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ORIGINAL ARTICLE

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Magnetic and ground probing radar measurements for soil pollution mapping in the industrial area of Val Basento (Basilicata Region, Southern Italy): a case study

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Abstract The joint application of electromagnetic techniques for near-surface exploration is a useful tool for soil pollution monitoring and can also contribute towards describing the spatial distribution of pollutants. The results of a geophysical field survey that was carried out for characterizing the heavy metal and waste disposal soil pollution phenomena in the industrial area of Val Basento (Basilicata region, Southern Italy) are presented here. First, topsoil magnetic susceptibility measurements have been carried out for defining the spatial distribution of superficial pollution phenomena in the investigated area. Second, detailed and integrated measurements based on a high-resolution magnetic mapping and ground probing radar (GPR) profiling have been applied to investigate the subsurface in two industrial areas located in more polluted sites that were identified during the first phase. Our monitoring strategy discloses the way to rapidly define the zone characterized by high pollution levels deriving from chemical industries and traffic emissions and to obtain the way information about the presence of local buried sources of contamination.

Keywords Soil Pollution · Magnetic Susceptibility · Magnetometry · Ground probing radar (GPR) · Basilicata Region (Southern Italy)

Introduction

During the last few years, interest in applying geophysical methodologies to environmental monitoring is increasing. The availability of handy and portable acquisition tools allows to carry out detailed and non-invasive field surveys. The development of new advanced tomographic techniques also allows to reconstruct the subsoil main features with a high spatial and temporal resolution, in real-time and in a robust way. Geophysical techniques have been applied to a wide range of different soil investigation fields such as research and definition of buried cavities (Chamberlain et al. 2000; Perrone et al. 2004), characterization of waste deposits (Orlando and Marchesi 2001), and research of buried metallic drums (Marchetti et al. 2002). In addition, the application of different geophysical techniques for characterizing and monitoring areas, interested by soil pollution phenomena, has acquired increasing interest (Hanesch and Scholger 2002; Mathé and Léveque 2003). Geophysical techniques have been applied to hydrocarbon soil pollution monitoring (Reynolds 2002) or to heavy metals monitoring in industrial and urban areas (Hay et al. 1997; Durza 1999; Hoffmann et al. 1999; Kapicka et al.

1999; Kapicka et al. 2000; Lecoanet et al. 2001; Xie et al. 2001).

The most suitable geophysical methodologies for soil and subsoil pollution monitoring seem to be the magnetic method, magnetic susceptibility measurements, and ground probing radar (GPR) profiles. These methods allow to investigate broad areas in a relatively short time-period with a great accuracy: they are rapid, noninvasive, and low in cost; they provide real-time results, which can be very useful to reduce the time intervention in a successive step (Chianese et al. 2004; Bavusi et al. 2004). In particular, magnetic susceptibility techniques allow obtaining information about the presence of magnetic properties in the soil and rock samples, by means of quick and noninvasive surveys (Yang et al. 1997; Bityukova et al. 1999), calculating the rates between induced magnetization and an inducing magnetic field (Schibler et al. 2002). During the last few years, interest in using soil magnetic susceptibility measurements as a proxy method for monitoring areas exposed to heavy metal pollution phenomena is growing (Petrovsky et al. 2000). The magnetic method provides information about the presence of buried objects in the subsoil characterized by high magnetization or high magnetic susceptibility values; this method, in particular, is suitable for identifying buried steel drums that are used for solid waste storage (Schlinger 1990; Marchetti et al. 1998; Marchetti et al. 2002). The GPR method can be used to identify buried objects and provide information about their type and shape. Recently, it has been employed also for solid waste dump monitoring (Orlando and Marchesi, 2001).

In this work a case study is presented, regarding two field surveys that were carried out by means of the joint application of three geophysical methods to study heavy metals and waste disposal soil pollution phenomena in a broad area embracing the industrial areas of Ferrandina and Pisticci (Basilicata Region, Southern Italy). In particular, magnetic susceptibility measurements seem to be a suitable tool for monitoring heavy metals soil pollution, whereas magnetometric measurements and GPR surveys allow highlighting the presence of buried objects. This area was characterized by pollution sources mainly deriving from chemical, metallurgical, and building materials industries. Moreover, the entire investigated area is crossed by the SS Basentana freeway, which presents a non-negligible traffic volume with relative pollution sources.

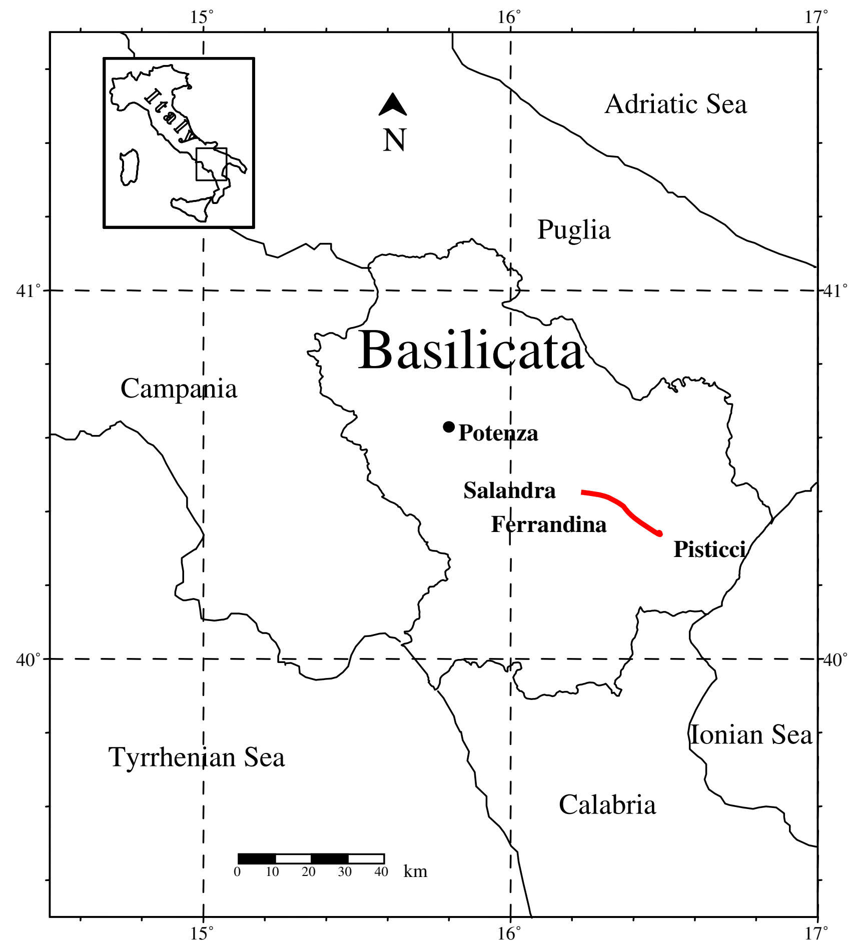

Fig. 1 Map of the Basilicata region with the location of the Val Basento industrial area, from Salandra to Pisticci

The geophysical campaigns have been carried out during March–April 2003 in a broad area of about 37.5 km^2. The field survey has been divided in two different steps: during the first preliminary acquisition phase a magnetic susceptibility measurement along the SS Basentana freeway crossing the entire investigated area was carried out, with the aim of defining the spatial distribution of superficial pollution phenomena. The second field survey was carried out in two industrial areas located in sites highlighted during the first phase as more interesting from an environmental point of view. It was aimed to investigate the soil and subsoil of the investigated areas to give information about the presence of heavy metals or waste disposal.

