DOI 10.4430/bgta0063

Characterization of Bagni di Lusnizza (Udine) sulphureous water resources by integrated geophysical metods

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(Received: August 17, 2011; accepted: February 23, 2012)

ABSTRACT The aim of this study is to characterize the sulphureous water resource feeding the Bagni di Lusnizza historical spring (located in the Rio dello Solfo valley, north-eastern Alps), through an integrated geological, geochemical and geophysical study. The reconstruction of the hydro-geologic framework in this complex mountain area, including the circulation pathways in the upper 100 m and the mixing zones between deep sulphureous and shallow aquifers, substantially benefits from the Electric Resistivity Tomography (ERT) and from the electromagnetic measurements (FDEM and VLF). They allow to image the buried geological structures (such as the morphology and fracturing of the bedrock), as well as to identify the mineralized water saturation zones in the debris deposits (resistivity values lower than 100 Ohm·m) and to speculate on the potential fracture zones through which the sulphureous water rise, providing a preliminary conceptual model for the hydro-geologic recharge. The shallow geophysical survey was first acquired to characterize the upper 10 m of debris deposits and outcropping rocks and to calibrate the indirect geophysical data with the geochemical measurements and geological information. The deep imaging was carried out to characterize the entire filling of the valley and possibly the buried bedrock. The successful results of the geophysical measurements provide the background model for a more focused survey in order to locate one or two wells intercepting the rising sulphureous water plume before it mixes with the overlying shallow aquifers, with the aim to exploit temperature and geochemical properties of the deep resource.

Key words: fractured aquifers, ascending sulphureous waters, ERT tomography, integrated geophysical methods, pumping wells location, NE Friuli Alps.

1. Introduction

The sulphureous cold springs in Bagni di Lusnizza (located in the municipality of Malborghetto-Valbruna, Udine, north-eastern Italy) are known since Roman times and were episodically used through the middle age till the last century (Fig. 1). The first spa hotel was built in Lusnizza in 1848. Gustav Jager, reported in 1873 that the source into the channel of Rio dello Solfo is “cold, large flow, rich in sulphur and very good for skin diseases, scrophularia and similar diseases”(Eder, 2007). The first chemical analyses were performed by Svoboda (1902). For a century the spa was an important resort venture, then, the Second World War left the area completely abandoned in spite of several aborted recovery initiatives. In the last decade, the

Fig. 1 - View of the investigation area from the northern side. The check dams are numbered according to the reference scheme adopted in the text.

Comunità Montana del Gemonese, Valcanale e Canal del Ferro, supported by the Regione Friuli Venezia Giulia funding, agreed to relaunch the balneotherapy, commissioning to the Trieste University a characterization study of the sulphureous water resources through an integrated geological, geochemical and geophysical study. The main objectives of the investigation are to reconstruct the buried geological structures in the study area, to understand the groundwater recharge system and the extent of the deep sulphureous aquifer and to identify the most favourable locations to drill one or more wells intercepting the upward migration pathways of the sulphureous waters through the fractured bedrock. The final goal of the entire program is to withdrawal sulphureous waters with temperature and geochemical characteristics similar to those present in the deep reservoir, before mixing with the shallow groundwaters flowing in Karst-type aquifers.

The study area (see Figs. 1 and 2) extends for about one kilometre in the N-S direction and for about 300-400 m in the E-W direction. It corresponds to the Rio dello Solfo valley, approximately oriented N-S. The creek merges from the hydrographic left into the Fella river, near the town of Bagni di Lusnizza. The valley is particularly narrow and impervious showing very steep and forested flanks. The creek has been regulated by 12 check dams in its lower section to limit the hydraulic energy downstream and to allow for the containment of blocks and sediment transport. Some of them are shown in the picture of Fig. 1 (6 to 12). The thickness of the layer of blocks and debris in the valley is unknown but it should not exceed 100 m. Across the Rio dello Solfo valley there are several sulphureous water emergencies mainly located in the mid-valley segment, between check dam 5 and 6.

In this paper, we refer to the main historical spring as the most representative of the distributed scenario of emergencies, positioned on the right hand side of the Rio dello Solfo (see location in Figs. 4 and 7). The spring was monitored at regular intervals during the past 10-20 years, showing almost constant geochemical characteristics (independent from seasonal variations). Due to their relatively high salinity, the sulphureous waters of this spring are excellent electrical conductors. Geophysical electromagnetic methods are therefore appropriate for the specific targets of this investigation because they satisfy the need to investigate large volumes of subsurface rocks, with special attention to the changes in saturation fluids (Hubbard and Rubin, 2006; Linde *et al*., 2006; Vereecken *et al*., 2006).

Several papers have been published on the use of Electrical Resistivity Tomography (ERT) for environmental and hydro-geological problems (e.g., Kemna *et al*., 2000; Binley *et al*., 2002; Meju, 2002; Lebourg *et al*., 2005; Maillett *et al*., 2005; Caputo *et al*., 2007; Deiana *et al*., 2007; Casas *et al*., 2008; Crook *et al*., 2008; Marescot *et al*., 2008; Sass *et al*., 2008; Yeh *et al*., 2008; Cassiani *et al*., 2009), salt intrusion monitoring (e.g., Slater *et al*., 1997), aquifer contamination (e.g., LaBrecque *et al*., 1996; Ramirez *et al*., 1996; Bentley and Gharibi, 2004) and solute transport assessment (e.g., Kemna *et al*., 2002; Slater *et al*., 2002; Singha and Gorelick, 2005; Cassiani *et al*., 2006; Monego *et al*., 2010). The use of the ERT technique is adequate to characterize the subsoil resistivity changes because of the rising of deep saline water into the shallow unconfined aquifer. Weiqun *et al*. (1997) and Magnusdottir and Horne (2011) dealt with geophysical methods applied to water investigations and geothermal resources, even though not many papers deal specifically with sulphureous waters investigations. Margiotta and Negri (2008) suggest the use of ERT and Induced Polarization to study sulphur waters, as integrative methods to field geology and borehole stratigraphy data.

The main aim of this study is to characterize the sulphureous water resource in Bagni di Lusnizza using integrated electrical and electromagnetic surveys, calibrated against field geology and geochemistry measurements. In particular, we reconstructed the shallow geological structures and we propose a preliminary conceptual model for the hydro-geologic recharge, including the pathways of sulphureous water down to 150 m depth. We used the Frequency Domain Electro Magnetic method (FDEM) for a preliminary mapping of the shallow resistivity (few meters), whereas we adopted ERT profiles around the principal sulphureous spring to extend the investigation to about 20 m depth, verifying and calibrating the electrical response against geochemical measurements. To penetrate at larger depths and to characterize the nature and geometry of the major tectonic discontinuities (expected to host fracture systems through which the sulphureous waters are expected to rise), we used ERT investigations across the entire area of interest, in combination with the Very Low Frequency (VLF) surveys to detect the presence of lateral electrical conductivity contrasts across sub-vertical discontinuities. Finally the single pole Mise a la Masse (MALM) method was used to complement the ERT survey and possibly discriminate the geometry and dip of the conductive upward channelling.

