Application of hydrochemical and preliminary geophysical surveys within the study of the saltwater uprising occurring in the Oltrepò Pavese plain aquifer

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(Received: January 07, 2010; accepted: July 19, 2010)

ABSTRACT The shallow aquifer of the Oltrepò Pavese plain sector is naturally polluted with Na-Cl rich waters, coming from the deep marine substrate at the base of the alluvial aquifer. This phenomenon is localised along an important, buried tectonic discontinuity known as the Vogherese Fault. Groundwater hydrochemical assessment was undertaken: for water sampling and analysis it encompassed, electrical conductivity logs within wells and continuous monitoring of electrical conductivity and piezometric levels of other wells. VLF-EM profiles across the Vogherese Fault were undertaken over the entire investigated area for an expeditious assessment of buried conductive bodies that could be connected to the saltwater uprising (tectonic discontinuities). Moreover, resistivity depth-soundings and one resistivity profiling were undertaken.

1. Introduction

The alluvial aquifer of the Oltrepò Pavese plain sector (Po Valley, northern Italy) is characterised by a form of natural pollution caused by Na-Cl rich waters that rise up from the Tertiary marine substrata and mix with the shallow groundwater. This contamination prevents the exploitation of the aquifer, not only for drinking water supply, but also for agricultural and industrial use.

The origin of the Na-Cl rich waters is connected to the brines (very high density fluids) that are remnants of evaporated marine waters from the late Messinian, trapped at the bottom of the Po plain aquifer (Conti *et al*., 2000). The occurrence of tectonic discontinuities within the marine deposits allows the meteoric waters first to infiltrate and leach brines, then rise towards the shallow aquifer. According to some authors (Ricchiuto *et al*., 1984; Coggiola *et al*., 1986; Nanni and Zuppi, 1986; Conti *et al*., 2000) even the compressive forces that act along the Po Valley margins can squeeze the brines from the marine deposits, causing this uprise of saline waters.

The existence of these mineralised waters in the Oltrepò Pavese area has been well known since Roman times. In fact, the waters were (and still are) exploited for thermal purposes (San Colombano al Lambro, Miradolo Terme, Salice Terme and Rivanazzano Terme are the most famous spa centres located near the investigated area).

Nowadays, even if the distribution of these waters is known and includes the Po Plain area at the bottom of the Apennine front (Bonori *et al*., 2000; Di Sipio *et al*., 2007; Toscani *et al*., 2007), the Central Apennines fore deep (Nanni and Zuppi, 1986; Desiderio and Rusi, 2004), and the

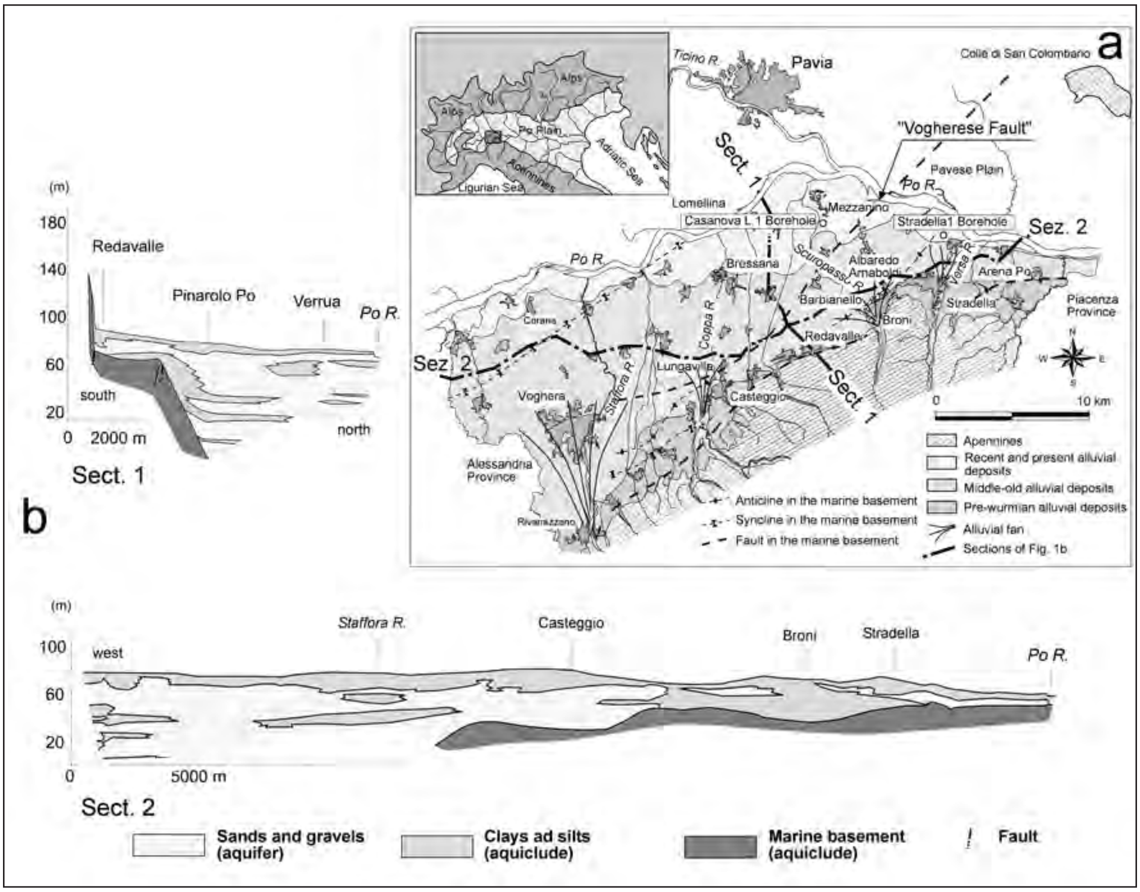

Fig. 1 - Geological map (a) and hydrogeological sections (b) (simplified from Cavanna *et al*., 1998).

areas of the Po Plain that correspond to bedrock structural reliefs, we do not know the mechanisms (i.e., like withdrawals and changes of total heads) that control their uprising into the shallow aquifer.

In the Oltrepò Pavese investigated area, this phenomenon, associated with the presence of the Vogherese Fault, a buried tectonic discontinuity along which the saline waters are mainly distributed, is discussed in a previous study (Pilla *et al*., 2007).

A hydrochemical study discussing the Na-Cl rich waters was undertaken. This study included periodical sampling of groundwater to monitor the chemistry and temperature and electrical conductivity logs. Continuous monitoring of chemical–physical characteristics by a multi-parameter data logger instrument was also undertaken.

However, the unfavourable distribution of sampling wells made it necessary to integrate the hydrogeological and hydrochemical study with geophysical surveys, like VLF-EM profiles, resistivity depth soundings (VES) and a resistivity profile. These allowed the investigation of the entire study area and an accurate investigation of the sectors where the uprising phenomenon of deep saline waters occurs.

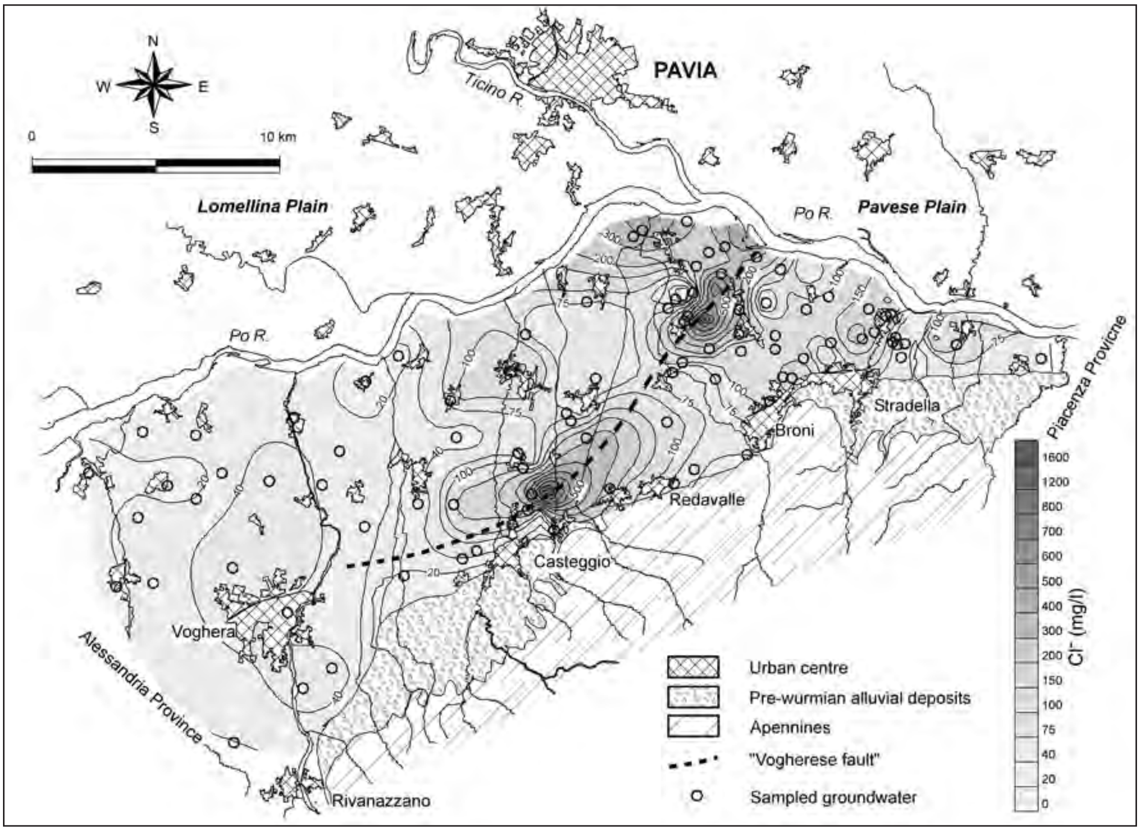

Fig. 2 - Areal distribution of Cl- concentration in the Oltrepò Pavese aquifer (from Pilla et al., 2007).

2. Geological and hydrogeological setting

The Oltrepò Pavese plain sector is geologically characterised by alluvial Quaternary deposits that cover impermeable Miocene – Pliocene marine deposits, formed by sandy-marls, sandstones, conglomerates, gypsum-rich marls and calcareous marls (Brambilla, 1992; Pellegrini and Vercesi, 1995).