The investigated area

The Val Basento industrial area covers an area of about 37.5 km^2 (Fig. 1) and the industrial settlements of three different towns: Salandra, Pisticci, and Ferrandina. The investigated zone is an alluvial area crossed by the Basento River and is surrounded by low hills. The highway SS Basentana delimits this area and so the volume of the commercial traffic causes a non-negligible contribution to the total emission rate. From 1958 to 1980, the most important anthropogenic activities characterizing this area were represented by chemical industrial plants for the production of tissues and chemical compounds. In particular, these plants turned out vinyl chloride (CVC and PVC), a highly toxic and noxious substance, and ETERNIT, determining a scattered asbestos contamination and serious effects on the working staff's health. Actually, this area is characterized by the presence of about 300 different industrial activities including many chemical industrial plants for the production of polymeric yarns, synthetic tissues, nylon films, polymeric additives, and PVC bottles. Concerning the metallurgic industries, there is the production of mechanical components, rolled iron and electrical motors. There are other industrial activities related to building materials and leather tanning. The industrial settlements are surrounded by areas in which the main land use is agriculture. Finally, the presence of waste dumps in Val Basento industrial area may produce local soil pollution phenomena. In addition, all the activities in the investigated area (industrial plants, commercial traffic, and agricultural practices) may cause heavy metal soil pollution.

Table 1 Nickel, zinc, lead, copper, and cobalt contents in soils from Ferrandina industrial area

	Ni (mg/kg)	Zn (mg/kg)	Pb (mg/kg)	Cu (mg/kg)	Co (mg/kg)
M	44	51	76	21	29
St. Dev.	8	16	33	6	5
Max	65	183	267	57	43
Min	27	28	45	10	17
N	74	74	74	74	74

M Mean, *St. Dev.* Standard deviation, *Max* Maximum, *Min* Minimum, *N* Number of samples

Soil sampling was carried out in this area. The soil samples were analyzed for a total fraction of five heavy metal contents by means of atomic absorption spectrophotometer: the results are shown in Table 1. From this analysis it can be noted that in the soil samples collected from Ferrandina area, heavy metal concentrations are high; in particular, Co, Pb, and Zn.

Geological settings

From a geologic point of view, the investigated area is located in the Bradanic trough, a Pliocene–Pleistocene foredeep deposits basin which partially lies, with an angular unconformity, onto the front of the southern Apennines and the Apulian foreland (Fig. 2a). The middle-Pleistocene closing deposits of the Bradanic trough are primarily conglomerates and marine sands arranged onto several marine terraces. These are delimited by marine and tectonic escarpments parallel to the coast of the Taranto Gulf and their altitude decreases towards the sea (Bentivenga et al., 2004).

The main rivers of the region, like the Bradano, Basento, and Cavone rivers, with their beds having NW–SE direction, section the marine terraces and the underlying lower and middle–Pleistocene clay and silt (Fig. 2b). The industrial areas of Ferrandina and Pisticci towns are located into the Basento valley and precisely onto the west side stream terraces. These are formed by Holocene alluvial conglomerates and sands with composition that is predominantly siliceous.

Methods

Magnetic susceptibility technique

Magnetic susceptibility measurements have been performed using a Bartington MS2 meter, a field survey loop MS2D with a diameter of 185 mm for surface measurements, and MS2F probe with a diameter of 15 mm for high-resolution surface measurements. The MS2 meter is a portable instrument with sensors for field and laboratory use. The MS2D loop is designed for rapid assessment of the magnetic susceptibility, approximately on the top 180 mm of the land surface. The MS2F probe is a miniature probe for the stratigraphic study of exposed geological and archaeological sections and is also used where difficult surface condi-

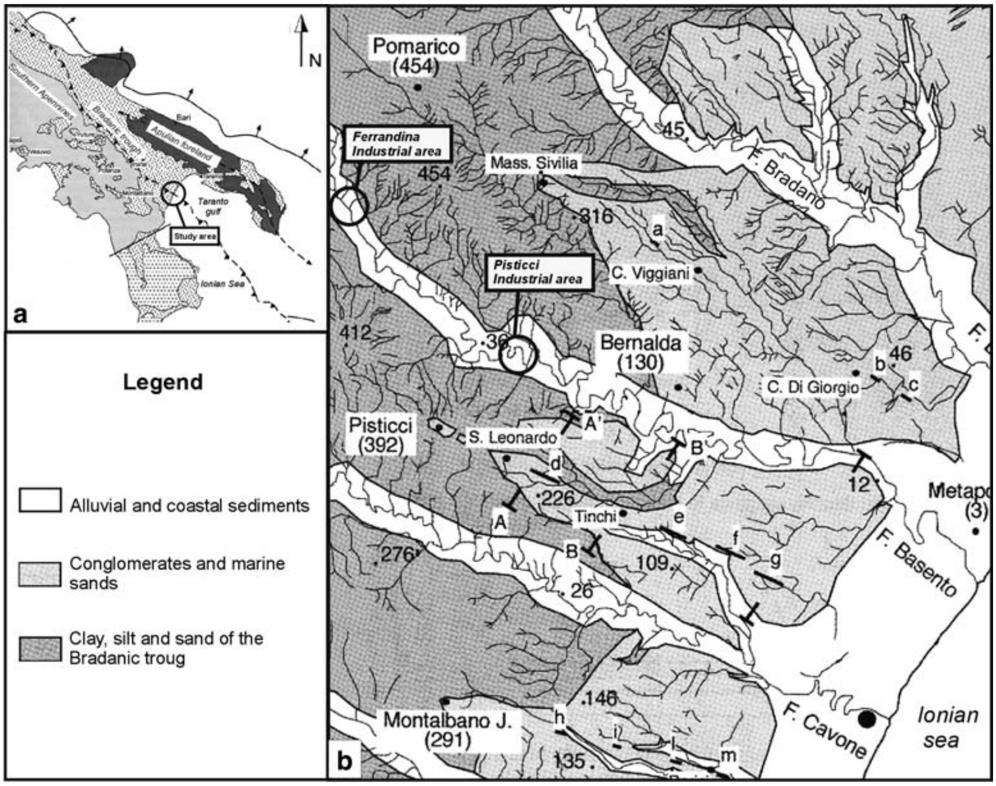

Fig. 2 Geological sketch-map of the Bradanic trough (**a**) and of the study areas (**b**). Bentivenga et al. (2004)

tions prevent good contact with the MS2D loop. This probe records the magnetic susceptibility values of the first few millimeters of the sample surface.