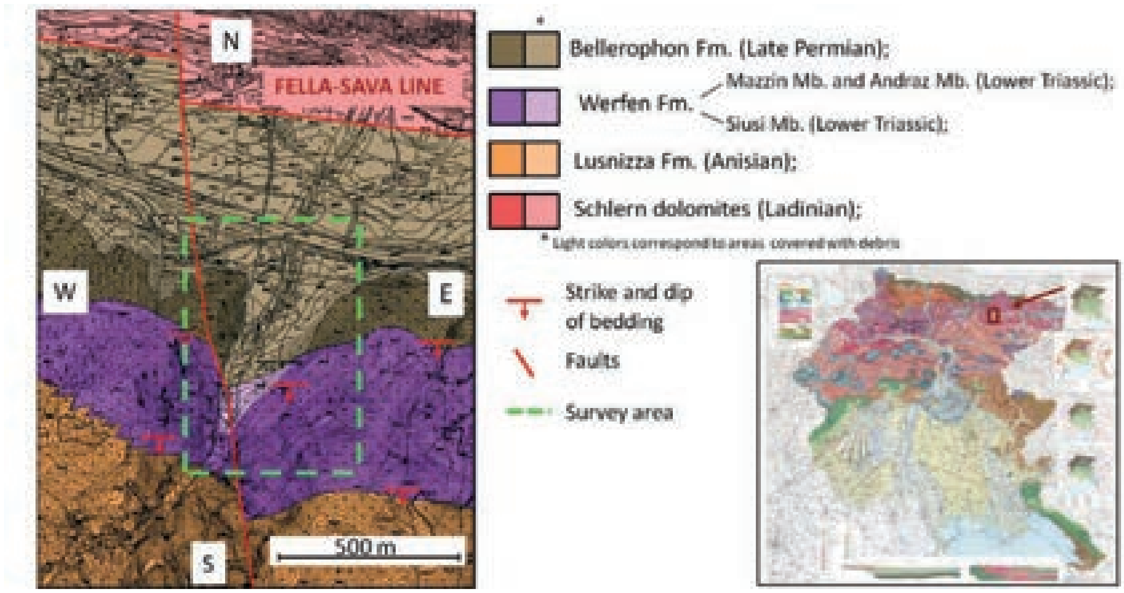

Fig. 2 - Geological sketch map of the survey area (modified from Carulli, 2006).

2. Geological settings and water geochemistry

The study area belongs to the active Fella-Sava N-S compressive thrust, which is E-W oriented and shows a high angle immersion to the south (Venturini, 1990). The compression overthrusts the base of the Bellerophon Formation (late Permian), outcropping in the southern portion of the Alpine chain onto the Schlern dolomites (Ladinian, early Triassic) by an inverse tectonics with about 4 km of vertical up throw (Merlini *et al.*, 2002).

The deformation belt extends across the entire northern border of the Friuli Venezia Giulia region and it has been interpreted (Venturini, 1990) as a potential back-thrust of the most important Peri-Adriatic lineament, running with a sub-parallel direction some 20 km to the south. Field geology investigations were carried out in 2009 and 2010 to recognize the formation outcrops, their stratigraphic limits and the major structural elements (Fig. 2).

The main formations recognized are the following:

- Bellerophon Formation (Late Permian): consists of evaporite deposits, marls, dolomites and limestones. In particular, it is formed by alternating dark carved dolomites, gypsum and limestones, and should be the deep parent reservoir of the sulphureous waters. Only the dark limestones outcrop in the area: they are in stratigraphic contact with the upper Mazzin Member limestones, belonging to the Werfen Formation;
- Werfen Formation (Early Triassic): consisting of a sedimentary sequences formed of limestones, marls, mudstones and sandstones. This is a very thick unit (up to 800 m) typically divided into several members. In the study area three members are outcropping:
  - the Mazzin Member, composed by grey limestones, is in stratigraphic sequence with the

Bellerophon Formation;
- the Andraz Member following in stratigraphic sequence, consists of marl and dolomitic limestones;
- the Siusi Member at the top is formed by alternating micritic limestones and marls;

- Lusnizza Formation (Middle Triassic): the units consist of dolomites or dolomitic limestones, that closely overlap the Werfen Formation. Its maximum estimated thickness is about 500 m.

The entire outcropping sequence has a 278° average direction and a dip of about 45° south (Fig. 2), nearly constant throughout the area.

A structural survey has been carried out in order to identify faults and possible structures (fractures, joints, cavities) that can act as preferential pathways in terms of groundwater circulation. The field observations and the published data (Ponton and Venturini, 2002; Carulli, 2006) allowed us to identify a new sub vertical fault approximately oriented NW-SE, having a slight transcurrent right component. Fig. 2 shows the location of this lineament (red line) identified on the basis of discontinuous elements such as: cataclastic layers, fractured zones and geo-morphological steps.

The geological and structural evidence shows that the main sulphureous spring of Bagni di Lusnizza spills out near the contact between the Bellerophon Formation and the Werfen Formation.

The massive black Bellerophon limestones likely constitute the low permeability barrier confining the deep sulphureous aquifer, characterized by anoxic conditions as reflected by the occurrence of dissolved H_2S, from the upper Werfen mixed waters aquifer. The still open question is about how and where the mineralized water passes from the source reservoir in the Bellerophon evaporitic units (below the Bellerophon limestones) to the upper reservoir in the cataclastic Werfen limestones. This could happen at the crossing between the lithologic transition (Bellerophon-Werfen) and the hypothesized fault with a NW-SE direction or other conjugated system.

Geochemical measurements made in November 2009 show that the waters of the Rio dello Solfo have reducing characteristics (mixing of bicarbonate waters and sulphureous anoxic waters) also upstream of the main spring, suggesting that the ascent can occur through several joints where the hypothesized fault or other eventual local fractures connected the deep aquifer with shallow fractured units.

The sulphureous water of the main spring (and of the others in the nearby valleys) is classified, on the basis of the major ion chemistry, as belonging to the Ca–Mg–SO_4 hydro-chemical facies, with concentrations exceeding 1000 mg/l of SO_4^{2-} and above 400 mg/l of Ca^{2+}. At the spring outflow, the electrical conductivity ranges between 1800 and 2100 μS/cm and temperature is around 9-10°C.

The field geology and the available geochemical data, allow to formulate a preliminary hydro-geological conceptual model of the circulation of sulphureous waters of Bagni di Lusnizza, schematically illustrated in Fig. 3 (the section across the study area has an approximate N-S direction), that needs to be validate by means of integrated geophysical and geochemical data.

Note from Fig. 3 that there are two different emergences spatially closely related, one draining an unconfined, shallow Ca-bicarbonate reservoir and the other having sulphureous

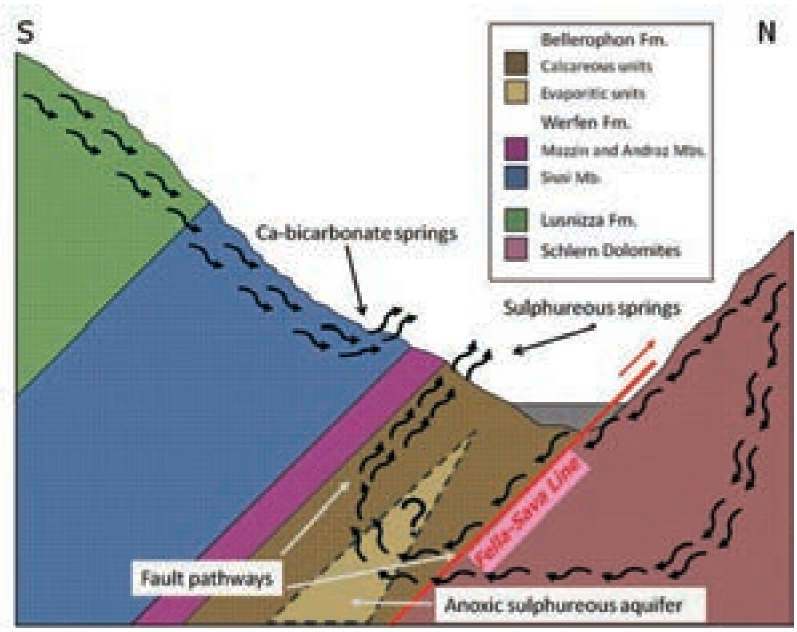

Fig. 3 - 2D cartoon of the conceptualized hydro-geologic circulation along a N-S section passing through the Rio dello Solfo. The fault system, N-S oriented as in Fig. 2, likely connects the deep sulphureous aquifer in the Bellerophon evaporates with the upper Bellerophon-Werfen cataclastic contact.

characteristics. These two aquifers are not connected and should be recharged through different hydrological pathways. We hypothesize that the hydro-geologic circulation recharging the confined deep sulphureous aquifer is fairly long and very slow: waters of meteoric origin, as revealed by oxygen and hydrogen stable isotopes, infiltrate through the Schlern Dolomites, reach the evaporitic units (400-600 m deep), cross the Bellerophon low permeability Formation through fault pathways and reach the upper Bellerophon-Werfen fractured layers from which outflow into the debris deposits of the valley.