The upper Quaternary sediments, deposited mainly by the action of the Po River and secondarily by the Apennine streams, represent the main water bodies of the area. Three different hydrogeological units can be defined within the Quarternary deposits (Fig 1): pre-Würmian alluvial deposits, middle-ancient alluvial deposits, recent and present alluvial deposits (Cavanna *et al*., 1998; Pilla *et al*., 2007). Only the latter two hydrogeological units are affected by the presence of Na-Cl rich waters.

The middle-ancient alluvial deposits occupy most of the Oltrepò Pavese plain sector and are formed by alternating sand and gravel, with interbedded clays or clayey silts.

The recent and present alluvial deposits, distributed mainly along the Po River, were originated by the post-Würmian depositional activity of this river, which was responsible for the finer deposits, like sand, sandy silt and silt. The most important Apennine streams also contributed to the deposition of these alluvial deposits. However, these latter streams were responsible for the deposition of coarser deposits, like gravel and sand.

Moreover, the constant presence of a clayey silty covering, which has a varying maximum thickness of between 10 to 15 m, in the sectors close to the Apennine margin, and a minimum of 2 m, in the meandering area of the Po River, limits infiltration and influences the aquifer recharge, that occurs in correspondence of the coalescent fans originating from the deposition of Apennine streams (Pilla *et al*., 2007). A recharge contribution from the Po River must be excluded. In fact, groundwater flow direction is towards the River Po with the exception of occasional flooding events (Pilla *et al*., 2007).

The structural setting of the Oltrepò Pavese plain (Fig. 1) is strongly conditioned by the presence of an important tectonic discontinuity, known in literature as the Vogherese Fault (Boni, 1967). This fault has a NE-SW direction, from west of Casteggio to the Colle of San Colombano, passing across the confluence of the Ticino and Po rivers. It is a normal fault with hanging wall to the NE, up to the Barbianello area. Here, it becomes an inverse fault to the south of Pinarolo, folding gradually towards west, north of Casteggio and Voghera (Boni, 1967).

The Vogherese Fault is responsible for the sudden deepening that affects the marine substrata in the northern sector of the Oltrepò Pavese plain, and is also responsible for the strong variability on the thickness of the aquifer. The aquifer shows a thickness of a few metres in the southern sector (Fig. 1), that represents the upper block, and hundreds of metres in the northern sector, the lower block (AGIP, 1972; Braga and Cerro, 1988; Cavanna *et al*., 1998; Regione Lombardia and ENI Divisione AGIP, 2002). There are two deep boreholes (500 m) in the area drilled for oil exploration (AGIP, 1972; Regione Lombardia and ENI Divisione AGIP, 2002). The Casanova Lonati 1 borehole (Fig. 1), which is located on the down-lifted block of the Vogherese Fault, intercepts the underlying marine deposits at a depth of 275 m. Brackish groundwater, which rises along the fault and flows into the continental deposits, is intercepted by the borehole at 136 m. Groundwater intercepts salt waters at 400 m. The second borehole, the Stradella 1 borehole (Fig. 1), located on the up-lifted block of the fault, intercepts the underlying marine deposits at a depth of only 36 m.

This particular setting facilitates the phenomenon of uprising saline waters which appears at its best in the southern sector of the plain where the aquifer is thinner. Here the Na-Cl rich waters cannot be diluted by the more abundant calcium-bicarbonated groundwaters. This outlined setting strongly influences the chemistry of the groundwater.

The uprising of saline waters is also facilitated by structural discontinuities localized in the bedrock of marine origin. These discontinuities represent preferential flow paths for the saline waters and facilitate the flow towards the alluvial aquifer. This is demonstrated (Pilla *et al*., 2007) by the chloride distribution within the groundwater (Fig. 2).

3. Methodologies

The hydrogeochemical study included sampling of forty private and public wells (Fig. 3), some of which were continuously monitored since July 2007. In situ temperature, electrical conductivity (EC) and pH measurements were undertaken with a WTW Multiline P4 meter. A Dionex DX 120 chromatograph was used to analyse the major ions while volumetric analysis was

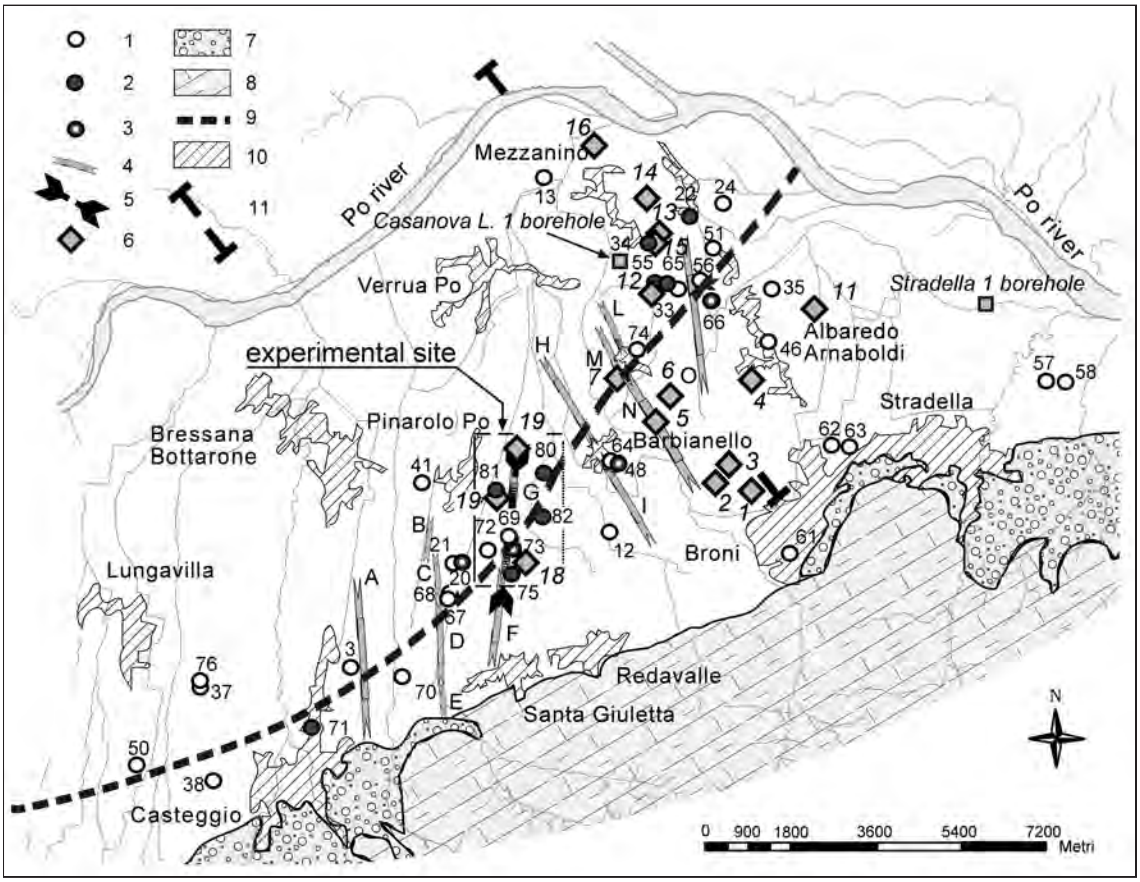

Fig. 3 - Investigations undertaken in the area. Legend: 1) sampled well; 2) electrical conductivity logs into well; 3) continuous monitoring well; 4) VLF profile; 5) resistivity profiling; 6) VES; 7) pre-Würmian alluvial deposits; 8) apennines; 9) Vogherese Fault from literature; 10) urban centre; 11) electrostratigraphic section from resistivity soundings of Fig. 10.

used for the determination of alkalinity.

A multiparametric probe with a 50 m line has been connected to the WTW Multiline P4 meter to acquire continuous EC and temperature data from 13 wells since July 2008.

Finally, continuous monitoring was also undertaken by means of two multiparametric Schlumberger CTD Diver loggers which have acquired temperature, EC and groundwater level data at 12 hour intervals since July 2008. The two loggers were used over different periods to monitor 4 wells that were considered of significance for the present study (Fig. 3).

Geophysical investigations were undertaken in three separate phases. The first two were preliminary investigations while the third was a more detailed investigation. During the first phase, 17 VES were undertaken along a cross section of the Vogherese Fault with the objective of reconstructing the geometry of the bedrock and the different hydrogeological units. These were undertaken in a sub-area that is considered representative of the entire study area and were necessary for the calibration of the investigations for the following phases. A Schlumberger array was used for these geophysical investigations. The maximum AB/2 distance varied from 300 m