For each sampling point, four independent soil magnetic susceptibility measurements were carried out at the vertices of a square with l = 1 m and the mean value was assumed as the magnetic susceptibility of the sampling point. For each measurement the grass was removed from the soil for better soil contact. Furthermore, the magnetic susceptibility measurements were georeferenced by using a portable GPS, for locating all the measuring points and to set up future field surveys, allowing comparisons between the different measurements detected at every point.

Magnetic mapping

The magnetic survey has been carried out using a cesium vapor magnetometer G-858 GEOMETRICS, in gradiometric configuration with two magnetic sensors mounted on a vertical staff at a distance 0.8 m apart from each other, to measure the vertical gradient of the magnetic field to automatically remove the diurnal variations of the natural magnetic field (Sharma 1997). Furthermore, to accelerate the magnetic data acquisition, a normal serpentine path across the survey area was followed, taking the data in a bi-directional pattern.

The magnetometric measurements have been collected using the *mapped survey* mode, which allows to specify a priori and visualize the survey area and to move around within the investigated area in a noncontinuous fashion by means of regular grids with variable sampling steps and sampling rate of 10 Hz.

GPR profiling

The GPR unit used is the subsurface interface radar (SIR) 2000, manufactured by Geophysical Survey Systems. The unit is backpack portable, requires one or two operators, and is powered by a 12 V DC battery. The SIR 2000 instrument consists of a digital control unit with a keypad, a VGA video screen, and a connector panel. The system was equipped with a 400 and 200 MHz nominal frequency antenna connected by fiber-optic cables. The line separation distance was chosen with respect to the resolution requested by the investigated site's dimensions.

The GPR profiles have been processed to eliminate the noise and antenna ringing. Data processing included distance normalization, header gain removal, "dewow", energy decay compensation, and bandpass filtering. Some radargrams needed 2D filtering like average removal and background removal filters.

Reconnaissance survey

Magnetic susceptibility measurements

Soil magnetic susceptibility values may be used as a proxy variable for indicating the presence of heavy metal soil pollution phenomena. From the analysis of the emission sources of Val Basento area, it may be assumed that one of the most important contamination sources of this area is heavy metals. During the first phase of the investigation a preliminary study of the investigated area was carried out by means of wide spot magnetic susceptibility measurements to obtain a screening of the most sensible sites in such a way that it could be detected where the next detailed geophysical investigation would be performed.

The magnetic susceptibility measurements have been carried out throughout the length of a freeway named Basentana, starting from the industrial site of Salandra up to the industrial site of Pisticci. Seventy-five measurements were carried out by means of the MS2D and MS2F probes, since the simultaneous employment of these tools allows inferring information about the magnetic susceptibility trend with the depth. Figure 3 shows the map related to the preliminary magnetic susceptibility measurements carried out by using the MS2D sensor. The radius of the circumferences is proportional to the magnetic susceptibility values.

As it can be observed, the magnetic susceptibility values vary from 5×10^{-5} to 28×10^{-5} SI along the entire investigated area; on the contrary, the highest values can be found in correspondence to the areas surrounding the industrial plants of Ferrandina and Pisticci. In particular, the highest magnetic susceptibility value was recorded for the MS2D probe of 88.5×10^{-5} SI near the Ferrandina industrial plant, as is indicated by a red ellipse in Fig. 3, and a value of 45×10^{-5} SI near the Pisticci industrial plant (blue ellipse). The lowest values are present in correspondence to the agricultural areas far from the industrial sites with a mean value of about 11.3×10^{-5} SI. Near Miglionico (black ellipse) a value of 8.4×10^{-5} SI was recorded, in an area very far from the Basentana freeway, to have a reference parameter of a nonpolluted area.

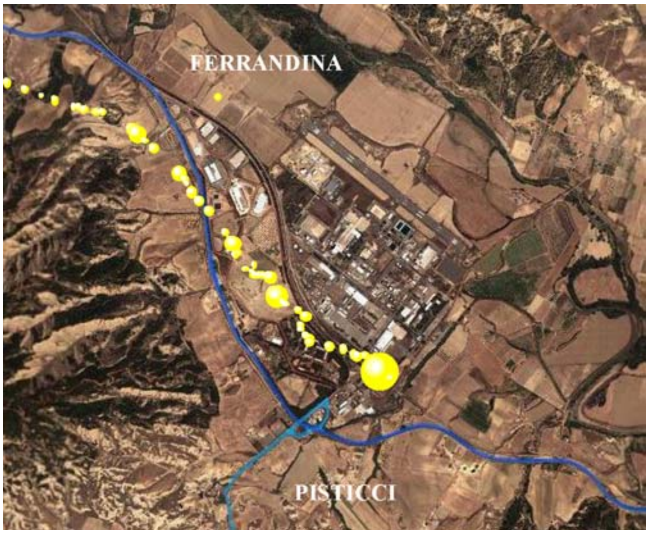

Fig. 3 Results of the magnetic susceptibility measurements by means of the MS2D Bartington probe across the Basentana freeway in the Val Basento industrial area. The highest values have been observed close to the Ferrandina and Pisticci industrials sites

The same measurements were carried out by using the MS2F field probe which put in light an analog magnetic susceptibility value distribution with the highest value for the MS2F probe of 68.8×10^{-5} SI recorded near the Pisticci industrial plant and a value of 28.8×10^{-5} SI near the Ferrandina industrial plant. The magnetic susceptibility measurements acquired by means of two sensors are in good agreement with a correlation coefficient of about 0.6.

Moreover, five heavy metals concentration (Co, Cu, Ni, Pb, and Zn) measured in soil samples were correlated with magnetic susceptibility measurements. The soil samples were collected in the same sampling points in which the magnetic susceptibility measurements were carried out. It should be noted that the magnetic susceptibility measurements are well correlated with heavy metals concentration. In particular, it can be confirmed that Cu, Pb, and Zn concentrations are correlated with MS2F magnetic susceptibility measurements with a significance level of 5% ($\rho_{Cu,MS2F}=0.4$; $\rho_{Pb,MS2F}=0.4$; $\rho_{Zn,MS2F}=0.7$) and Cu and Zn concentrations are correlated with MS2D magnetic susceptibility measurements with a significance level of 5% ($\rho_{Cu,MS2D}=0.4$; $\rho_{Zn,MS2D}=0.5$).

Geophysical field surveys: results

Since the preliminary survey put in light the presence of higher magnetic susceptibility values corresponding to the industrial areas of Ferrandina and Pisticci, integrated geophysical surveys were carried out in these two areas to obtain more detailed information about the soil pollution level.