3. Geophysical survey: data acquisition and processing

The geophysical survey was designed on the basis of the geological and geochemical results to reach the following main objectives:

1 - define the geometry and heterogeneity of the debris deposits (basement topography);

2 - map the sulphureous water saturation in the debris filling;

3 - identify the main structures and electric properties of the rock basement;

4 - identify the upward pathways of rising waters through the bedrock.

To reach these objectives we first tested the ERT acquisition near the main sulphureous spring, to compare the resistivity values with the geochemical surface information, and then we tested the FDEM to map the surface conductivity over the area of interest.

Given the good results of the electrical response, we acquired longer ERT lines to achieve a deeper penetration and possibly identify the rising sulphureous water. Two VLF lines were also acquired to verify the presence of vertical conductivity contrasts and to integrate the results of the deep ERT investigations.

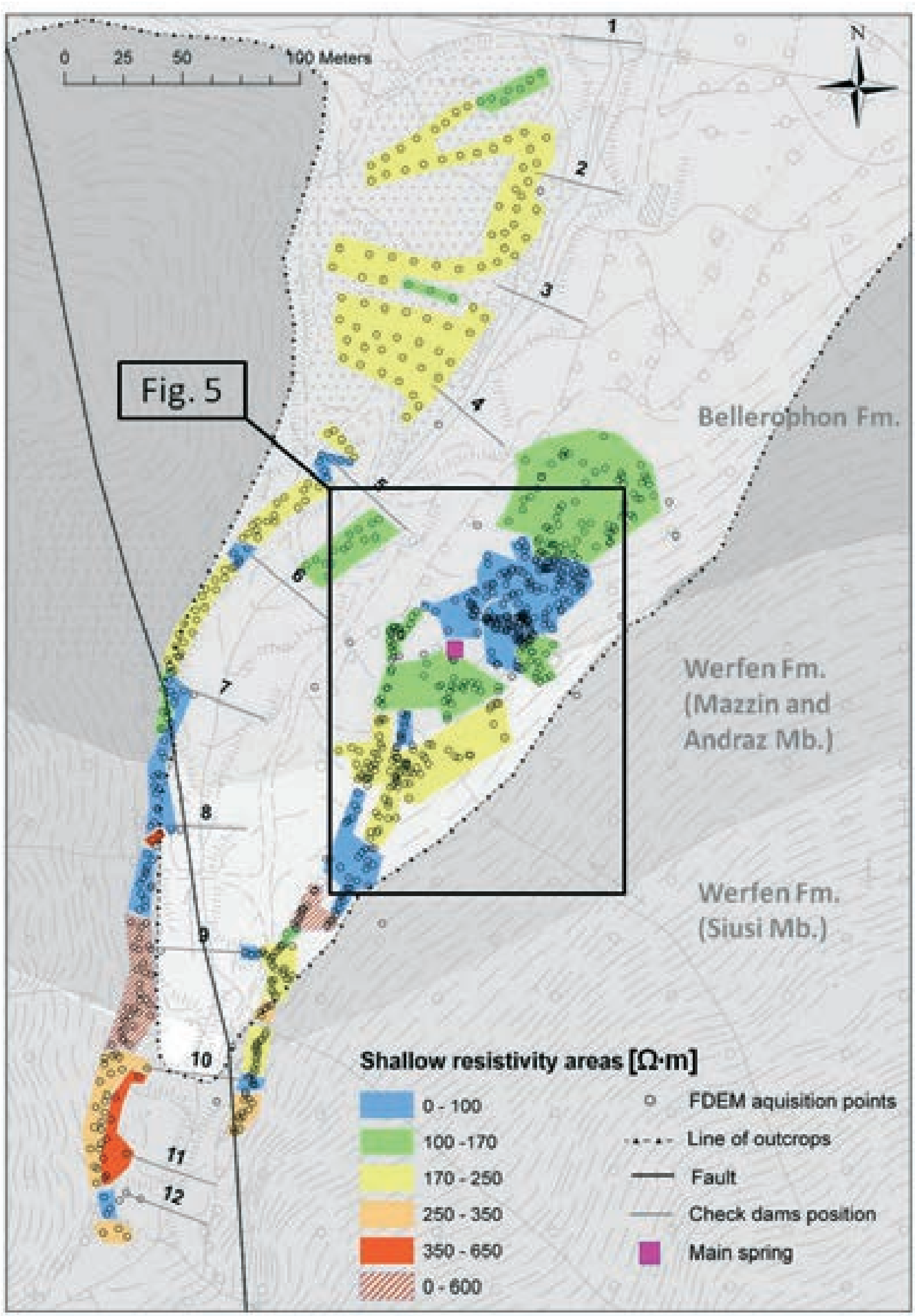

Fig. 4 - Distribution map of the shallow single station data from the electromagnetic survey (FDEM) with 3 m and 6 m (maximum penetration depth) probes, overlapping the geology map, as in Fig. 2.

The MALM method was carried out at the end to evaluate whether the method could be used to define the dip of the rising conductive bodies.

Geographic positioning was done by means of GPS differential receivers, where possible, and integrated by traditional topographic survey.

3.1. FDEM

The FDEM method, used to map the superficial electrical conductivity, is based on the electromagnetic induction principle. The EM transmitting antenna generates a harmonic electromagnetic field in the ten of kHz frequency range, which propagates beneath the surface activating a secondary field modulated by the characteristics of subsurface resistivity, which is recorded by the receiving antenna. The intensity of the recorded secondary field is related to the electric conductivity of the shallow terrains (Telford *et al*., 1990). In order to map the electrical conductivity distribution in the upper 3-6 m of debris deposits we used FDEM over the accessible parts of the area of interest, mainly to identify the areas interested by the presence of sulphureous waters. Data acquisition was performing using two CMD electromagnetic conductivity probes of the GF Instruments, Brno (CZ):

- CMD-2: 10 kHz frequency, antennas distance 1.89 m, maximum depth of investigation 1.5 to 3 m;
- CMD-4: 10 kHz frequency, antennas distance 3.77 m, maximum depth of investigation 3 m to 6 m.

On the left bank of the creek (to the west), the FDEM data were acquired with the CMD-4 probe because of the open space available, whereas on the eastern side we had to use the CMD-2 probe, because of the logistical constraint caused by the woods.

The FDEM instrument was used in combination with a Trimble GPS receiver, working in differential positioning. The converted coordinates were then plotted in ArcGIS on the Regional Technical Map (Fig. 4) as resistivity values to be directly comparable with the ERT results. The resistivity values were grouped in areas with different ranges of electrical resistivity as shown in Fig. 4.

3.2. ERT

ERT is an active geoelectrical prospecting technique used to obtain 2D and 3D high-resolution images of the electrical resistivity distribution for underground characterization (Griffiths and Barker, 1993; Loke and Barker, 1996; Daily *et al*., 2005). The measurements of the electrical potential at the surface depend on the geometry and the characteristics of the four electrode measuring array and on the subsurface distributions of electrical resistivities. The electrical tomography requires the deployment of a large number of electrodes to achieve both penetration and resolution. The electrodes are connected to an electronic switching unit which selects automatically the pairs of current and potential electrodes for each measurement along a fixed profile, using various configurations [Wenner-Schlumberger (W-S), dipole-dipole (D-D), etc.] in order to better highlight the different target at depth. In this way, it is possible to reconstruct the lateral and vertical variations of apparent resistivity.

