at understanding the complex relationship between continental and marine



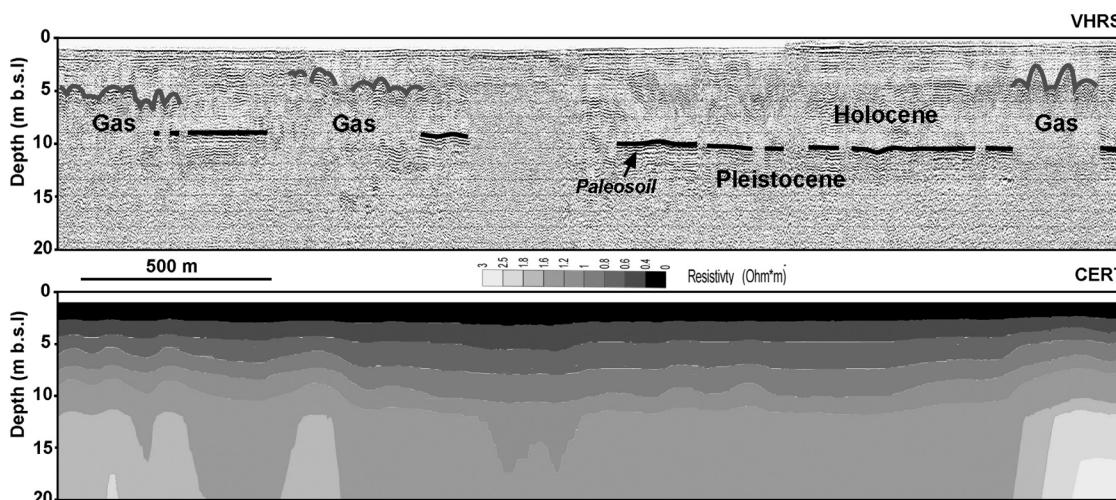


Fig. 9 - Preliminary result of the VHRS-CERT test. The seismic profile (a) shows gas plumes rising from the Pleistocene layers where the electrical resistivity section (b) highlight increasing values. The location of the section is shown in Fig. 7.

groundwaters, i.e., the saltwater intrusion, in two coastal areas: Venice Lagoon in Italy and Laizhou Bay (Shandong Province) in China. The salt contamination in these two areas is generally the result of seawater encroachment, but significant contributions are also due to the water exchange between the bed of the major rivers and the subsurface. In fact, the reduced freshwater discharges that occur during dry periods allow the seawater to flow upwards from the river mouths for several kilometres. Saltwater intrusion is enhanced by the presence of several ancient sandy fluvial ridges crossing the farmland with a main direction from inland to the lagoon boundary and the coastline, and possibly acting as preferential pathways for groundwater flow and solute transport. Also, fossil saltwaters can play an important role in the inland portion of the two study sites.

The most important outcomes of this work are twofold. First, the implementation of the VHRS-CERT coupled survey in very shallow water; and secondly, the successful identification of geomorphological features and gas plumes and their vertical and lateral resistivity changes in the Venice Lagoon subsoil. Although, to date, the correlation between seismic and electrical variation is a conjecture, because core sample and geochemical analyses are not still available, the VHRS-CERT coupled survey appears as a promising and powerful tool for the hydrogeological characterization of fresh-salt water mixing in shallow coastlands such as Laizhou Bay.

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