For this purpose, three geophysical techniques were used: the magnetic susceptibility technique, which allows to obtain information about the magnetic features of the surface soil; the magnetic method, which allows to obtain information about the presence of buried objects located at depth between the field level and about 6 m (depending on the sensibility of the G-858 magnetometer), by measuring the natural magnetic field variations; and the GPR technique, which allows to obtain information about the presence and the depth of disconti-

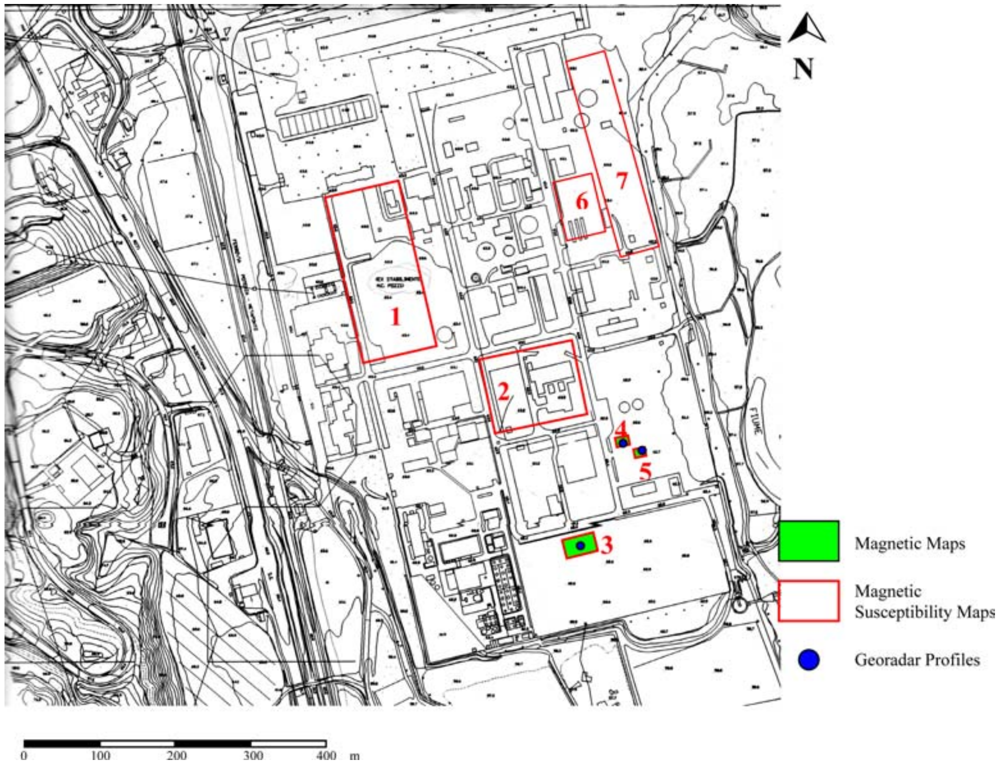

Fig. 4 Map of Ferrandina industrial settlement with the location of the magnetic susceptibility, magnetometric, and GPR surveys

nuity surfaces in the subsoil, by sending electromagnetic waves emitted by a transmitter–receiver antenna into the subsoil at different frequencies.

Ferrandina site

In the discontinued industrial area of Liquichimica at Ferrandina, seven magnetic susceptibility maps, three magnetic maps, and several GPR profiles were carried out in the same three areas (Fig. 4).

The two maps shown in Fig. 5 refer to site 1 in Fig. 4, covering an area of 90×240 m^2, in which magnetic susceptibility measurements were carried out by means of both MS2D and MS2F probes, with a sampling step of 30 m. In these maps the experimental points were plotted in front of the magnetic susceptibility maps. Both maps put in evidence the highest values in a measuring point located in the upper east part of the investigated site with values of 332×10^{-5} and 583.8×10^{-5} SI, respectively. Furthermore, there is a good agreement between the measurements made by means of the two sensors, with a correlation coefficient of about 0.9. This occurrence implies that where the magnetic susceptibility measurements show highest values, there is a presence of ferromagnetic substances in the first few centimeters of the subsoil.

The other magnetic susceptibility maps show similar results, evidencing spot-on high values for both the sensors in the same points and high correlation coefficients.

However, the most interesting results have been obtained in site 3 of Fig. 4, where both magnetic and electromagnetic measurements were carried out.

First, magnetic measurements covering an area of 51×30 m^2 were made, with a sampling step of 3 m. As seen in Fig. 6, there is an intense gradiometric anomaly in the lower part of the investigated area, evidenced by the black oblong from 25 to 35 m along the x direction with magnetic gradient values higher than 10,000 nT/m. These intense values are probably due to the presence, in the subsoil, of storage drums with great magnetization. Finally, the magnetic map evidences the presence of a large anomaly in the western part of the investigated area, with values of about 1,000 nT/m in modulus. These anomalies can be due to the presence of broad buried bodies with great magnetization values.

In a second step, to obtain information about the magnetic properties of the investigated subsoil, a magnetic susceptibility map was carried out by means of the MS2D probe, partially covering the area of site 3, with dimensions of 36×54 m^2 and with a sampling step of 6 m, which anyway did not produce any significant result. This occurrence allowed inferring that the sources of the magnetic anomalies were probably located at a depth greater than 20 cm.

Starting from the magnetic results observed in the investigated area, two series of GPR profiles were car-