To evaluate the shallow response of electrical resistivity tomography we used an IRIS Syscal-Pro Switch 72 channels georesistivimeter. Around the main spring, we planned the acquisition of five lines (named BL5, BL6, BL7, BL8 and BL9), with 48 channels and electrode spacing of

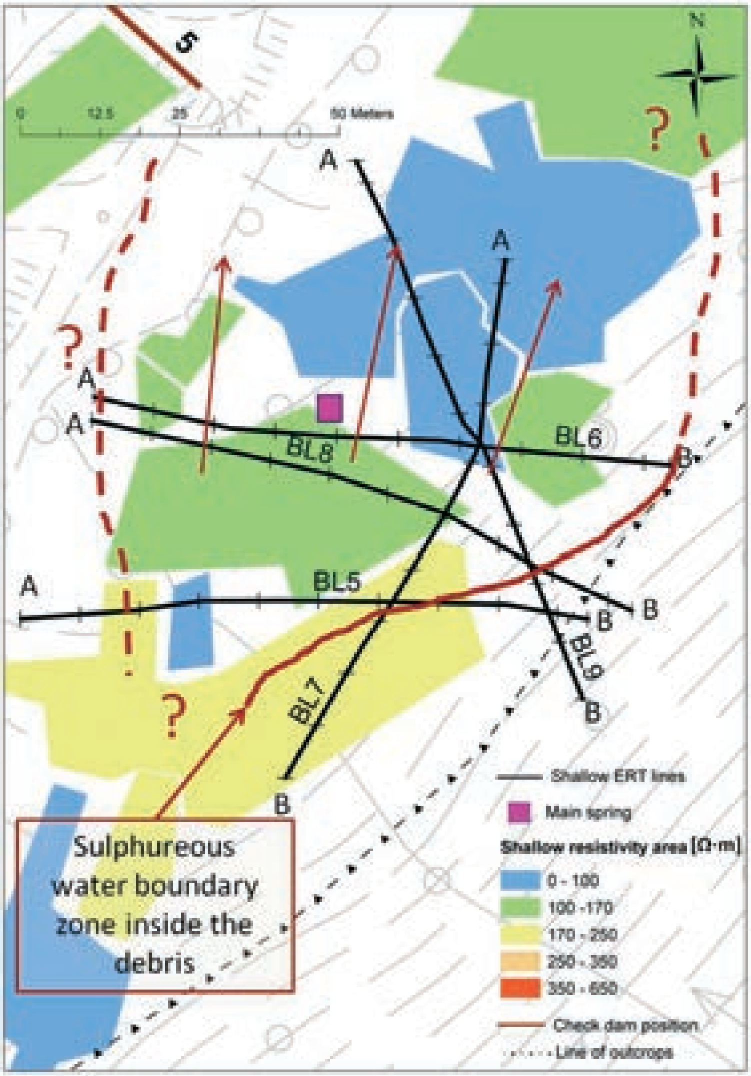

Fig. 5 - Location map of the shallow ERT profiles (2 m spacing) in the main spring area. The resistivity areas from FDEM survey are also shown (Fig. 4), superimposed on the technical map.

2 m (penetration depth of about 20 m). The lines are located as shown in Fig. 5. The topography of the area and the presence of woods did not always allow us to carry out linear profiles.

The following configuration parameters and settings were selected:

- quality factor: 5% (standard deviation percentage);
- stack min-max: 3-6 (minimum and maximum number of stacks for each quadrupole measurement);
- current injection time: 500 ms;
- maximum potential to the electrodes of transmission: 800 V;
- minimum potential to the electrodes of receipt: 20 mV.

In order to extend the ERT survey outside the main spring area and to a greater depth, we acquired three longer ERT profiles. Two of them (BL-West and BL-East) are 355 m long (5 m spacing between electrodes) and were acquired in roll-along mode (12 channels overlap). They run almost parallel to the creek banks, one on each side (Fig. 7). The third line (BL10) is 710 m long (10 m spacing).

All profiles with 2 and 5 m electrode spacing were acquired using both W-S and D-D configurations to obtain a more accurate model (Loke, 1999; Hauck and Vonder Mühll, 2003; Friedel *et al*., 2006). The BL10 ERT profile was acquired using a W-S configuration only, because it is too long to give good results with the D-D array in skip 0 configuration (i.e., with 10 m dipole length) due to the small signal to noise ratio.

Direct and reciprocal measurements were taken for each quadrupole, in order to study the error associated to each measurements (Daily *et al*., 2005). The quality control of the ERT measurements is particularly important when morphology, topography and physical proprieties of the terrain are heterogeneous and complex, as in this study area.

All the ERT lines were analyzed for the error distribution, including the integration of the two distinct configuration acquired (D-D and W-S) to improve the resolution and the stability of the model (Friedel, 2003). The pre-processed resistance data were inverted through the free code Profiler 2.5 (A. Binley - Lancaster University). The inverse solution is obtained using an Occam approach (e.g., LaBrecque *et al*., 1996) and is based on a regularised objective function, combined with weighted least squares, as in Binley and Kemna (2005).

3.3. VLF-EM

VLF is a passive frequency domain method which uses electromagnetic waves from powerful military transmitters operating in the low frequency band (10-25 kHz) of the EM spectrum to map strong lateral electrical conductivity changes between buried bodies (Telford *et al*., 1990; Benson *et al*., 1997; Shivaji and Gnaneshwar, 1999). The VLF-EM receiver, used in the field, can measure in-phase and in-quadrature components of the secondary electromagnetic field generated by the lateral conductivity variations in the underground rocks.

VLF single station measurements were collected with the Wadi system receiver (manufactured by ABEM) along BL-West and BL-East ERT profiles (Fig. 7). The Wadi recording unit has been tested for the reception of clear VLF signals. Three different frequencies were received to conduct VLF-EM survey in the Rio dello Solfo valley on August 31 and September 1, 2010: 16.4 kHz (Helgeland – Norway), 19.6 kHz (Rugby – England) and 23.3 kHz (unknown). The survey was carried out using all three frequencies available to validate the results by comparing the different measurements. Raw data were filtered using a Fraser (1969) filter, which emphasized the first derivative of the signal related to the largest lateral variations in electrical conductivity of rocks. The quality of western line was good, whereas the eastern line had problems during acquisition (bad signal reception).

3.4. MALM

The MALM method is an electrical prospecting technique used to map the lateral extension of the conductive zone at depth, when a conductive mineralized zone has been already identified at the surface (Manshina and Mwenifumbo, 1983), and also to qualitatively infer the dip of the conductive layer at depth, assuming, as a first approximation, that the mineralized layer has a constant thickness and that its lateral extension is larger than the survey area.