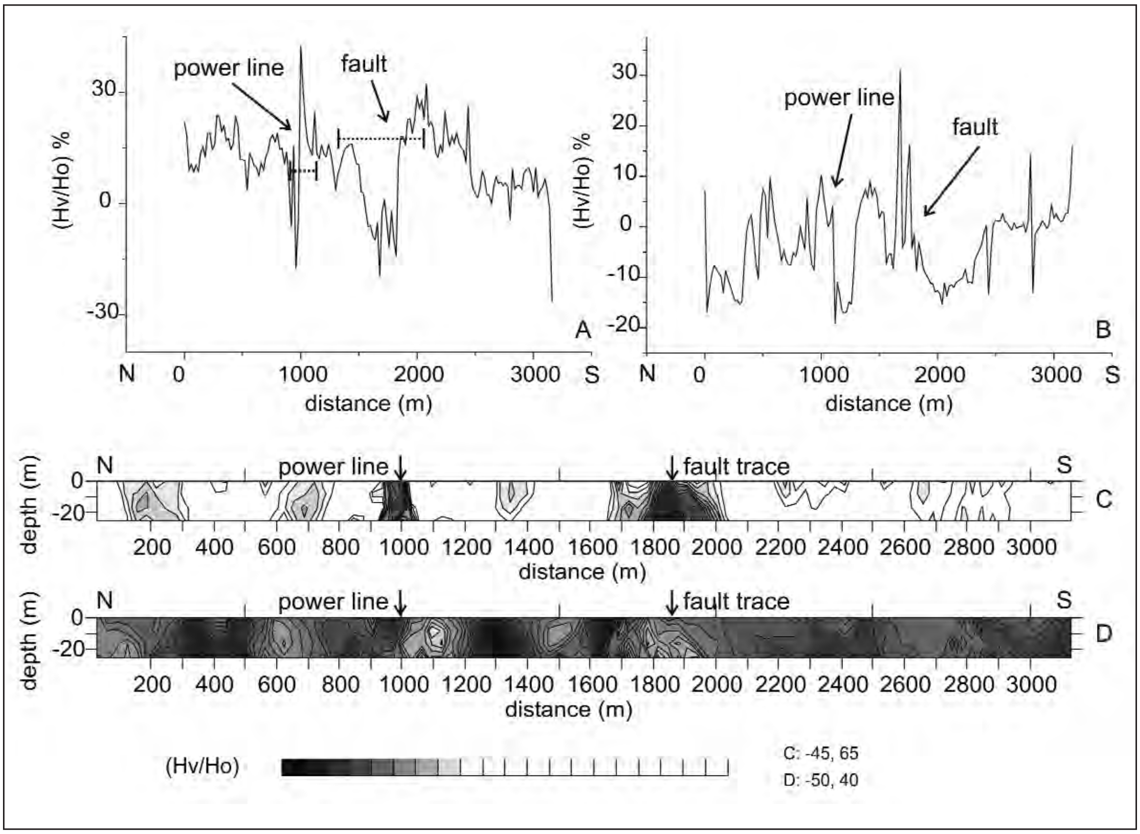

Fig. 4 - Real component (A) and imaginary component (B) of the magnetic field of VLF-EM profile 1 (percentage ratio between the vertical and horizontal components); pseudo-sections (H_V/H_0) of the real part (positive values) obtained through a Fraser filter of VLF-EM profile 1 (C); pseudo-sections (H_V/H_0) of the imaginary part obtained through a Fraser filter of VLF-EM profile 1 (D).

to 1000 m. Data analysis was undertaken by applying the auxiliary method, comparing the experimental curve with the three layer theoretical curves.

The second phase involved VLF-EM investigations over vast areas for a expeditious assessment of sub-vertical conductive bodies connected to the up-rising of high salinity waters through structural discontinuities (Fig. 3). Thirteen profiles were undertaken using a WADI instrument by ABEM, which detects the ratio (%) between the vertical and the horizontal components. A total of 24 km of profiles were acquired over an area of approximately 35 km^2. The profiles have a length ranging between 650 m and 3860 m, with an average length of 1837 m. These profiles, oriented in a NS and NW-SE direction, were undertaken along footpaths and secondary roads in an attempt to avoid urban areas that are sources of electromagnetic noise and agricultural land that is often difficult to access. The orientation of the investigations was such that the measurement direction was always perpendicular to the Poynting vector. Signals originating from available, suitably oriented (with respect to the fault orientation) transmitting stations. were used during the acquisition (Russian and French). These stations are sufficiently stable and have the correct energy. A compass was used to determine the perpendicularity between the azimuth measurement and the link measuring point of the selected station trasmitter position. The measurements were acquired with a spatial sampling interval (Δx) ranging between 10 and 20 m, which is considered appropriate in relation to the size of the conductivity anomalies. VLF real and imaginary data components (Fig. 4) have been processed in order to provide a simple process for semi-quantitative interpretation. These components also allow a reduction of noise through a low-pass filter and the removal of the asymmetry inherent in the dip-angle data. The components also allow us to obtain the equivalent current densities (Fraser, 1969, 1981; Karous and Hjelt, 1977, 1983; Ogilvy and Lee, 1991; Sundararajan *et al*., 2006; Torrese *et al*., 2009) at a constant depth which would cause a magnetic VLF data field. The magnitudes of the currents that flow at different depths to produce a given anomaly have been obtained through application of filtering for different measured intervals (n ¢x with n=1, 2, 3, 4, 5, 6). Kriging geostatistical gridding methods have been used to interpolate the filtered values and achieve both pseudo-sections (Fig. 4). Cultural noise is associated with well-defined narrow anomalies with sub-vertical edges, on the pseudo-sections of the real component. Additionally, these anomalies are not associated with any negative or positive anomalies of the imaginary component as occurs with anomalies of natural origin (Fig. 4; Torrese *et al*., 2009). Directional interpolation, low-pass filtering and application of the first derivative perpendicular to the fault direction (Torrese *et al*., 2009) were used to highlight possible aligned anomalies in the magnetic map. The depth of penetration of the VLF investigation can be estimated on average just over 20 m on the basis of the signal frequency used and the shallow mean resistivity achieved by the resistivity depth soundings (Torrese *et al*., 2009).

A resistivity profile and three VES were undertaken at a selected site in the third, more detailed phase of the investigations. The site was selected on the basis of the observations from the second phase which had highlighted the presence of the fault and wells with high salinity. The 2160 m profile carried out along the “Strada Provinciale delle Saline” (“Salt Pan Provincial Road”), crosses the fault zone in a N-S direction and overlaps a significant length of the VLF section which is 2200 m long (Fig. 3).

A gradient array with aligned electrodes was used. Two to six measurements were acquired for each section with AB=80 m and MN=10 m. During the data analysis phase, separation of the measurements acquired at the centre of the array from those acquired near the current electrodes allowed us to obtain information from deeper strata (20 m) and shallower strata (10 m) respectively. Smoothing was not applied to the profile. The three resistivity depth soundings were undertaken along the profile in order to obtain a localised calibration and to understand the vertical resistivity variations at the selected site. The Schlumberger array was used with maximum AB/2 of 147 m, 215 m, and 410 m for resistivity depth soundings 18, 19, and 20, respectively. The profile and the resistivity depth soundings were undertaken with a SYSCAL Junior Switch 48 (IRIS Instruments) resistivity meter. The resistivity depth sounding data were processed through inversion of the experimental curve.

4. Hydrochemical study

Two main hydrochemical facies can be identified within the Oltrepò Pavese groundwater: a calcium-bicarbonated hydrofacies, which characterises most of the groundwater of the Oltrepò

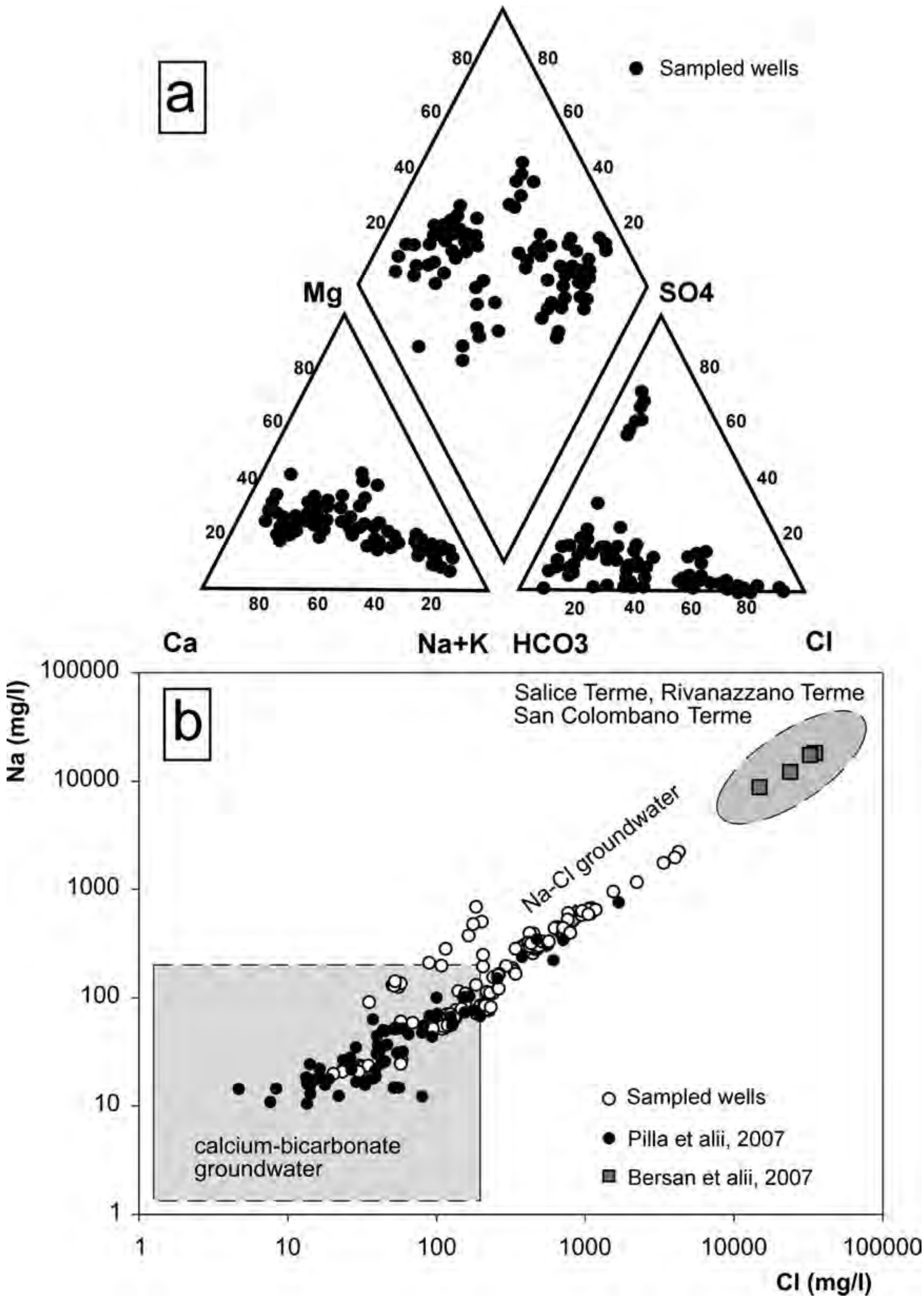

Fig. 5 - Piper diagram (a) and Na vs. Cl diagram (b) of groundwater within the Oltrepò Pavese aquifer.