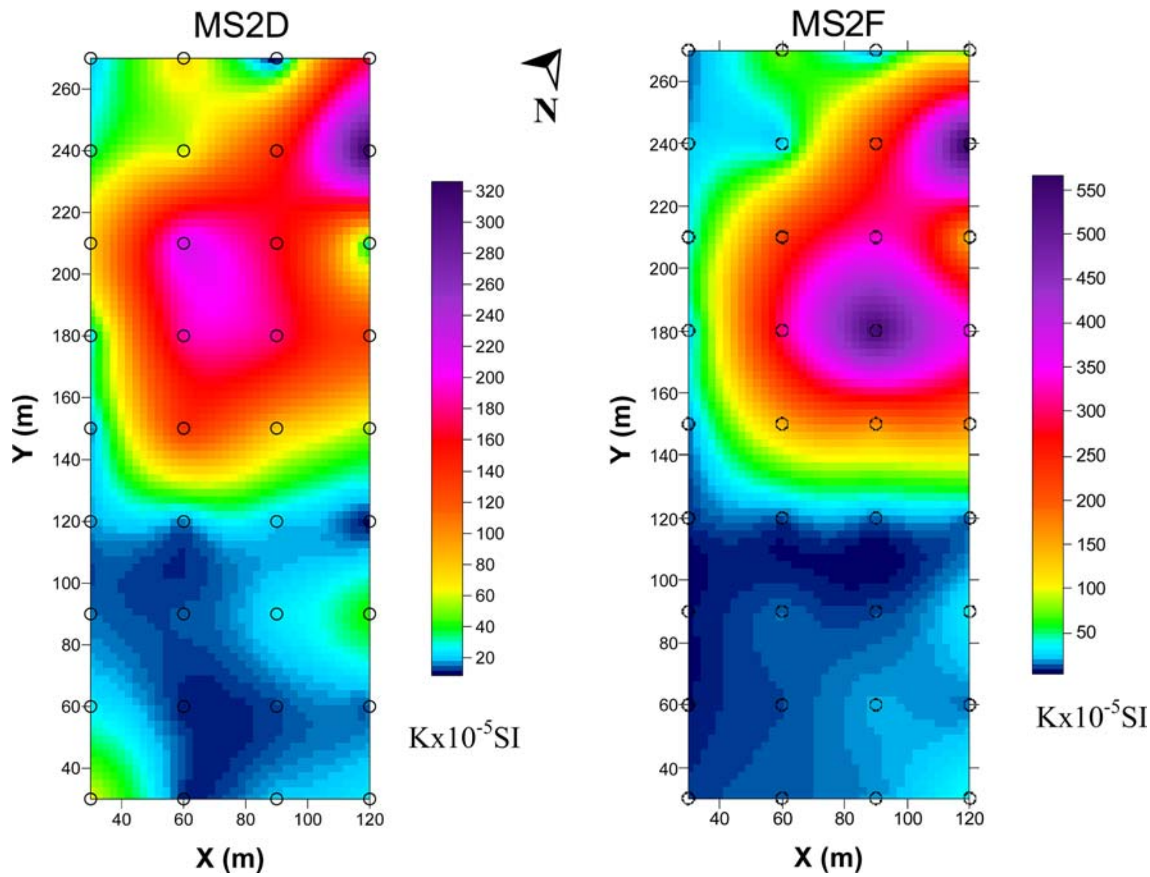

Fig. 5 Magnetic susceptibility maps carried out by means of MS2D and MS2F probes at site 1 of Fig. 4. The maps are obtained by means of a kriging interpolation procedure. The distance between the sampling points is 30 m. The highest values have been observed in the upper right part of the investigated area

ried out to obtain more detailed information about the depth and the extension of the anomaly sources, as evidenced in Fig. 6, indicated by the two yellow oblongs ABCD and EFGH, respectively.

In the ABCD area three radargrams were carried out, with dimensions of 30 m×45 ns at a distance of 3 m from each other, using the 200 MHz antenna.

Radargram 1 of Fig. 7 shows only a branch of hyperbola between 0 and 6 m and a substantially homogeneity of the subsoil. Instead, radargrams 2 and 3 of Fig. 7, in addition to the same branch of hyperbola, show some interesting reflections from 3 to 21 m as highlighted by the arrows. In particular, some strong reflections between 6 and 10 m, and between 18 and 21 m, can be observed in radargram 2 of Fig. 7. Furthermore, a dip surface is shown between about 10 and 15 m.

The reflections are stronger in radargram 2 than in radargram 3, possibly because the buried objects are not located precisely into the plan section of radargram 3. However, a well-defined irregular surface is showed in radargram 3.

Most interesting reflections of ABCD area are located between 6 and 9 m, 10 and 15 m, and 18 and 21 m. With reference to Fig. 6, these locations correspond to three transition zones into the magnetic anomaly.

In the EFGH area (Fig. 6) ten radargrams have been carried out. Five radargrams, at a distance of 1.5 m from each other and sized 10 m×45 ns, have been obtained by using the 200 MHz antenna. On the same survey lines, five radargrams have been again carried out with dimensions 10 m×26 ns by means of the 400 MHz antenna (Fig. 6). Radargrams related to the 200 MHz antenna (from 1a to 5a in Fig. 8) show soft and narrow hyperboles, evidenced by black arrows, and other diffraction figures revealing the presence of little objects with respect to the antenna wavelength. On the other hand, the radargrams related to the 400 MHz antenna (from 1b to 5b in Fig. 8) show strong reflections.

Comparing each radargram of the two series, the following can be observed:

1. Radargram 1a shows a hyperbolic reflection between 30 and 31 m and a branch of hyperbola from 30 to

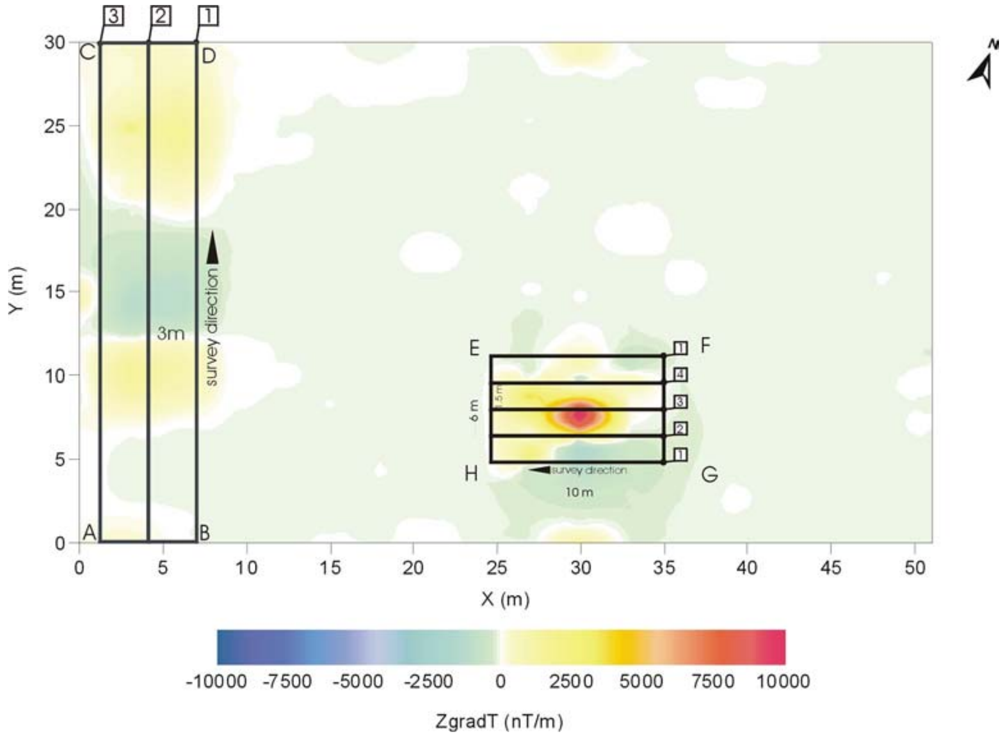

Fig. 6 Magnetic gradient map carried out by means of G-858 magnetometer at site 3 of Fig. 4. The black EFGH oblong is located around a very strong gradiometric anomaly, with magnetic gradient values higher than 10,000 nT/m. Location of the two series of radargrams (ABCD and EFGH black oblongs) carried out by means of the 200 and 400 MHz SIR2000 antennas at site 3 of Fig. 4

35 m starting from 28 ns. These features are not shown in the corresponding radargram 1b.

2. Radargram 2a, b show a spike at 30 m and 8 ns, but this reflection appears more evident in the radargram obtained by using the 400 MHz antenna (2b); this reflection falls on the southern margin of the strongest anomaly into the magnetic map of Fig. 6.
3. Radargram 3a is very noisy and no significant reflections can be observed. In radargram 3b only a weak reflection can be observed at about 29 m and 14 ns. This reflection could be the effect of a buried object out of the section.
4. Both radargrams show two reflections between 29 and 30 m and between 32 and 33 m, respectively. Both reflections are located at 14 ns and in the radargram 4a they assume a well-defined hyperbolic shape. These reflections fall on the northern margin of the strongest anomaly into the oblong EFGH of Fig. 6.
5. Radargram 5a shows a weak spike at 15 ns between 28 and 29 m that becomes a small reflection in the radargram 1b, where a strong hyperbola is showed, between 29 and 30 m, at 15 ns.