The method uses an active current dipole, with one electrode within the conductive body at the surface and the other electrode placed at a large distance away. The potential dipole has one reference electrode at large distance and the other roaming the investigation area. If the electrical

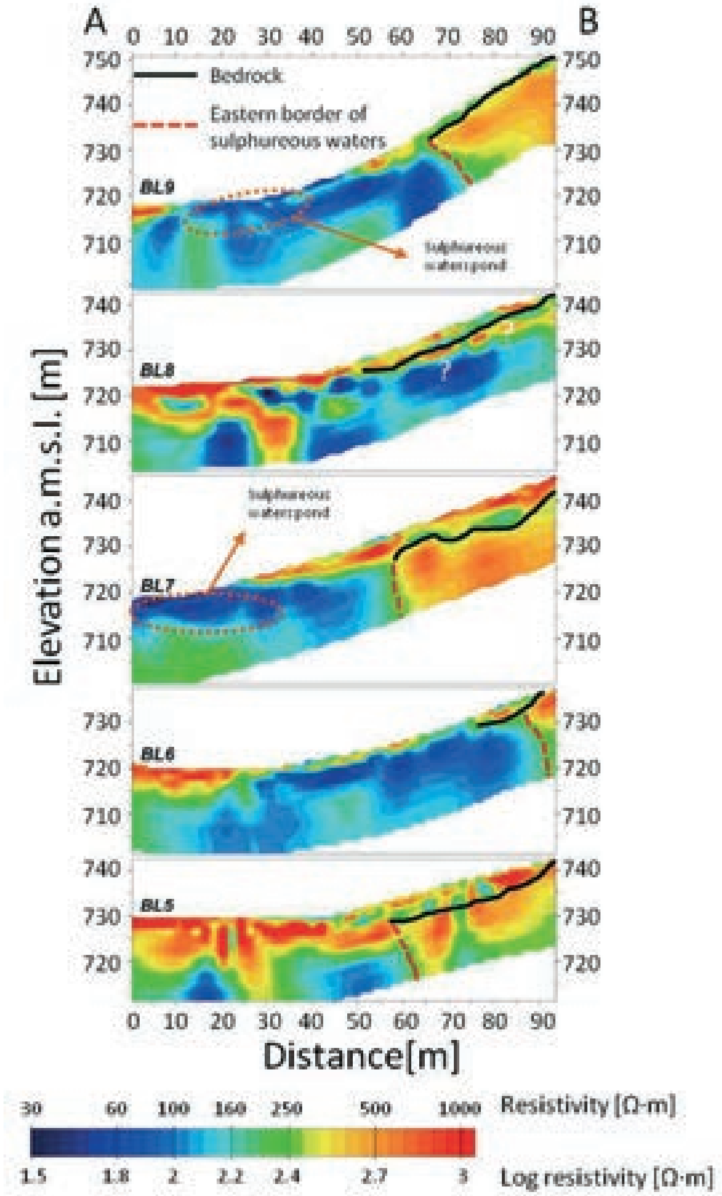

Fig. 6 - 2D sections from the shallow ERT survey results near the main sulphureous spring. See Fig. 5 for positioning. Near vertical dashed red lines indicate the eastern extension of the sulphureous waters. The possible bedrock location is suggested on the eastern flank of the valley.

resistivity of the anomalous body is very low (less than about hundred Ohm·m), there will be relatively little potential drop across the body itself and the conductive body can be presumably mapped at the surface of the Earth, as a zone of low potential (Beasely and Ward, 1986).

We tested MALM data acquisition using a Syscal-Pro Switch 72 channels, along the BL10 ERT profile putting one current electrode into the sulphureous spring and the other at infinity.

The results are presented as electric potentials compensated for current (Jamtlid *et al*., 1984; Eloranta, 1985; Beasley and Ward, 1986) and plotted on the geo-referenced map in Fig. 11.

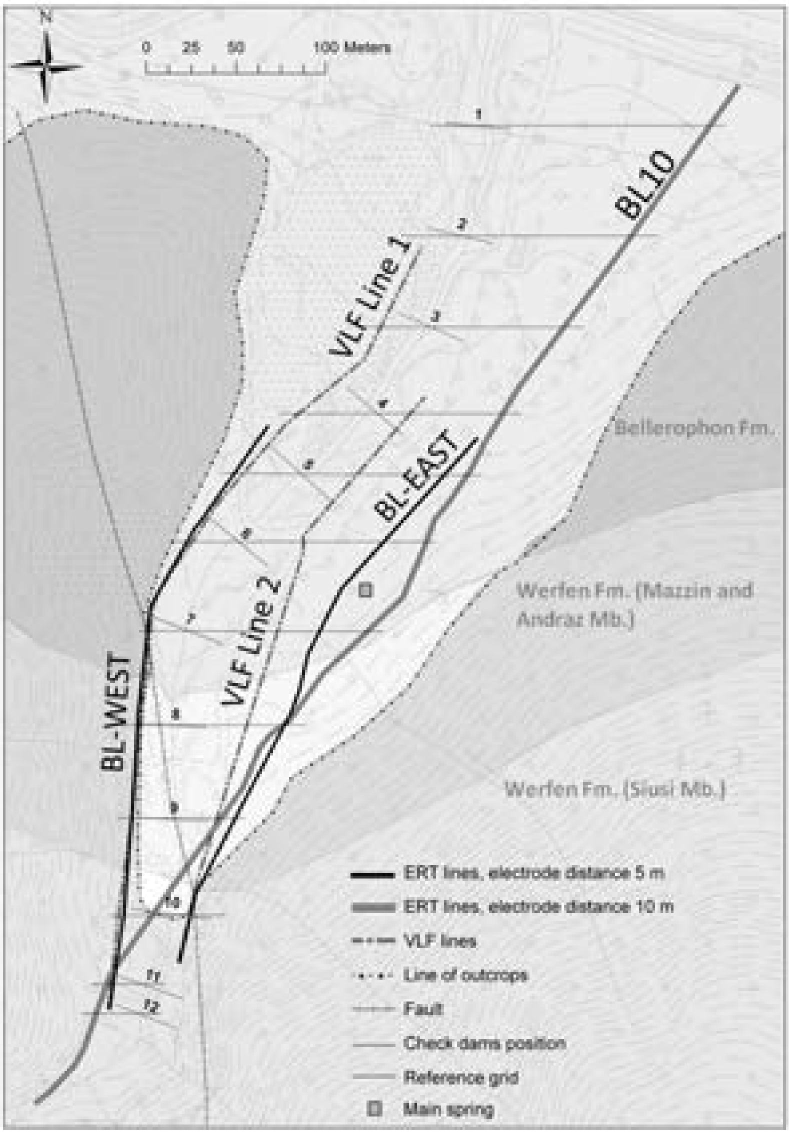

Fig. 7 - Location map of the deep ERT profiles BL-East, BL-West, BL10, and of the 2 VLF lines. The main spring and the reference grid passing through the check dams are also shown on top of the field geology.

4. Results

The geophysical characterization of the Bagni di Lusnizza area was conducted in two sequential phases, corresponding to shallow and deep imaging respectively. The shallow survey was first acquired to characterize the upper 10 m of debris deposits and outcropping rocks and to calibrate the indirect geophysical data with the geochemical measurements and geological information. The deep imaging was carried out to characterize the entire filling of the valley and possibly the buried bedrock. As expected, the electrical resistivity distribution was particularly sensitive to the presence of sulphureous waters, indicating circulation pathways and mixing zones.

4.1. Imaging of shallow structures

The FDEM survey provided a first map of the shallow electrical conductivity in the area of interest and was useful to integrate the geochemical, hydro-geological and geoelectrical results.

The higher values of electrical conductivity are concentrated in line at the main spring and in the surrounding depression saturated with sulphureous waters which extend to the NE for about 60 m (Fig. 4). These results could provide quantitative information on pore water characteristics if we use Archie's (1942) relation for a formation 100% saturated with water and with no appreciable amount of clay:

$$\rho_0 = \frac{a}{\Phi^m}\rho_w \qquad (1)$$

where: ρ_0 is the resistivity of the rock aggregate, Φ is porosity, ρ_w the resistivity of the saturating water, m is the empirical cementation factor and a is the tortuosity factor. With no specific knowledge of m and a, which could only be estimated through careful laboratory tests, it is only possible to speculate on the variability range of the electrical resistivity of sulphureous waters and on the average porosity of the aggregate. We calculated two ranges of resistivity related at the presence of sulphureous waters (ρ_w =6 Ohm·m at the spring) for:

- clean debris: $10 < \rho_0 < 65$ Ohm·m (using: $0.2 < \Phi < 0.35$, $0.4 < a < 0.6$ and $1.2 < m < 1.6$);
- carbonate rocks: $85 < \rho_0 < 4000$ Ohm·m (using: $\Phi < 0.2$, $0.8 < a < 1$ and $1.8 < m < 2.2$).