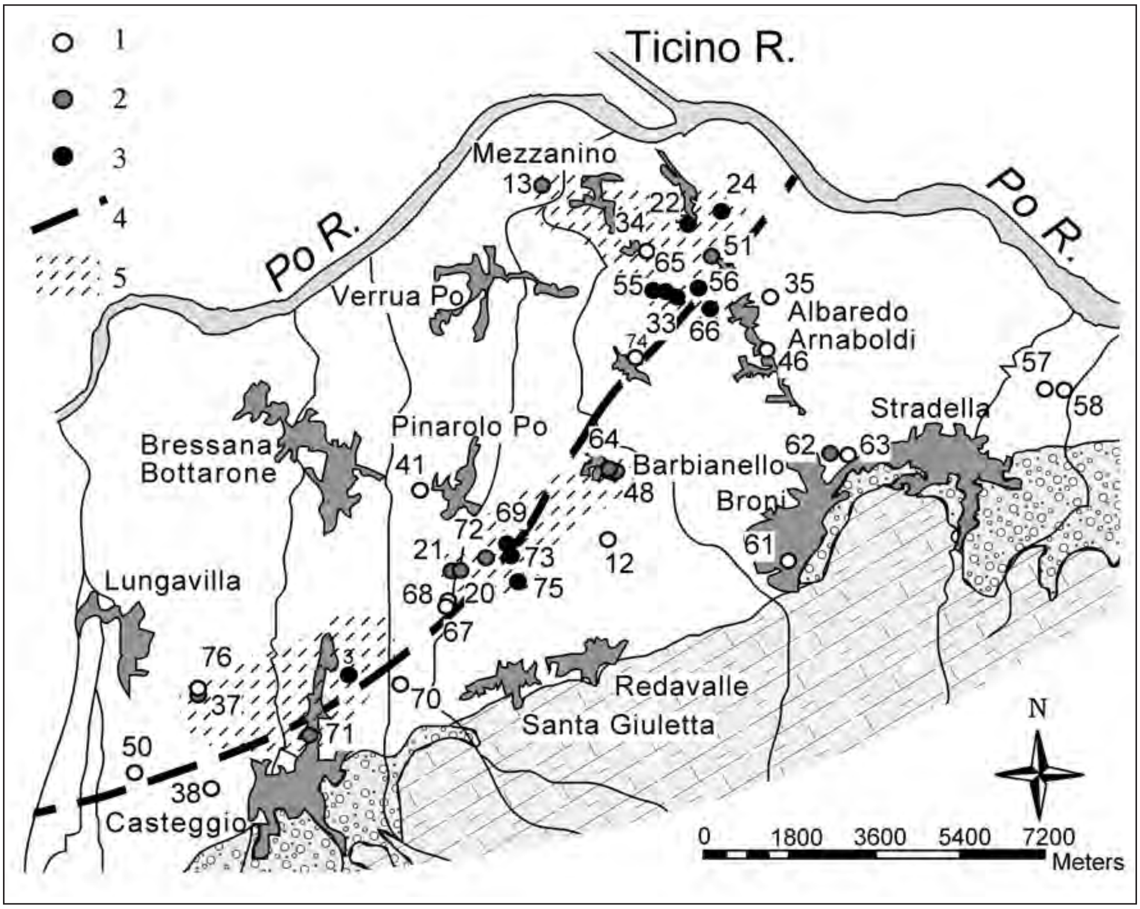

Fig. 6 - Areas that show higher groundwater salinity of the Oltrepò Pavese aquifer. Legend: 1) chloride concentrations < 200 mg/l; 2) chloride concentrations 200÷500 mg/l; 3) chloride concentrations > 500 mg/l; 4) trace of the Vogherese Fault from literature; 5) areas of high groundwater salinity.

Pavese alluvial aquifer; a sodium-chloride hydrofacies, which locally characterises the groundwater in some sectors of the Oltrepò Pavese area along the Vogherese Fault (Fig. 5a). The earlier hydrofacies has low-to-medium mineralisation (EC between 800 and 1200 μS/cm) while the latter has higher mineralisation but is extremely variable over the area. The variability of the Na-Cl groundwater is associated with the different degrees of mixing between the shallower groundwater and the deeper saline waters (brines of the Pianura Padana). Evidence of this variability is represented at the surface with the thermo-mineralised springs at Salice Terme, Rivanazzano Terme and San Colombano Terme (Fig. 5b).

Undesirable metals, like iron, manganese, arsenic and selenium represent another peculiarity of the Oltrepò Pavese groundwater (Pilla *et al.*, 2007). These metals, which compromise the quality of the waters even more, frequently accompany the already high chloride and sodium concentrations, often above the Italian drinking water standards (250 mg/l for chlorides; 200 mg/l for sodium - Decreto Legislativo n. 31/01).

The calcium-bicarbonated waters in the Oltrepò Pavese area are characterised by chlorides

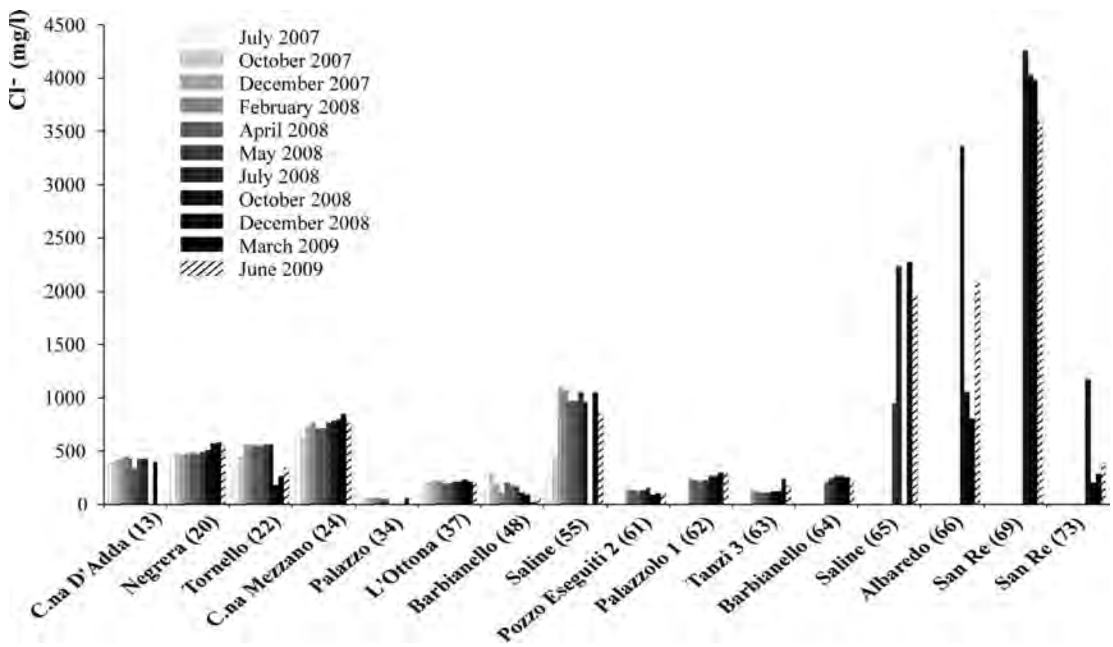

Fig. 7 - Variations of chloride concentrations for groundwater within monitored wells (period from July 2007 to June 2009).

that do not exceed 100 mg/l; concentrations of bicarbonates vary between 300 and 700 mg/l, calcium varies between 50 and 200 mg/l, magnesium varies between 30 and 50 mg/l and sulphates vary between 30 and 100 mg/l.

The sodium-chloride groundwater has a significantly higher mineralisation (EC values can be above 12000 μS/cm, and is on average between 2000 and 4000 μS/cm). The EC values are related to the solubilised chloride and sodium given that the concentrations of other major ions are relatively similar to those of the calcium-bicarbonated water described earlier. Well 48 at Barbaniello is the only exception. The EC values recorded at this location, sometimes above 5000 μS/cm, are mainly connected to the high sulphate concentrations that vary between 800 and 2700 mg/l. The origin of this calcium-sulphated groundwater can be connected to evaporite layers within the Gessoso-Solfifera Formation which are present at the base of the aquifer (Bersan *et al*., 2010).

Hydrochemical investigations have shown three areas along the Vogherese Fault where the phenomenon seems to be more intense and widespread (Fig. 6): the area to the north of Casteggio where the chlorides can exceed 1500 mg/l; the area to the west of Barbaneillo (San Re) where the highest concentrations (above 4000 mg/l) of chlorides were recorded and finally, the sectors that includes Mezzanino and Albaredo Arnaboldi, where chloride concentrations can reach 3000 mg/l.

While the distribution of the sodium-chloride groundwater is controlled by the trend of the Vogherese Fault at a regional scale (Figs. 2 and 6), higher variability in the distribution of the saline groundwater is observed at a local scale within the aquifer. The chloride concentrations mentioned earlier are the highest measured concentrations for each of the areas. However, groundwater with lower concentrations (300-400 mg/l) was sampled in nearby wells, which is indicative of ongoing natural contamination, although with different intensities.

Besides the more or less spatial variability of groundwater salinity observed between wells, time series data has also shown variability of groundwater salinity over time (Fig. 7). Chloride concentrations of sampled groundwater generally increased by a few mg/l between July 2007 and December 2007, with the exception of well 55. An increase of over 600 mg/l was recorded at this latter location. Instead, a decrease of a few mg/l was observed for chloride concentration over the period from February to May 2008. This can be observed from the samples of wells 13, 24 and 55. An initial significant increase in groundwater mineralisation was observed during the summer-winter period of 2008 (wells 13, 20, 24, 55, 64, and 65) which was followed by decrease in salinity of the groundwater due to autumn rainfalls, as shown by the decrease of chloride concentrations observed from wells 66, 69, and 73.

Variable conditions were identified from one well to another during February to March 2009. Increase of chloride concentrations within wells 20, 24, 55, and 65 were observed with values even higher than those recorded in June 2009. On the other hand, chloride concentrations decreased more or less abruptly within wells 22, 66, 69, and 73. Abundant and prolonged rainfalls were recorded in spring of 2009; additionally, the Pò River and other minor rivers flooded the northern areas (Comunes of Mezzanino and Albaredo Arnaboldi) of the studied zone in April 2009. The well heads of wells (13, 22, 24, 34, 55, 65, 66) located in the flooded areas remained below the surface water level for several days. Therefore, surface water flowed into the aquifer both through infiltration of the saturated soils and through the well heads of the flooded wells. This obviously influenced the chemistry of the groundwater, which was diluted by the surface water. It explains the opposite trends of chlorides for wells located in different areas, which were or were not affected by flooding over the following months.