The velocity analysis carried out on the hyperbola of the radargram 4b of Fig. 8, between 33 and 34 m at 14 ns, provided a velocity of 0.08 m/ns. Assuming this value as the representative for all the survey lines carried out in site 3 of Fig. 4, it can be concluded that the tops of the buried objects are located at a depth variable from about 0.8 to 2.0 m, for the ABCD area, and from about 0.8 to 2.0 m for the area EFGH.

Pisticci site

The preliminary magnetic susceptibility measurements in evidence that the industrial area of Pisticci was concerned by the soil pollution phenomena. However, because of the presence of many metallic structures in this industrial plant, magnetic measurements in these sites could not be performed. Therefore, attention was directed to an airstrip located near the industrial area, characterized by the presence of a discontinued waste deposit. Three magnetic susceptibility mappings, three magnetic maps, and several GPR profiles were carried out in two of the three areas beside the airstrip of Pisticci (Fig. 9).

In the first investigated area (site 1 in Fig. 9), located upon an old waste deposit, a magnetic mapping was carried out, covering an area of 50×20 m^2, with a sampling step of 2 m. As observed in Fig. 10, there is a broad magnetic anomaly in the central part of the area, evidenced by a black ellipse, with gradiometric values coming from 20 to 50 nT/m. This anomaly does not seem to have a well-defined geometry, so it is not due to the presence of a magnetic object, but is most probably due to the scattered material with a great magnetization. Furthermore, this magnetic anomaly is located in correspondence to a ground inhomogeneity observable also

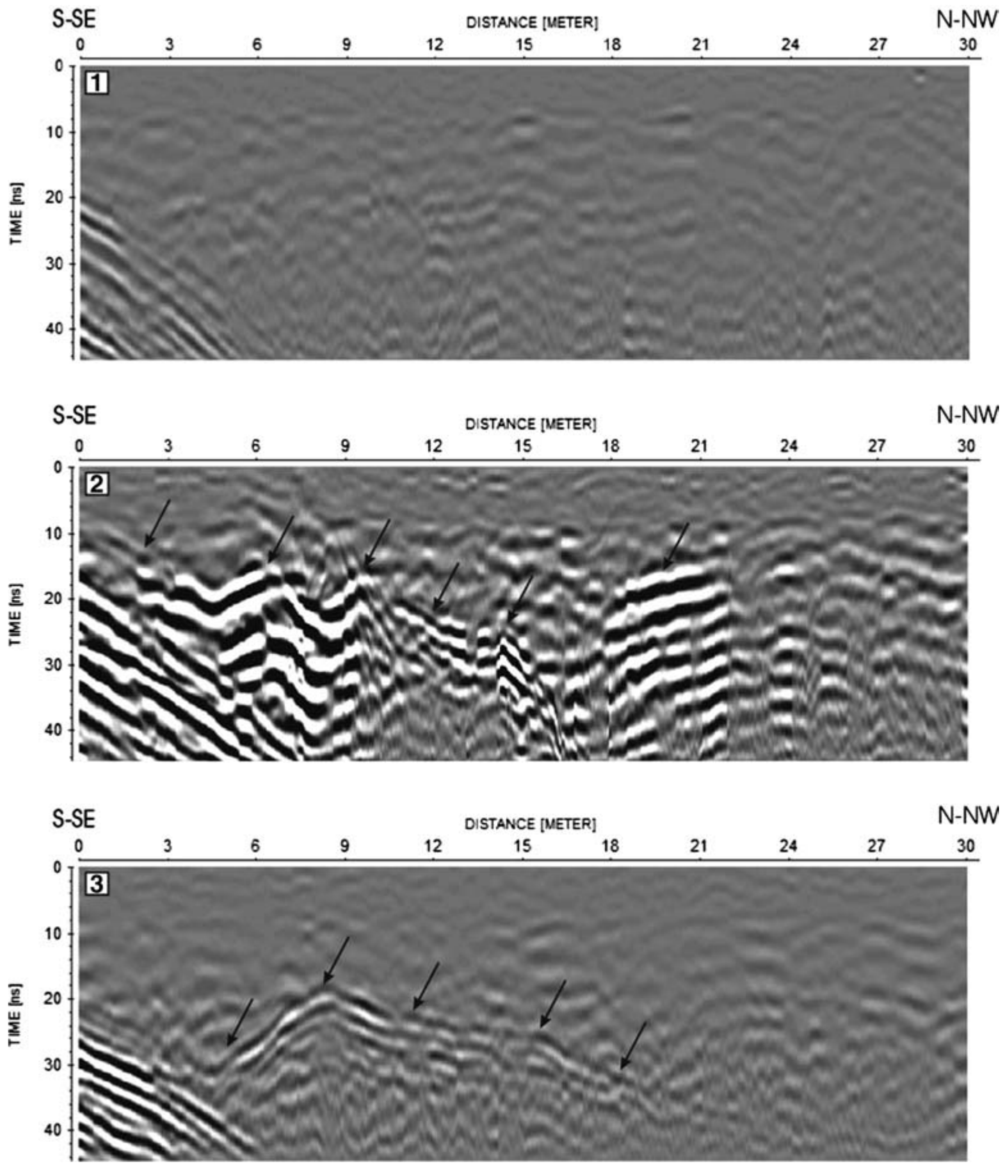

Fig. 7 Results of the three GPR profiles on the ABCD oblong in the magnetic map at site 3 of Fig. 3 carried out by means of the 200 MHz antenna

on the ground surface (Fig. 11). On the other hand, a well-defined magnetic anomaly has been observed in the right section of the investigated site (Fig. 10), crossing the entire area, with magnetic gradient values ranging from −150 to −200 nT/m. Because of the linearity of the anomaly, this occurrence could be due to the presence of an extensive magnetized body in the subsoil.

In a second step, this area has been investigated by means of 25 magnetic susceptibility measurements, covering the lower part of the magnetic map and the entire central part, to obtain information about the magnetic properties of the investigated site. These measurements have been performed by means of both the MS2D and the MS2F probes. Both series of measurements have put in light the presence of highest magnetic susceptibility values in correspondence to the magnetic anomalies. A value of 129.7×10^{-5} SI for the MS2F probe and 368.8×10^{-5} SI for the MS2D probe was found in the eastward anomaly of Fig. 10, while for the magnetic anomaly evidenced by the ellipse a value of 113.6×10^{-5} SI was obtained for the MS2D probe and a lower value of 21.3×10^{-5} SI for the MS2F probe, probably due to the fact that the anomaly source is located at a depth greater than a few centimeters. Finally, the fact emphasized is that the results obtained by means of the two susceptibility probes show a perfect agreement, having a correlation coefficient of about 0.97.