Since the spring of sulphureous water outflows from the debris deposit and since the resistivity values from ERT and FDEM in this area are lower than 100 Ohm·m, we can therefore relate those low resistivity values to a strong presence of sulphureous waters (blue polygons in Fig. 4). Also the FDEM results show resistivity values lower than 100 Ohm·m between the seventh and ninth check dams, on both sides of the creek. Other spot blue areas are close to the check dam shoulders, but they can possibly be linked to the high conductivity of the reinforced concrete foundations.

The resistivity values are higher than 650 Ohm·m between the check dams 9 and 12. These are likely associated with the presence of rock outcrops. Elsewhere in the region of interest, FDEM data show intermediate values (green polygons in Fig. 4) that may be associated to the presence of mixed waters zones (meteoric waters mixed with sulphureous waters).

To extend the shallow electromagnetic information to depths exceeding 6 m and to define lateral boundaries of the rising sulphureous waters near the main spring area, we integrated FDEM with 5 ERT lines, 94 m long (depths of about 20 m), investigating the historical site of the sulphureous springs as shown in Fig. 5.

The results of the inversion show areas with very different resistivity values, from 40 to about 1500 Ohm·m (Fig. 6). The presence of sulphureous waters in the upper 20 m is well imaged in all the ERT line and it is quite distributed across the area. Mineralized waters are both within the debris deposits (mainly to the NW of the main spring) and within the bedrock underneath. From these ERT images, it is not possible to recognize everywhere the rock basement, because of limited extension and penetration of the surveys. The basement interpretation is proposed on the eastern and south-eastern sides of the valley, where field geology and outcrops help the reconstruction. Moreover, it seems that there are no shallow rising pathways of sulphureous waters on the eastern side of the valley (see Fig. 5). This is clearly visible on BL5, BL6, BL7 and BL9 ERT lines (dashed red line in Fig. 6, bounding the conductive plume). The best image of the sulphureous water rising plume is recognizable on line BL6 at 40 m from the A end. The values of resistivity next to the main spring are well below 100 Ohm·m, because there is a negligible mixing with Ca-bicarbonate waters. The mineralized water feeding the main spring does not rise vertical from beneath, but rather it seems to flow down-hill within the debris overlying the bedrocks from some 50-80 m distance (see BL5 at 50 m from A end on Fig. 6 and its positioning in Fig. 5).

The combined interpretation of ERT and FDEM shows as they are consistent and complementary. The blue area on the FDEM map (Fig. 5) is crossed by ERT lines BL7 and BL9, whereas BL6 is on the border. These lines confirm the presence of resistivity values lower than 100 Ohm·m down to 15-20 m, similar to those observed at the surface.

BL8 and BL5 lines are to the south of the more conductive area, in fact they show higher resistivity values at the surface.

To understand where sulphureous waters outflow from the bedrock it was necessary to increase the depth of investigation widening the electrode spacing.

4.2. Imaging of deep structures

To characterize the deep structures of the area, we integrated the entire geophysical data set (FDEM, ERT, MALM, VLF) with the geology and geochemical data. The shallow ERT profiles provide the resistivity of both the outcropping bedrock and of the saturated debris with either: fresh water (ρ_w = 20 Ohm·m), or a mixing of fresh and sulphureous or the sulphureous water end-member (ρ_w = 6 Ohm·m).

The deeper investigation was conducted using the two 355 m long ERT lines located as shown in Fig. 7. The investigation depth increased to about 50 m depth, showing the continuation of high resistivity contrast to the depth (Fig. 8).

BL-West line is positioned (Fig. 7) on the western unsatured embankment, at 6 m above the Rio dello Solfo level. This justifies the presence of the high resistivity values at the surface (Fig. 8).

On both BL-West and BL-East, the resistivity values lower than 100 Ohm·m were associated with the presence of sulphureous water (from check dam 5 to check dam 9). The bedrock topography is not easy to reconstruct because the signal of the conductive sulphureous waters almost completely overprints the transition between saturated debris and rock basement. It is tentatively inferred in Fig. 8 also on the basis of the geology and morphology of the valley. The lateral resistivity changes in the basement rock resistivity distribution are associated to fractured or more compacted rock.

Nonetheless, in correspondence of check dams 5 to 9 in the BL-West, it is possible to recognize at 40-50 m depth the presence of the mineralized water rising from below.

In the BL-East line the presence of sulphureous water appears from check dam 9 to the northern end of the line and it reaches the surface at check dam 6, in correspondence with the main spring.

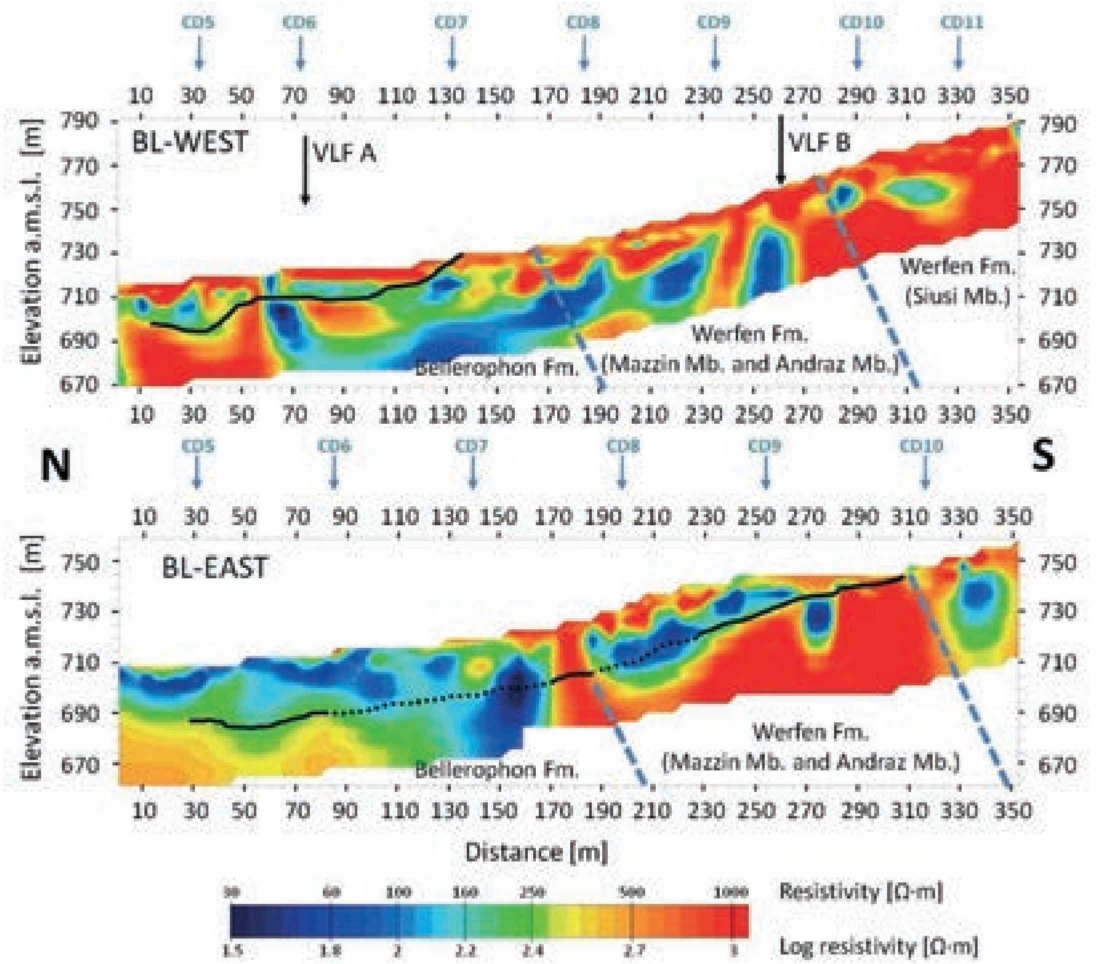

Fig. 8 - BL-West and BL-East ERT images crossing the Rio dello Solfo valley (see Fig. 7 for location). The bedrock topography is suggested (black lines), together with the inferred geology layering of the Permo-Triassic formations.