The investigations that were undertaken for some sectors of the studied area allowed identification of the transition zone between the shallow fresh groundwater and the heavily mineralised deep groundwater. In general, groundwater salinity starts to increase at depths of between 6 and 8 m. This can increase to depths of 12-15 m like in the case of well 20. In other cases, the depth is just below ground level like in some sub-areas of the studied area where saline waters were found in the surface drainage network which is buried in the first few metres of the drift deposits (Bersan *et al*., 2010).

Acquired data shows that groundwater above and below the transition zone do not show the same degree of mineralisation. This indicates that the intrusion of saline waters within the aquifer is not evenly distributed within the study area (Fig. 8).

A strong increase of salinity with depth (EC increased from 3000 to approximately 14000 μS/cm) was recorded in some wells (well 66), while salinity was less variable (within a few thousand μS/cm) along the vertical of other wells (wells 20, 22, 48, and 55).

The correlation between the chemistry of the aquifer and the trend of the Vogherese Fault is not always observed. Some wells, although close to the fault, show low mineralisation of the groundwater (wells 71, 73, and 75).

Investigations repeated over different periods of the year allowed us to identify the recharge

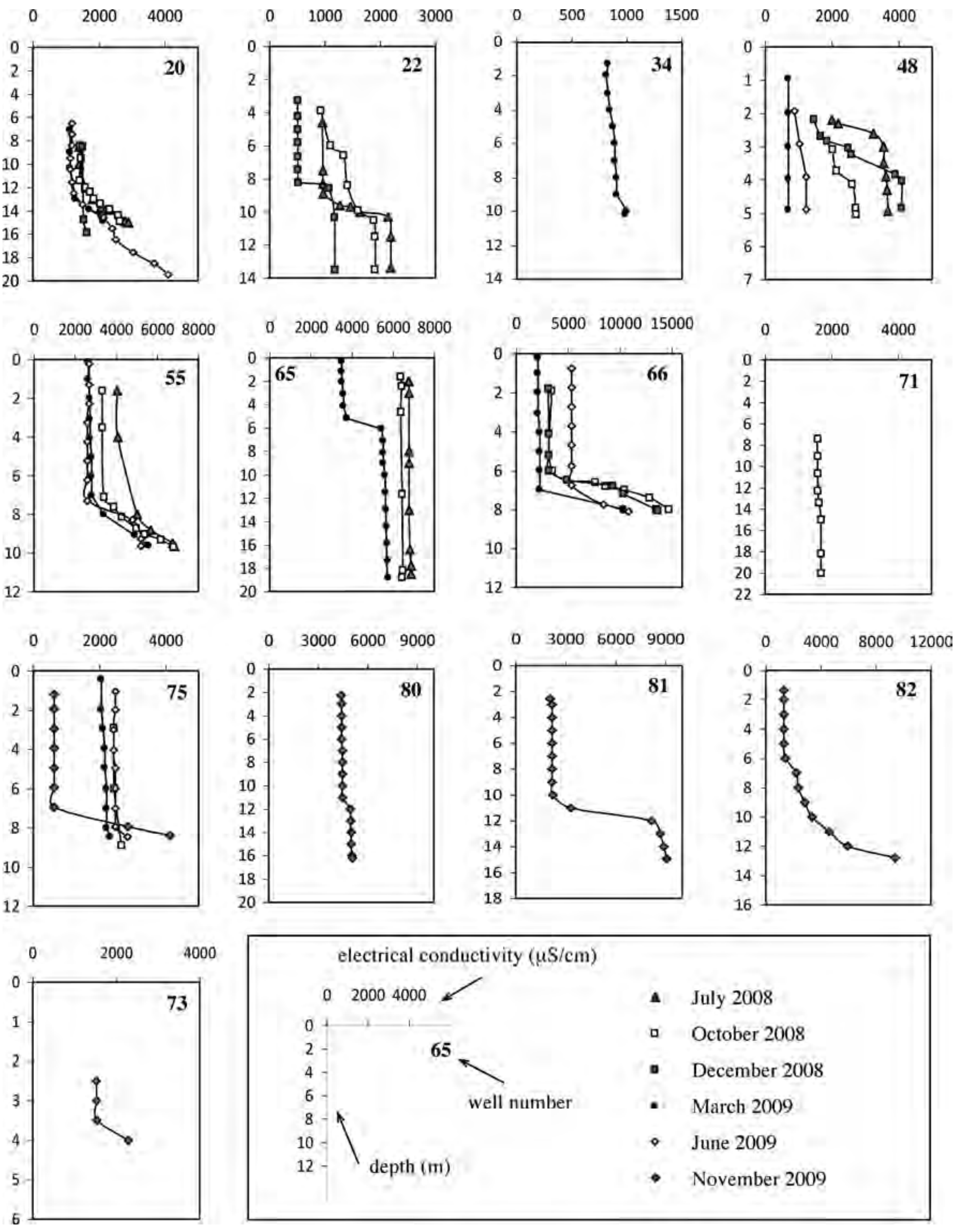

Fig. 8 - Electrical conductivity logs undertaken within some of the wells.

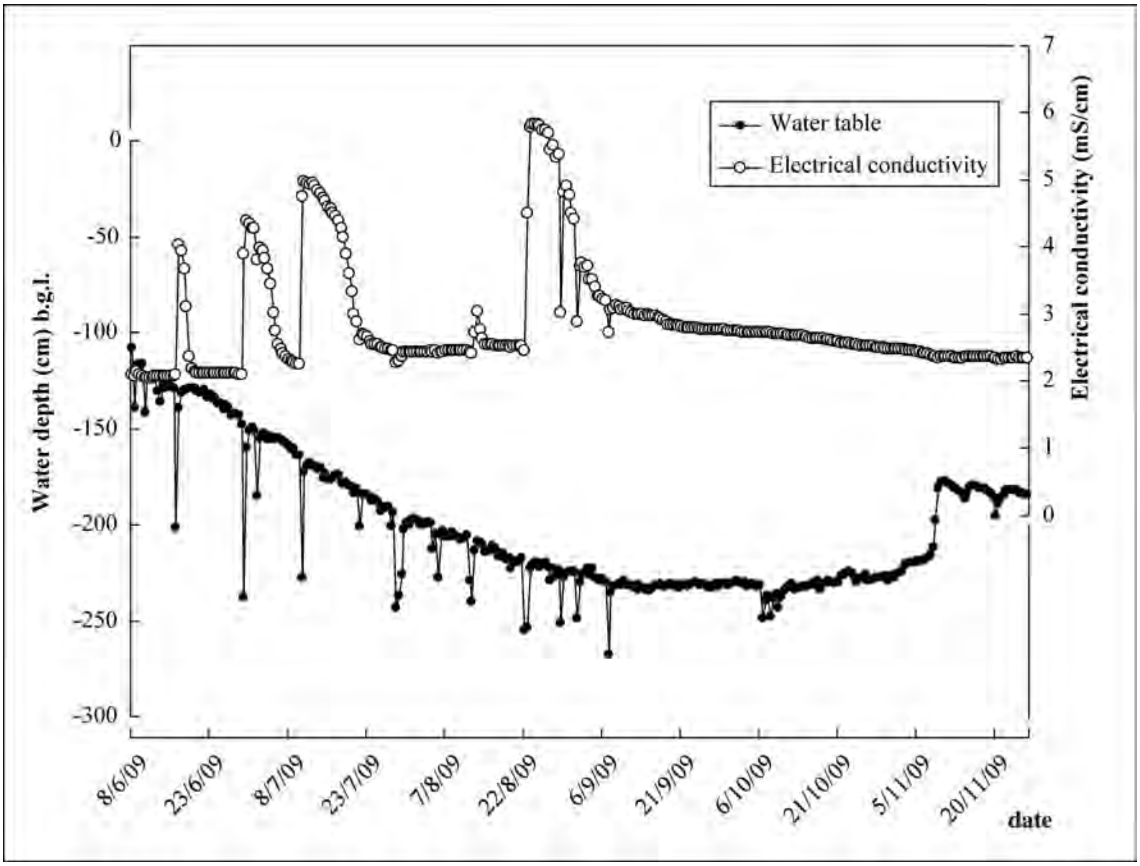

Fig. 9 - Continuous monitoring of piezometric head and electrical conductivity of well 73 from June 2009 to November 2009.

events of autumn 2008 and spring 2009. Data from logs indicate that the sectors of the aquifer that show a high mineralisation (wells 66 and 55) are not significantly affected by the dilution caused by recent recharge events. The response is clearly identifiable and rapid in other sectors where the intrusion of saline groundwater is less pronounced (wells 20, 22, and 48).

Only well 48 showed a different response when compared to the other wells. In fact, a substantial decrease of EC within the first few metres of the aquifer corresponded to a significant increase of salinity in the deeper part of the aquifer. Conversely, during the spring of 2009, the same well showed a substantial decrease of groundwater mineralisation.

It is likely that these changes in the mineralisation of the groundwater in well 48 are connected to the relatively shallow depth (5 m) and poor installation of the well, which cause anomalous hydrochemical responses during recharge events.

No substantial variation of the fresh water – salt water interface was identified in some of the wells (wells 22, 55, and 66) during the course of the year. Other wells (wells 20 and 48) showed more substantial vertical changes of this interface which are mostly connected to an increase of the fresh water volumes from the arrival of recent groundwater recharge fronts.

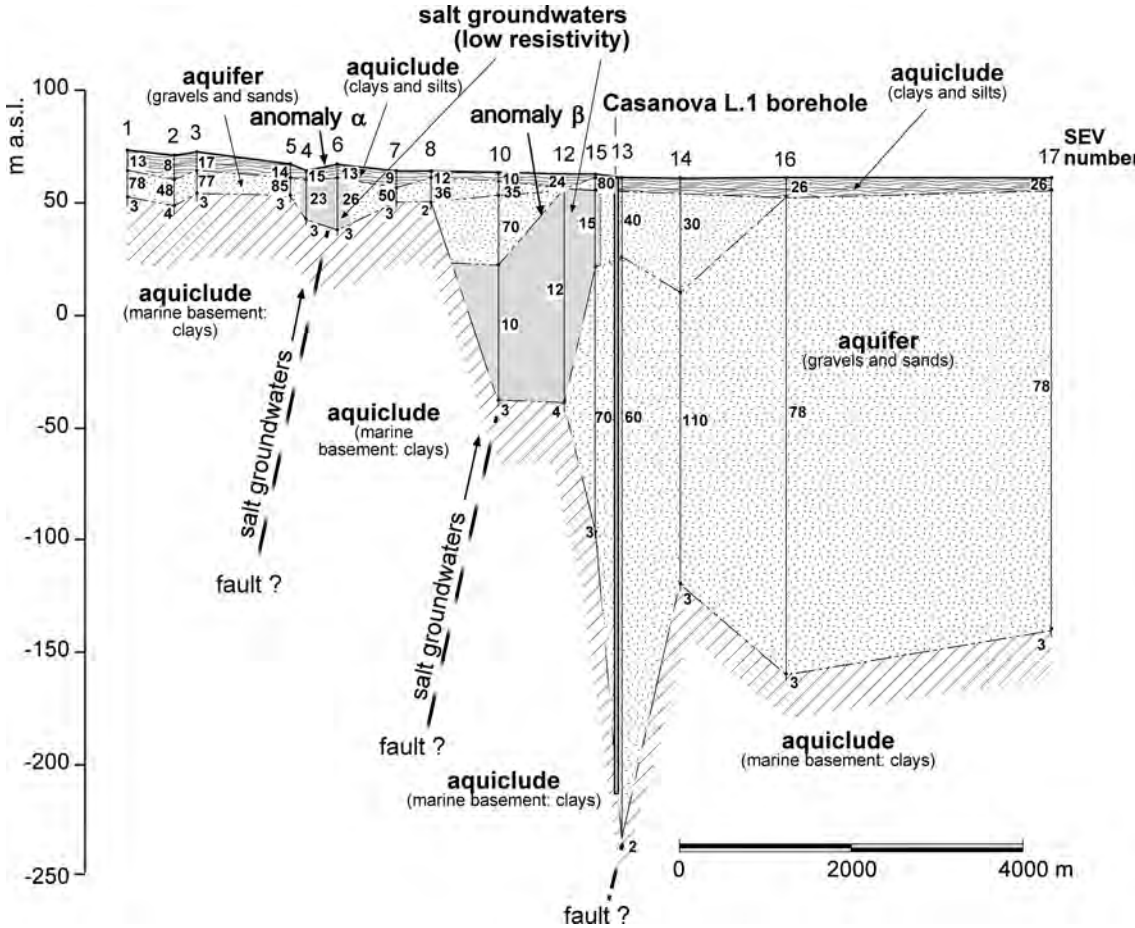

Fig. 10 - Electrostratigraphic section from resistivity soundings (values in Ω·m) showing the Casanova L. 1 deep borehole location.

Continuous monitoring of groundwater piezometric levels and EC in well 73 has shown some interesting results for groundwater salinity with respect to the hydraulic head. The well is a private potable water supply located at San Re, at a short distance from well 69 which is the well that reaches the highest absolute contamination from saline waters. Continuous monitoring started in June 2009 and is still ongoing (Fig. 9).

Data collected to date shows that during the summer period a progressive decrease of the piezometric level, due to low rainfall, corresponds to an increase of EC from 2000 to 2600 μS/cm.

Some increase of groundwater salinity (5800 μS/cm) corresponding to decreasing piezometric levels is observed on the same diagram of Fig. 9. These can be explained by the induced effects of groundwater abstractions from the well on the equilibrium between the superficial fresh groundwater and the deeper higher salinity groundwater. The aquifer returns to the pre-disturbed conditions once abstractions cease.

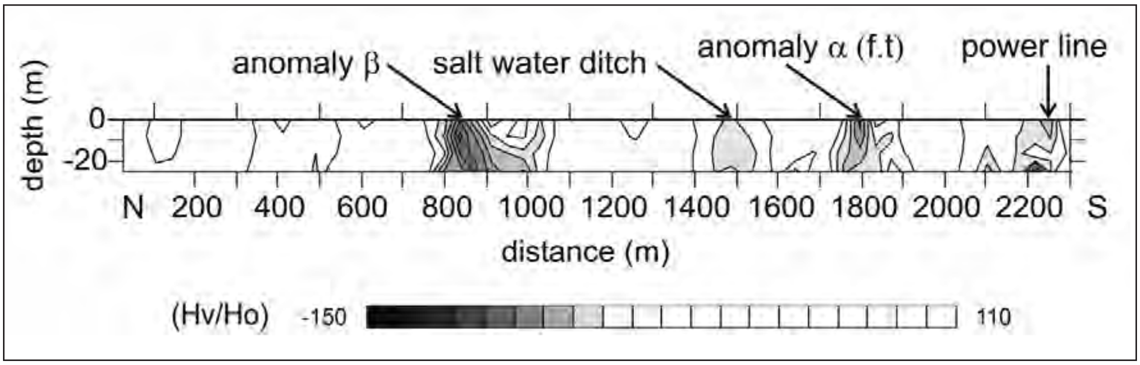

Fig. 11 - Pseudo-sections (H_V/H_0) of the real part (positive values) obtained through a Fraser filter of VLF-EM profile 22.

5. Geophysical study

Phase 1 of the investigations has shown that the marine substrate at the base of the continental deposits is deeper in the north-western areas and is also characterized by morphological irregularities (small troughs and/or dorsals), partly shaped by tectonics and partly shaped by the Scuropasso and Versa paleo-rivers. In particular, the electro-stratigraphic section (Fig. 10) that falls in the NE of the study area shows that the upper clayey silty deposits have resistivity values between 8 and 26 Ω·m.

They also show that the gravelly-sandy aquifer has resistivity values between 26 and 85 Ω·m and that the marine substrate causes a sharp change in the resistivity values which change to 2-4 Ω·m. Two anomalous areas are identified: one is located between VES 4-6 (anomaly α in Fig. 10) and the other between VES 10-15 (anomaly β in Fig. 10). They are characterised by resistivity values between 10 and 25 Ω·m that are significantly lower (oblique line in Fig. 10) than the surrounding values.

The first anomaly is related to the sandy-gravelly deposits that lie beneath the clayey-silty deposits and extends to a depth of between 5 m to 25 m; the second anomaly, which is still located within the sandy-gravelly deposits and extends beneath the clayey-silty deposits, extends to a depth of between 7 m to 100 m which is the depth of the aquiclude. These low resistivity values correspond to two anomalies located along VLF profile 22 (Fig. 11).

The anomalies identified on the VLF 22 profile are congruent with the results of the resistivity depth soundings.

The VLF-EM α and β anomalies shown in Fig. 11 in the NE of the study area, which are aligned along segments 4 and 5, correspond to the low resistivity anomalies (10-25 Ω·m) localised respectively between VESs 4-6 and 10-15 (Fig. 10). These anomalies are also found in the VLF-EM pseudo-sections of Fig. 11. These sections are congruent with the results of the resistivity depth soundings and show a superficial narrow anomaly and a deep anomaly (Fig. 10) that has the same dip as the Vogherese Fault. These results indicate that the uprising mineralised waters that originate from the Mio-Pliocene deposits contaminate the superficial aquifer in correspondence of several sub-parallel discontinuities oriented in a NW-SW direction.

A magnetic anomaly map (Fig. 12) depurated from cultural electromagnetic noise (i.e., high

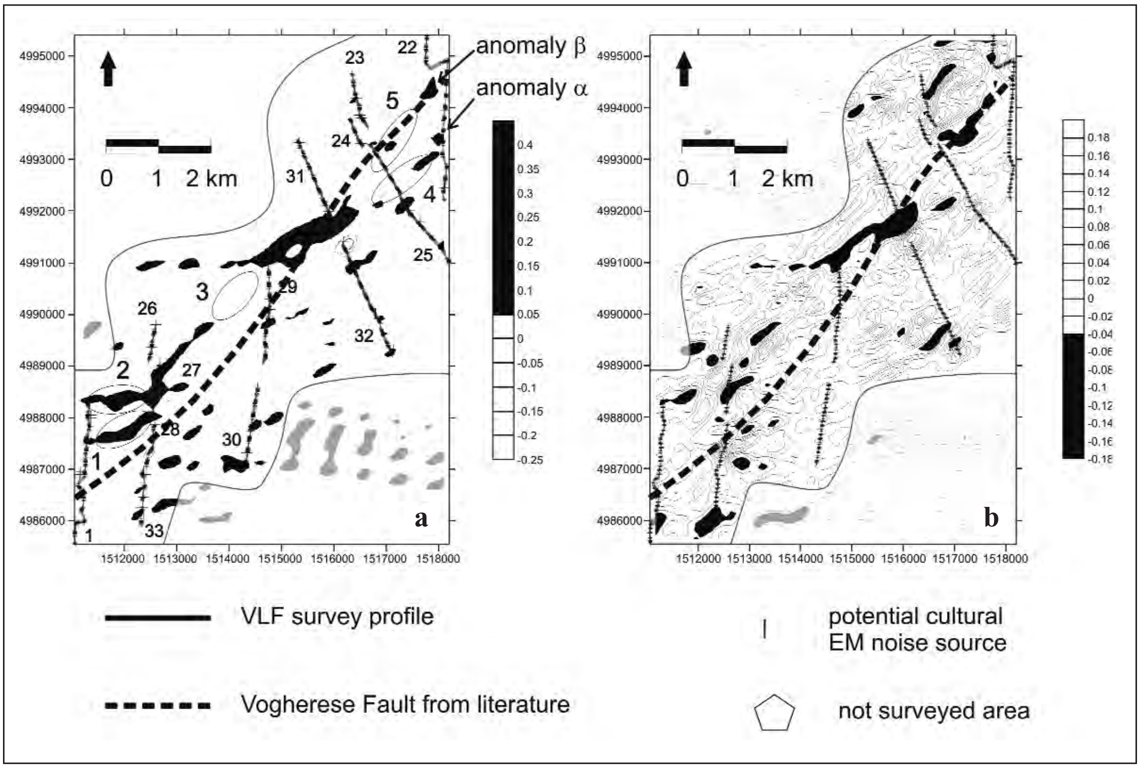

Fig. 12 - Map of the magnetic anomalies (H_V/H_0): real component obtained through the application of Fraser filter, directional Kriging interpolation, low pass filter and directional first derivative (a), imaginary component obtained through the application of Fraser filter, directional Kriging interpolation, low pass filter and directional first derivative (b).

voltage electroducts) has been derived through filtering and interpolation. The map shows that there is no correspondence between significant anomalies and potential EM noise sources located on the field. Given the low lateral sampling of VLF-EM data, the map is only an attempt to verify an anomaly trend occurrence and the relationship with the fault orientation and the localisation of the known high salinity waters.