Comparing the results of the shallow ERT investigation with the deep ERT survey, we can interpret the high resistivity values (more than 400 Ohm·m) as representative of low porosity rock, whereas from check dam 9 downstream to the north, the outflow of sulphureous waters in the debris cover (< 100 Ohm·m) and its mixing with the shallow groundwater causes significant resistivity changes in the subsoil ($100 < \rho < 400$ Ohm·m).

To assess the results of BL-East and BL-West ERT lines we also acquired VLF measurements, along the same direction (located as shown in Fig. 8), at three different frequencies (16.4 Hz, 19.6 Hz and 23.3 Hz). The results are shown in Fig. 10. The positive values indicate the presence of conductive bodies. The VLF line 1 (West line), in all the range of frequency acquired, compared with the corresponding ERT line, confirms the presence of significant conductive bodies, called A, B in Fig. 10. There are also positive value with lower amplitude from 220 m to 330 m and at 150 m that confirm the presence of conductive bodies but not as deep as the others. The results

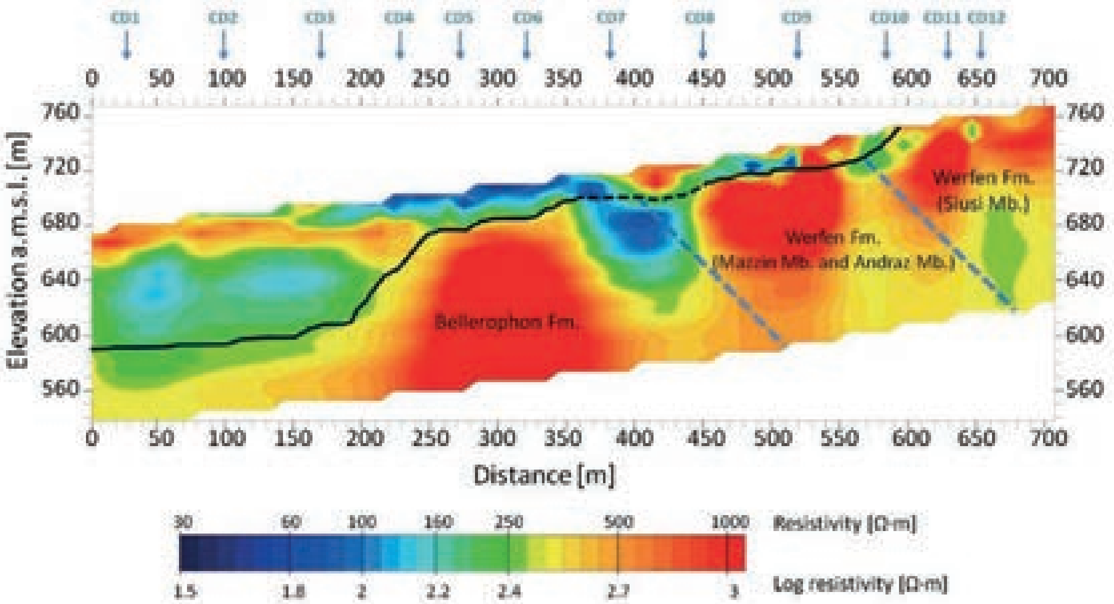

Fig. 9 - Results of the BL10 ERT survey crossing the entire Rio dello Solfo valley (see Fig. 7 for location). The bedrock topography is suggested (black lines), together with the gross geology layering of the Permo-Triassic formation.

from these two profiles suggest that the ingression of sulphureous waters into the debris wedge occurs in the area immediately to the south of the springs between check dam 5 and check dam 9. It is however still unclear whether the input comes from diffuse fracturing in the upper portion of the Bellerophon carbonates or it is mainly related to a specific fault zone.

In order to reconstruct geometry and physical proprieties of the deep sulphureous ascent through the basement, feeding the mineralized aquifer in the debris deposits (extending about 200 m in N-S direction),we acquired a further ERT line (BL10, positioned as in Fig. 8, close to BL-West), 710 m long, for an expected maximum penetration depth of 160 m.

The interpretation of the results of this line (Fig. 9), integrated and calibrated with the other lines, defines:

- the presence of sulphureous water as deep as 100 m, between check dams 7 and 8;
- the presence of mineralized water in the first 40 m of subsoil from check dam 3 to check dam 7;
- the shallow or outcropping bedrock with high resistivity, approximately matching the expected geological sequence.

Along BL10 we also acquired MALM data with the aim to check if the method can be useful to understand the dip of the fractures system carrying sulphureous water. The electric potential data were acquired along the BL10 ERT line and near the main spring area (Fig. 11). The results show that the highest values (blue in the map) represent the more superficial presence of conductive bodies, localized in the area of the spring of sulphureous water. It is reasonable that

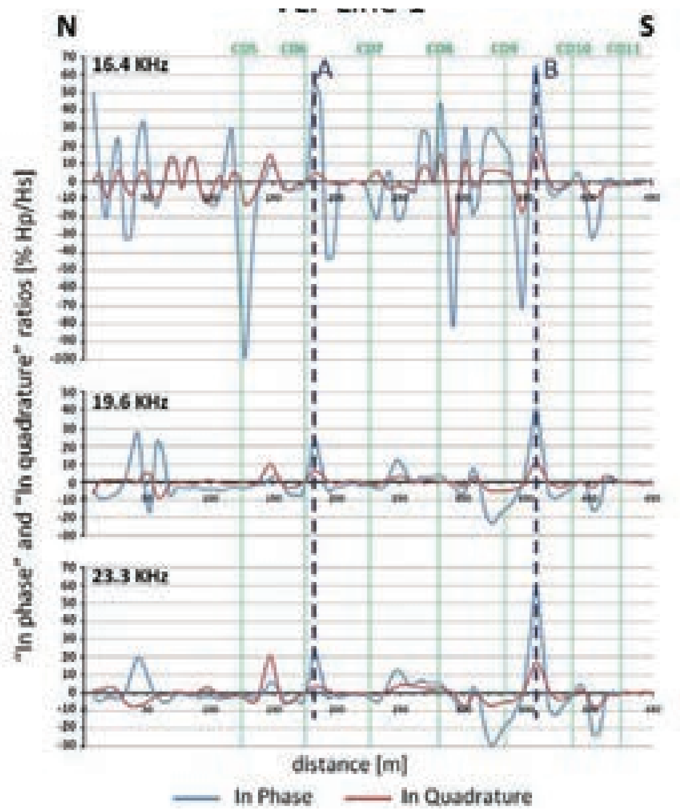

Fig. 10 - Filtered VLF data (Fraser filter) acquired on the western flank of the valley Line 1 (see Fig. 7 for location). Main electrical conductivity contrast are also shown (A, B anomalies).

lower MALM potential values (red dots in Fig. 11) indicate much deeper the sulphureous water. The trend of the normalized potential along the BL10 profile was also plotted (Fig. 11, inset). The near symmetrical shape of the MALM anomaly suggests that the electrically conductive body (the uprising sulphureous water) is not far from the vertical. However, a lack of symmetry away from the peak could indicate a correlation with the dip of the south of the Bellerophon-Werfen contact or an extra-contribution of the conductor body in the basement, highlighting in grey (Fig. 11).

5. Conclusions

This paper is an attempt to characterize the shallow sulphureous aquifer resource in Bagni di Lusnizza and some of the water rising pathways, in a complex and heterogeneous area, using the integration of geophysical methods with field geological and geochemical information.