Fig. 12 shows the magnetic anomaly map. A main NE-SW aligned trend and at least one secondary alignment towards SE of high conductivity anomalies are shown in Fig. 12a. Their orientation is similar to that of the Vogherese Fault and therefore they can be correlated with the up-rise of mineralized waters along the fault zone. Worthy of note are the following: segments 1 and 2 in the SW, where a bifurcation of the main alignment occurs; segment 3 in the middle where no anomalies are observed and segments 4 and 5 in the NE where the anomalies are discontinuous. The magnetic anomaly map of the imaginary component is shown in Fig. 12b. This map confirms the main trend previously discussed, while secondary alignments are hardly visible due to their poor continuity.

The VLF-EM observed conductivity anomalies aligning along the Vogherese Fault (Fig. 12). In particular, the principal alignment runs parallel to the Vogherese Fault trace, shifted towards NW by approximately 0.5-1 km in the southern area. The alignment intersects the fault trace in

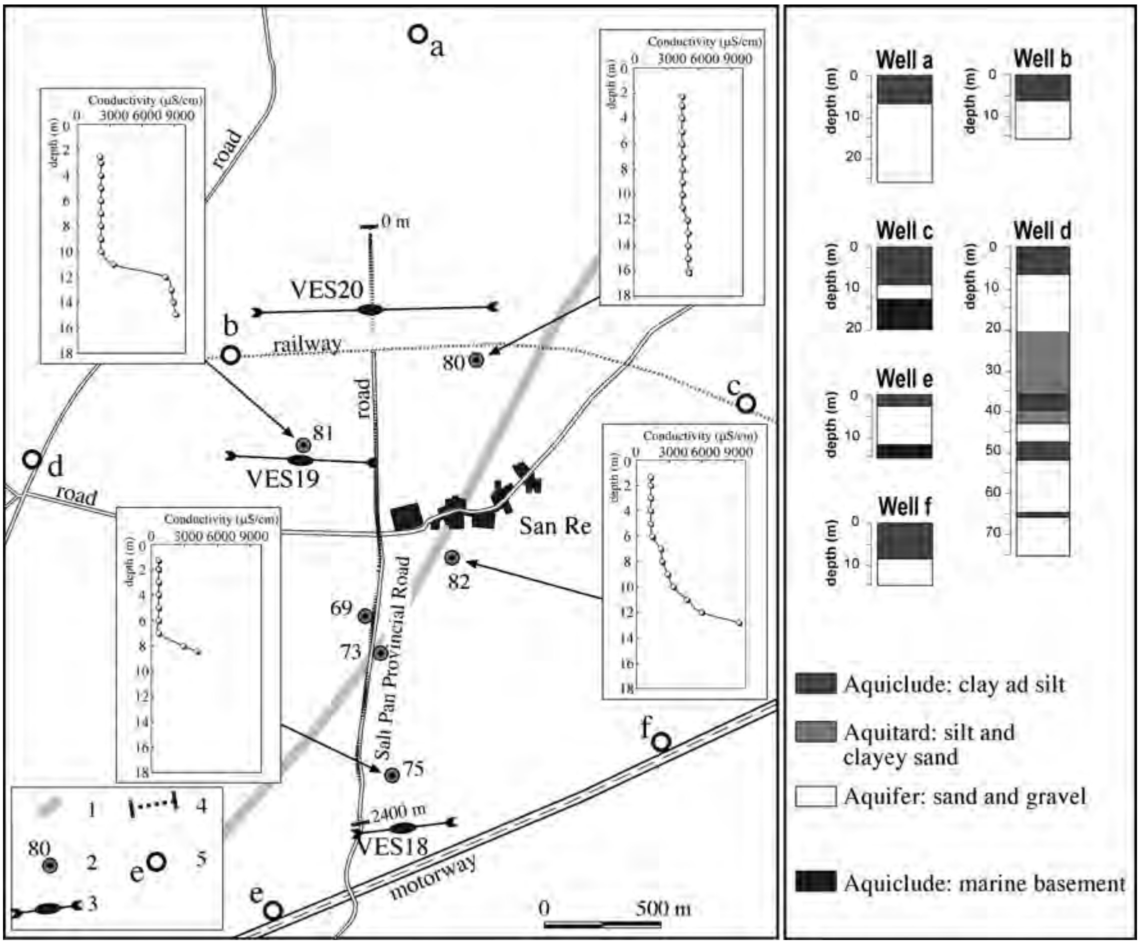

Fig. 13 - Investigation undertaken within the selected site shown in Fig. 3 legend: 1) trace of the Vogherese Fault (assumed from pre-existing investigations) in plan view; 2) well; 3) VES; 4) resistivity profile and VLF line 29; 5) well with stratigraphy.

the central-northern area. The secondary alignments that are traceable with greater uncertainty (and hardly visible in the imaginary component) are localized at 0.5-1.5 km SE-wards of the fault.

The complexity of the geometries of the areas where the high salinity groundwater are found in proximity to the fault (this is shown in the plan view in the magnetic anomaly map and in the section by the electrostratigraphic profile and the pseudo-sections of equivalent current density) was also identified at the local scale within the selected site (Fig. 13). In this area, the bulk resistivity values are strongly affected by the groundwater resistivity within gravelly and sandy alluvial deposits occurring below the continuous overlying superficial deposits and the bedrock resistivity at a higher depth.

The greater anomaly identified along pseudo-section 29 (at 400-680 m, Fig. 14a) can be identified in correspondence of a strong apparent resistivity variation along the profile at 650 m

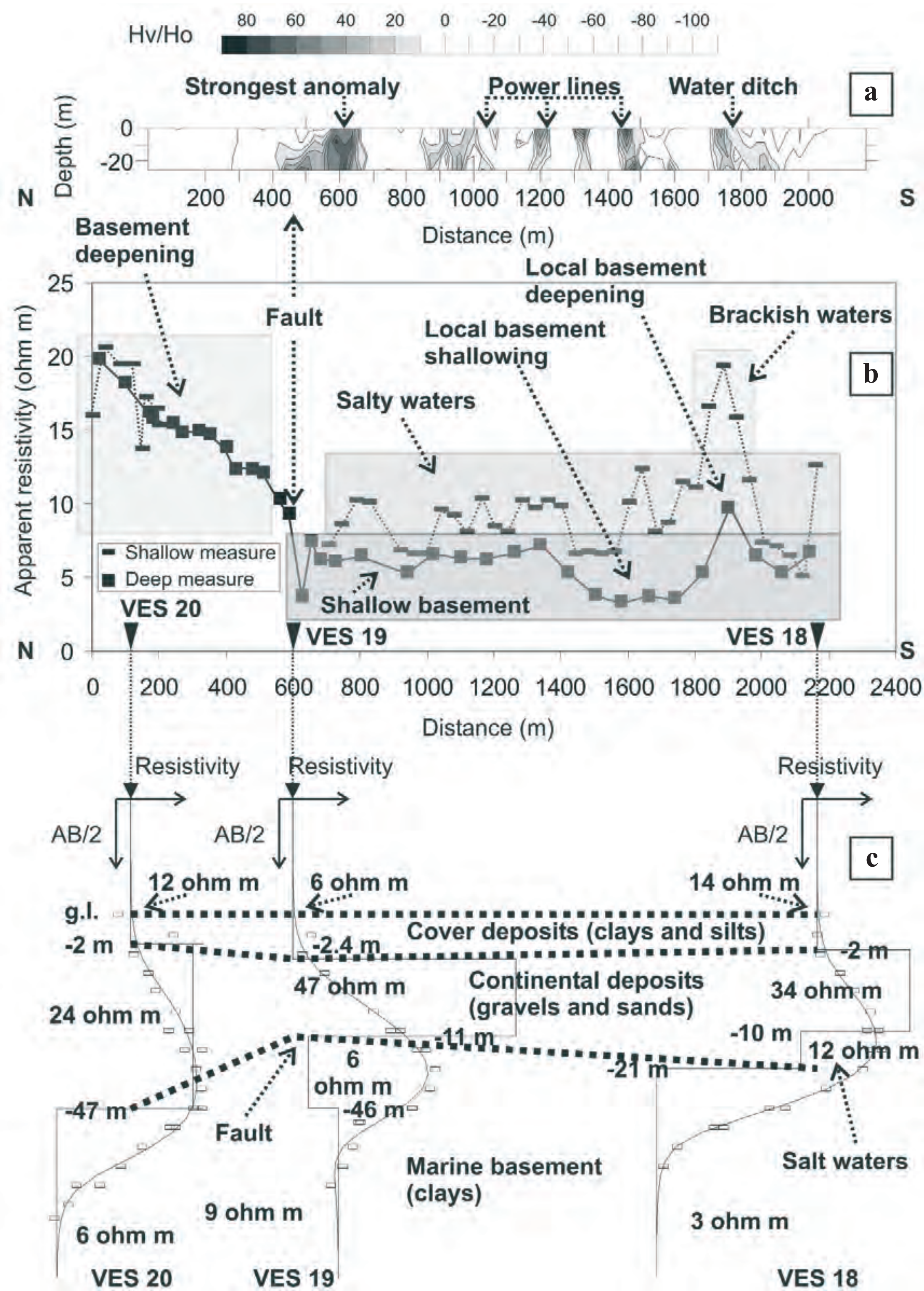

Fig. 14 - Pseudo-sections (H_V/H_0) of the real part (positive values) obtained through a Fraser filter of VLF-EM profile 29 (a); resistivity profiling (b) obtained through gradient array with AB=80 m, MN=10 m; resistivity depth-soundings (VES) 18, 19, 20 and electro-stratigraphic section obtained (c).

(Fig. 14b), very close to SEV 19. This identifies a change between two zones: the increase in apparent resistivity (from approximately 7 Ω·m to 20 Ω·m) towards the north (from 0 to 650 m along the section) is indicative of the deepening of the clayey bedrock (VES 20 indicates a depth of -47 m at 50 m along the section) and of groundwater that has medium salinity; the low apparent resistivity values towards the south (from 650 to 2160 m) indicate a shallow depth of the clayey bedrock and a widespread but not continuous presence of saline waters. In particular, the apparent resistivity values relative to the greater depths (~20 m) in this area are essentially related to a qualitative description of the geometry of the bedrock. Although the latter remains at a shallow depth (-11 m at 600 m as indicated by VES 19 and -21 m at 2160 m as indicated by VES 18, Fig. 14c) the apparent resistivity values indicate local shallowing of the bedrock from 1500 m to 1750 m along the section where the values are typical of the bedrock resistivity (3-4 Ω·m). Higher apparent resistivity values indicate a deepening of the bedrock at 1900 m along the section.

Conversely, the measurements relative to the shallower depths (approximately 10 m) which show greater variability in apparent resistivity values indicate the non-continuous presence of salty waters which lie just above the bedrock and brackish waters at 1900 m. The earlier salty waters have apparent resistivity values of approximately 10 Ω·m, which are similar to those identified for VLF-EM the anomaly equal to 10-15 Ω·m (Fig. 11). The latter brackish waters at 1900 m are the result of dilution of the salty waters caused by the deepening of the bedrock and have apparent resistivity values of around 15-20 Ω·m, which are similar to the values identified for the VLF-EM anomaly equal to 23 Ω·m (Fig. 11).

This hydrogeological configuration is confirmed by VES 18, 19, and 20 (Fig. 14c) which identifies shallow bedrock to the south and the above mentioned deepening of the bedrock to the north. This geological setting suggested by the resistivity profiling and depth soundings is congruent with the wells stratigraphies. Indeed, while wells a, b, and d, located in the NW sector do not intercept the bedrock with respect to the fault trace wells c and e, located in the SE sector, intercept it at a shallow depth (Fig. 13). Furthermore, resistivity depth soundings confirm the complex geometry of the areas affected by the high salinity groundwater which depends on the trend and fracturing of the bedrock. In fact, the salty groundwater is not continuously widespread. Within the aquifer VES 18 identifies, deeper strata (between -10 m and -21 m with resistivity of 12 Ω·m) with salty groundwater and one or more shallow strata (between -2 m and -10 m with resistivity of 34 Ω·m) with fresher groundwater, whereas VES 19 and 20 identify a single strata with fresh and saline groundwater respectively. Furthermore, in correspondence with VES 18, the profile indicates a value of 13 Ω·m for the shallow depth (approximately –10 m) which is due to the intercepting of the aforementioned salty groundwater, and a value of 7 Ω·m for the greater depth, which is connected to the intercepting of the bedrock.

6. Conclusions

The Oltrepò Pavese alluvial aquifer is locally characterized by strong natural contamination on behalf of fossil sodium-chloride groundwater with high salinity, which originates from the tertiary marine bedrock. This particular form of contamination is strictly controlled by the peculiar geological and structural configuration of the area. This configuration includes an

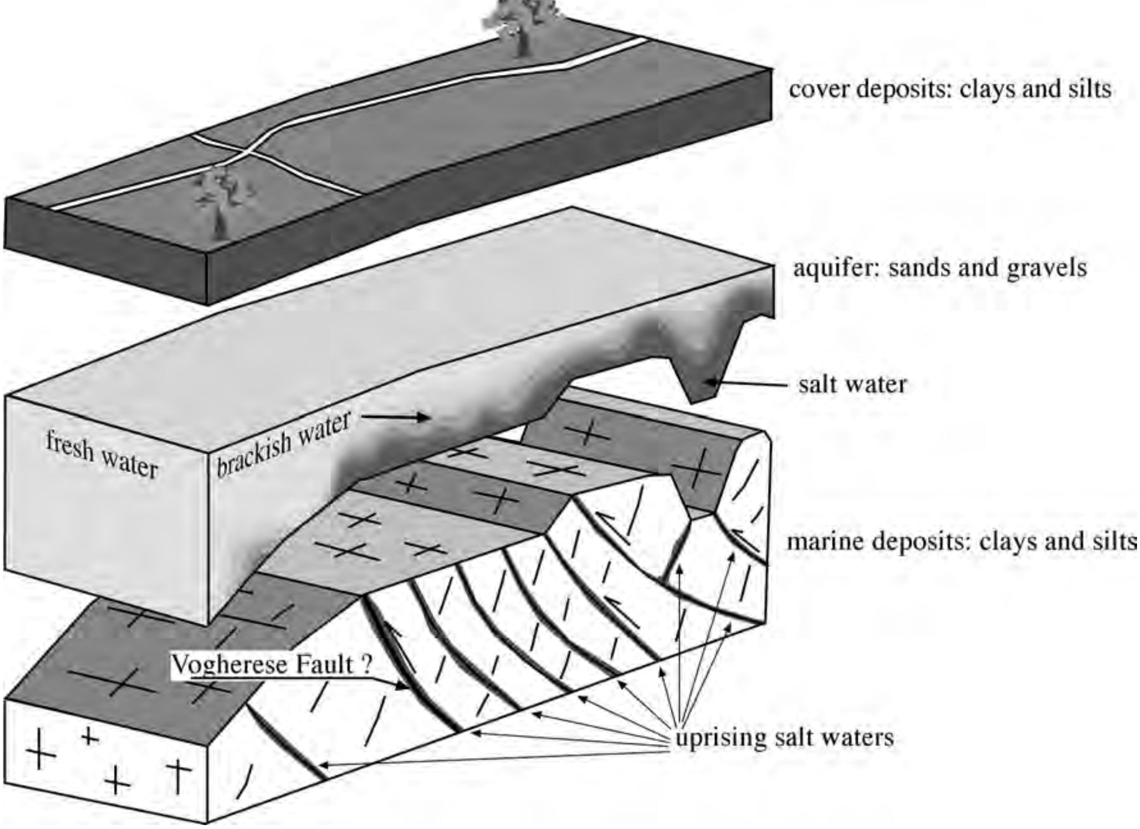

Fig. 15 - Block diagram showing the conceptual model of the contamination with highly salty groundwater within the selected area of the Oltrepò Pavese alluvial aquifer.

important structural discontinuity within the Miocene-Pliocene substrata which is known in literature as the Vogherese Fault. The fault facilitates the uprising of hyper-saline groundwater towards the shallower deposits. The peculiar geological and structural configuration also includes the fact that the tertiary deposits, which host the salty groundwater, also tend to be shallower in these areas.

Other factors influence the rising up of the salty groundwater: the reduced thickness of the superficial aquifer; lateral and vertical changes in EC values of the groundwater with the alluvial aquifer; over the past years the excessive groundwater abstraction, especially for irrigational purposes, has become non sustainable in the long term.

New and important data have been collected from the investigations undertaken in this study. This data will aid the understanding of how this contamination phenomenon occurs within the Oltrepò Pavese alluvial aquifer.

Firstly, three distinct areas were identified from hydrochemical analyses where the rising up of high salinity groundwater within the alluvial aquifer is more intense and widespread. Two of the identified areas fall approximately along the Vogherese Fault while the third area, which is the northern most one, extends in a northerly direction towards sectors of the area that are quite far from this structural discontinuity.

There is not always a correspondence between the superficial trace of the Vogherese Fault as stated in literature, and the alignment of the major electromagnetic anomalies which are believed to be related to the important structural discontinuity as highlighted by the geophysical investigations, especially the electromagnetic investigations (VLF). Other minor sub-parallel structural discontinuities (faults and fractures), which are also capable of acting as preferential flow paths for the salty groundwater towards the superficial aquifer were also identified by the electromagnetic investigation. These minor discontinuities show geometries and directions (NW-SW) that are coherent with those of the Vogherese Fault and are therefore genetically connected to the major structural discontinuity.

The geophysical investigations undertaken at the selected site (resistivity depth soundings, resistivity profiling and VLF profiling) have helped to clarify the complexity of the aquifer geometry in the areas that are affected by high salinity groundwater near the Vogherese Fault. In particular, the investigations have shown that the bedrock of marine origin, which underlies the aquifer and from which the salty groundwater originates, does not have a regular spatial trend. It is rather identified by a series of high-standing and low-standing morphologies that are located in correspondence of faults and fractures that are often associated with electromagnetic anomalies. The morphology of the Tertiary bedrock and the spatial distribution of the structural discontinuities are likely to be partially controlling the distribution of salty groundwater, originating at depth, within the alluvial aquifer (Fig. 15).

Contamination from salty waters is not spatially and vertically homogeneous within the aquifer as highlighted by the hydrochemical investigations. This non-homogeneity, which is mostly shown from the EC logs, is likely to be affected by other factors like the permeability of the aquifer and the aperture of the discontinuities within the Tertiary substrata. These discontinuities put the shallow alluvial aquifer in communication with the salty groundwater that is stored at depth within the Tertiary deposits and facilitate the rising up of the salty groundwater at varying intensities.

The conceptual model of the studied phenomenon has identified several plumes of high salinity groundwater that reach the alluvial aquifer. Here, they diffuse and mix with the fresh groundwater of the shallow aquifer, thus originating different degrees of groundwater salinity within the aquifer. Highly mineralised groundwater is identified even at very shallow depth in correspondence of each plume, which is located above a structural discontinuity. On the other hand, there is a lower degree of contamination in those sectors of the aquifer that are further away from the structural discontinuities and generally only involves the deeper parts of the aquifer.

Finally, the increase of fresh groundwater due to recharging events tend to relegate the highly mineralised groundwater to the lower sections of the aquifer, while excessive groundwater pumping in the summer period and the contextual absence of rainfall allow the highly mineralised groundwater to flow towards the more superficial sectors of the aquifer.

The present study shows that it is necessary to use a multidisciplinary approach (which includes the integration of hydrochemical and geophysical investigations within the hydrogeological assessment), when it comes to understanding extremely complex forms of groundwater natural contamination, similar to the contamination that has been identified in the Oltrepò Pavese area where several intervening factors can influence the contamination.

Acknowledgement. The authors are grateful to an anonymous reviewer and to Giorgio Ghiglieri for helpful comments and to Antonio Gennarini for reviewing the English.

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