The principal results attained with the used methods are:

a) identification of the mineralized water saturation zones and the heterogeneity of the debris deposits using FDEM, ERT (2 m spacing), geochemical and field geology information;
b) structure and morphology of the bedrock via large scale ERT (5 and 10 m spacing) and VLF;

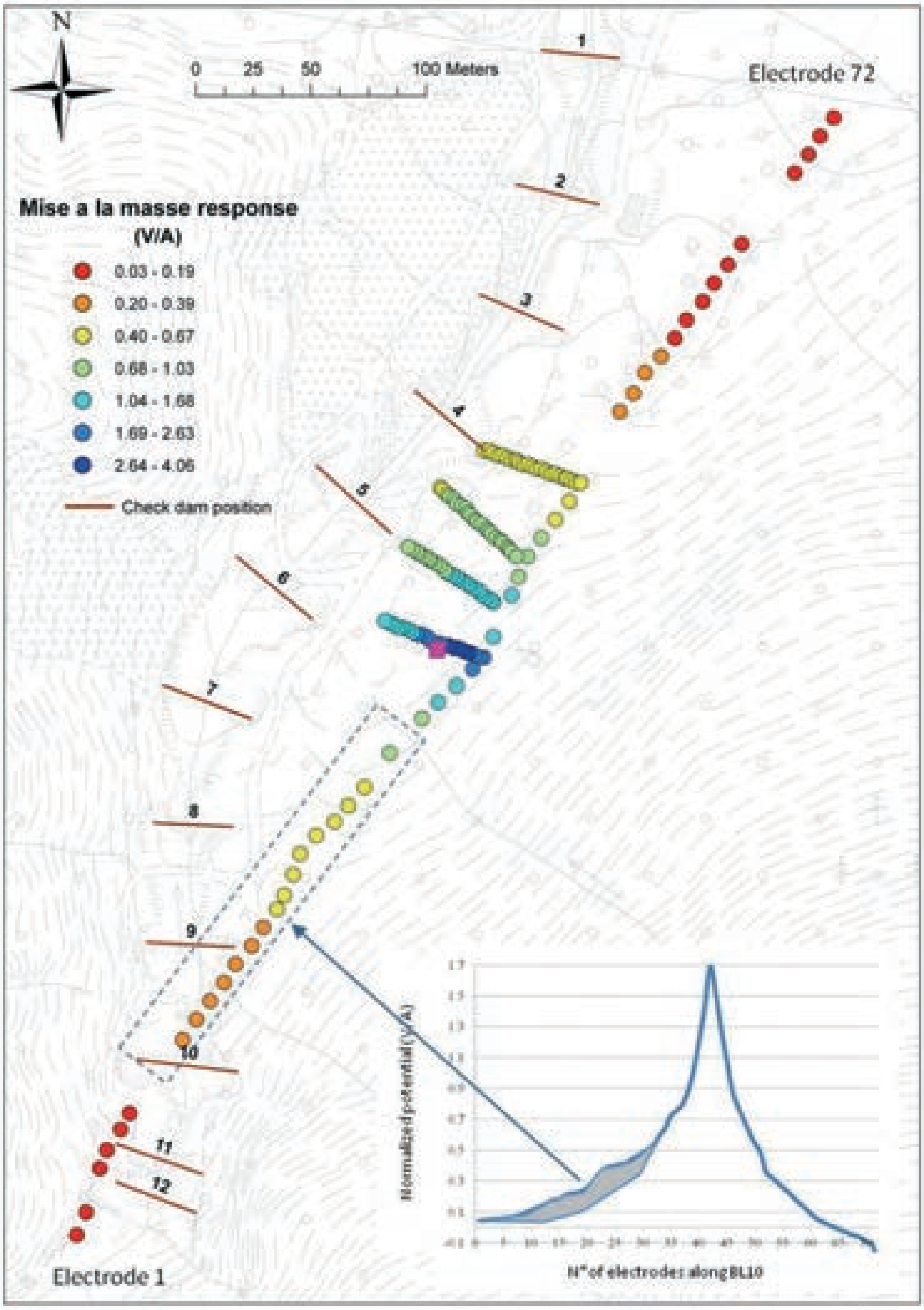

Fig. 11 - Positioning map of MALM electric potential data acquired along the BL10 ERT line and near the main spring area. The normalized potential measurements are colour-coded according to the scale indicated. The inset map shows the trend of the normalized potential along the BL10 profile. In grey the location of the conductive zone in the bedrock from BL10 (Fig. 9).

c) recognition of potential fracture zones and faults through which the sulphureous water rise (all methods).

In particular, the distribution of mineralized water in the debris deposits was determined by:

1. mapping the electromagnetic response with FDEM of the area of interest (Fig. 4), that shows the zones with high concentration of sulphureous water (from check dams 7 to 9 and 5 to 6) and marginally the outcropping bedrock;
2. correlating the ERT results with the geochemical superficial information in the ERT profiles (2 m spacing) and showing a clear resistivity contrast due to the presence of mineralized water (<100 Ohm·m);
3. interpreting all ERT images together with the field geology information and tracing a boundary of the sulphureous water and the bedrock limit.

The deep ERT investigations, integrated with surface geology, allowed us to reconstruct the bedrock topography of the area: the depth to the basement to the south does not exceed 20-30 m, whereas in the lower part to the valley this interface reaches a depth of the order of 80 m. Between check dams 3 and 4 the bedrock shows a steep change in slope from 670 to 600 m a.m.s.l.. On average the bedrock exhibits high resistivity (> 800 Ohm·m) excluding the contact area Bellerophon-Werfen through which the sulphureous water comes up. The strike and dip of the bedrock formation could be approximately recognized in the BL10 ERT section (Fig. 9).

The interpretation of BL10 ERT profile highlights the major upward pathway of the sulphureous waters, in correspondence from check dams 7 and 8, more than 150 m depth, passing through the Bellerophon-Werfen Formation contact, and reaching the surface in correspondence with check dam 6 (in the main spring area). The crossing between the NNW-SSE trending fault and the highly fractured contact at Bellerophon-Werfen boundary likely produces a lateral spreading of the uprising sulphureous waters within the bedrock formations.

As a result of the geophysical investigations, the initial hydro-geological conceptual model, shown in Fig. 3, was largely confirmed.

The principal limitation of this study is related to the complex morphology, difficult logistics and the presence of forest that prevents a good positioning of the profiles, thus making it difficult to produce linear profiles, limiting their length and therefore their penetration depth (particularly for ERT). In such conditions the use of seismic methods, Time Domain Electromagnetic and Magnetotelluric would be equally or even more problematic.

The ERT data, integrated and supported with other geophysical methods (FDEM, VLF and MALM) are nevertheless adequate to produce useful information for the problem at hand, given the limited geological and geochemical information available. Since there are no boreholes available to calibrate the ERT response, we used different spatial scale for the survey, starting from the near surface structures and continuing to the depth reached with BL10 (over 100 m). The measurements of electrical conductivity of emerging sulphureous waters and the resistivity of the shallow saturated aquifer around the spring allowed us to assess qualitatively the possible mixing between mineralized waters and fresh groundwater.

In order to locate one or more new boreholes intercepting the rising sulphureous waters, it will be advisable to acquire new ERT lines to evaluate the 3D lateral extension of the bodies. Furthermore we suggest to extend or complete MALM method to evaluate the dip of the fractured bedrock feeding the sulphureous spring.

Acknowledgements. We acknowledge U. Aviani and R. Petrini (Dipartmento di Geoscienze, Università di Trieste, Italy) for the support in field geology and geochemical measurements and for fruitful discussion. Logistic support by G. Meton and G. Brancatelli (Dipartimento di Ingegneria Civile ed Architettura, Università di Trieste, Italy) is also gratefully acknowledged. We would like to thank prof. Andrew Binley (University of Lancaster, U.K.) for his kind support.

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