To obtain information about the depth of the magnetic sources of anomalies in this area, 26 GPR profiles were carried out finally (Fig. 10), with a length of 20 m and spaced 2 m of each other, by using the 200 MHz antenna, which provides a greater depth penetration and

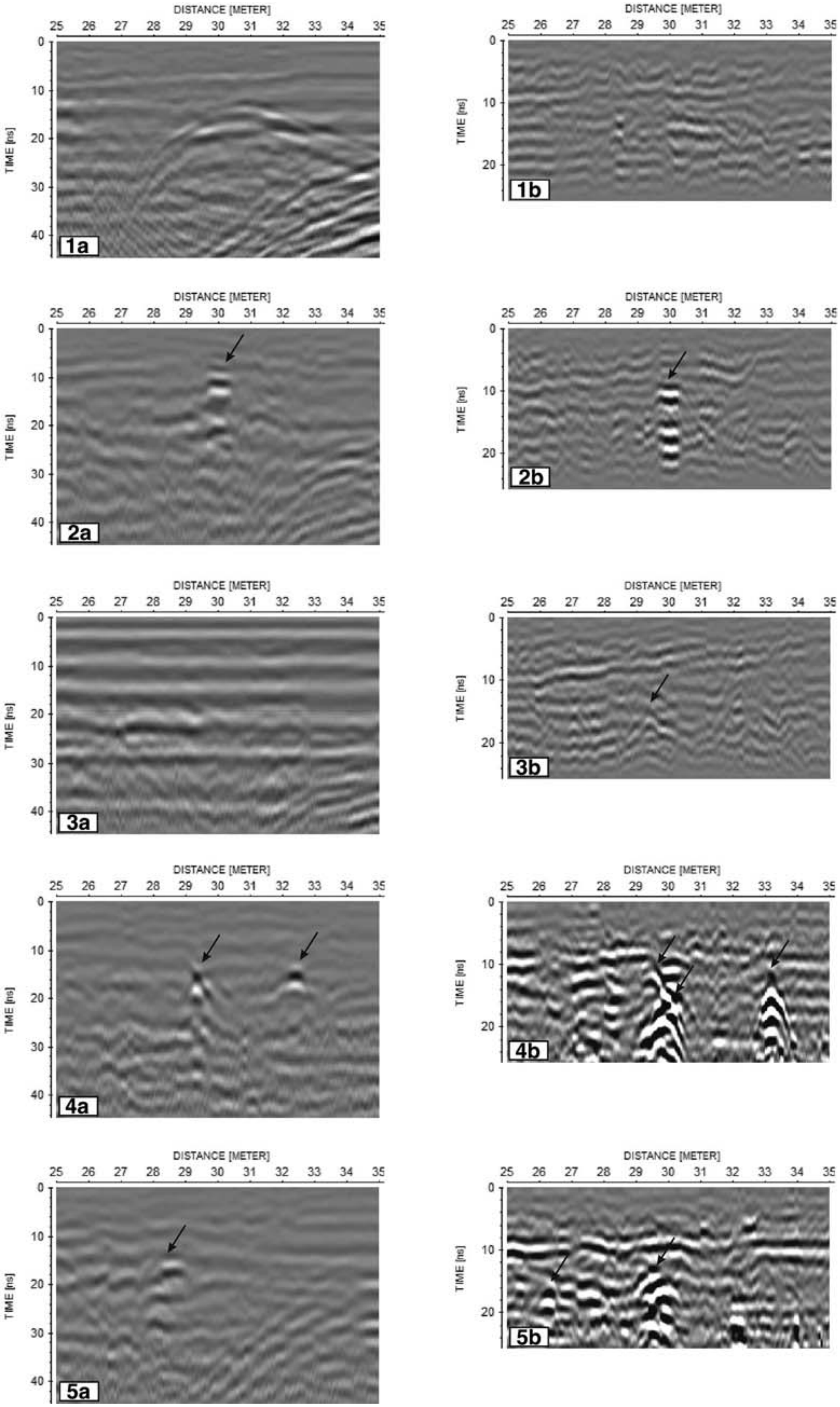

Fig. 8 Results of the five GPR profiles on the EFGH oblong in the magnetic map at site 3 of Fig. 4 carried out by means of the 200 MHz (1a–5a) and 400 MHz (1b–5b) antennas

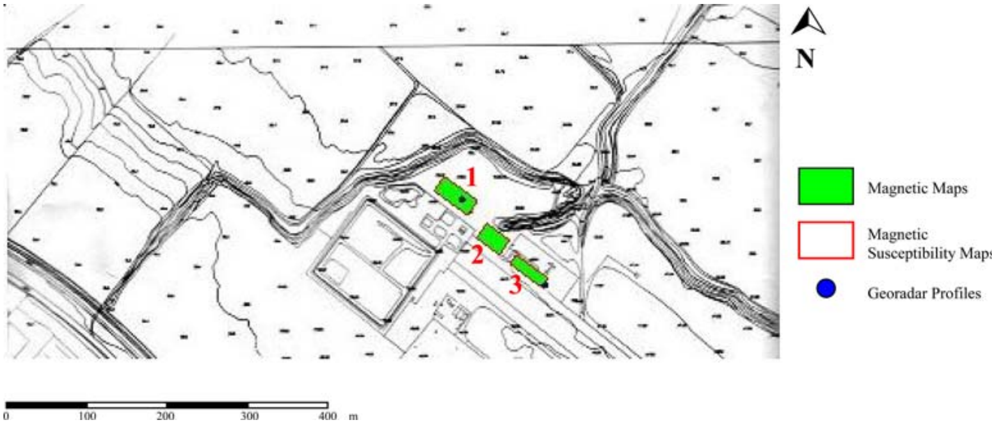

Fig. 9 Map of Pisticci industrial settlement with the location of the magnetic susceptibility, magnetometric, and GPR surveys

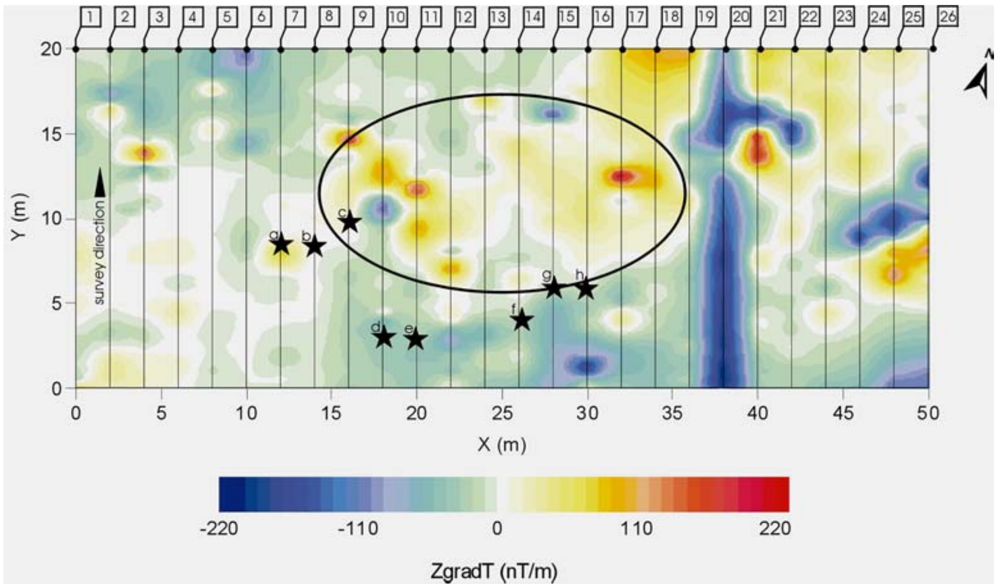

Fig. 10 Magnetic gradient map carried out by means of G-858 magnetometer at site 1 of Fig. 9. The black ellipse is located around a broad gradiometric anomaly, with magnetic gradient values ranging from 20 to 50 nT/m. Location of the 25 radargrams carried out by means of the 200 MHz antenna at site 1 of Fig. 9. The stars indicate the position of the reflections in most significant radargrams

is less sensitive to the ground roughness than the 400 MHz antenna. The most interesting profiles have been grouped in three main series:

Radargrams 7, 8, and 9 show some reflections that could be related to the same object. Infact, the hyperbolas (a, b, and c, respectively, in Fig. 12) are located between 8 and 10 m in all radargrams. The velocity analysis of hyperbolas provided a high value, around 30 cm/ns, which does not change along the time axis. This could be due to the objects located out of the ground like branches of trees, piles, and walls.Radargrams 10 and 11 show a narrow reflection between 3 and 5 m and between 18 and 22 ns.Radargrams 14, 15, and 16 show a well-defined hyperbola between about 4 and 6 m at 54, 35, and 25 ns, respectively. In these cases the shape of the hyperbolas should be related to the shape of the objects and not to the velocity of the subsoil.By

Fig. 11 Inhomogeneous composition of the soil observed in correspondence to the broad magnetic anomaly in Fig. 10

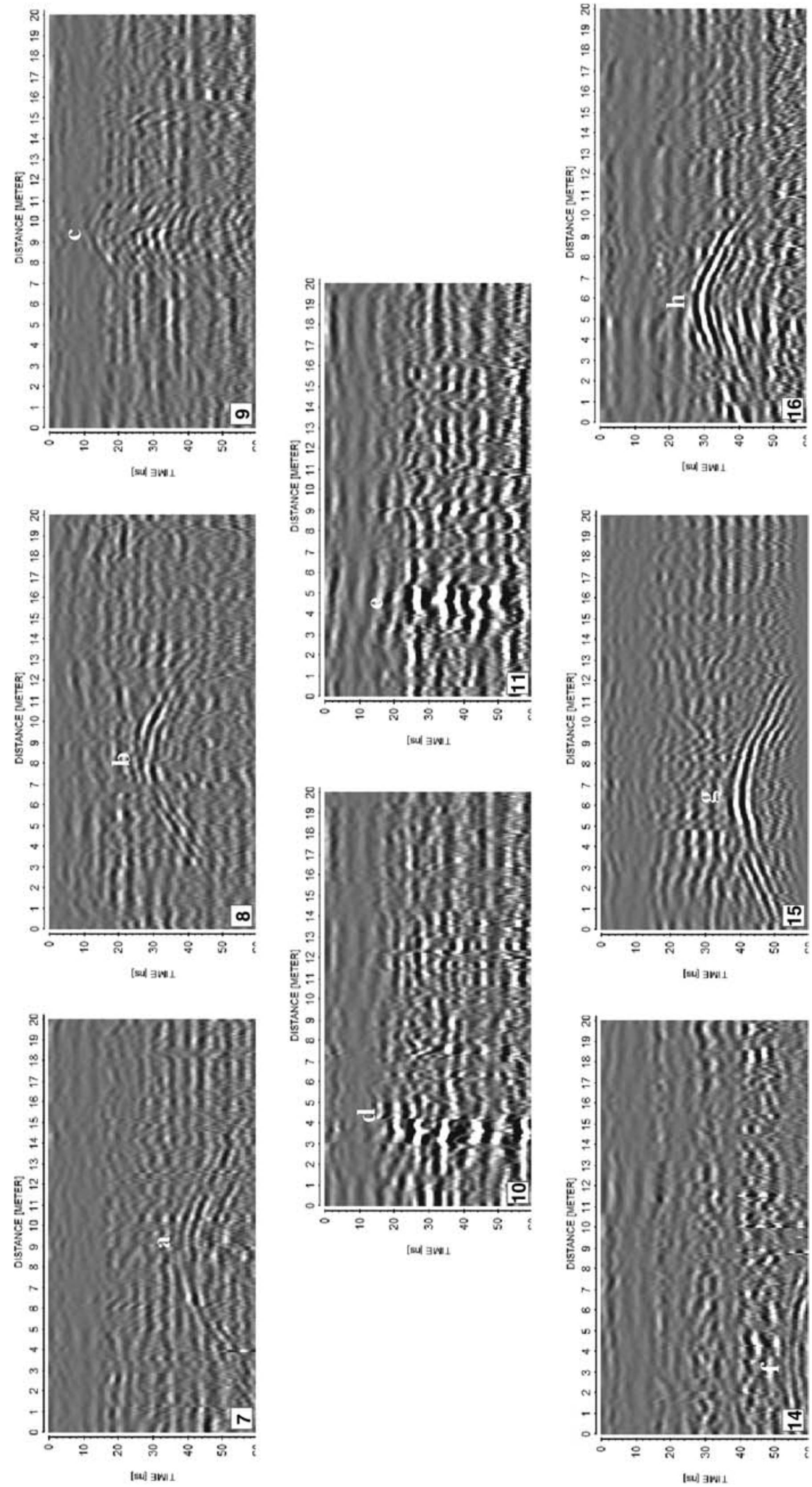

Fig. 12 Results of the three most interesting series of GPR profiles carried out by means of the 200 MHz antenna in the magnetic map at site 1 of Fig. 9. The letters that indicate most significant reflections correspond to the stars in Fig. 10

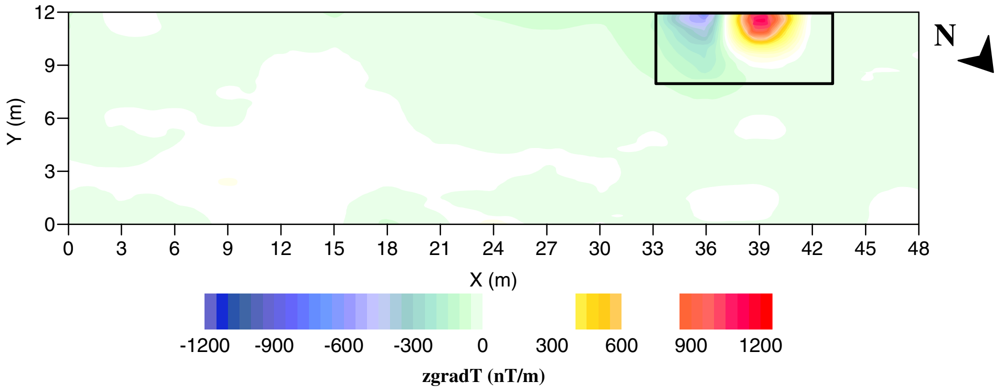

Fig. 13 Magnetic gradient map carried out by means of G-858 magnetometer at site 3 of Fig. 10. A well-defined dipolar magnetic anomaly is present in the upper right part of the map, with magnetic gradient values greater than 1,000 nT/m in modulus

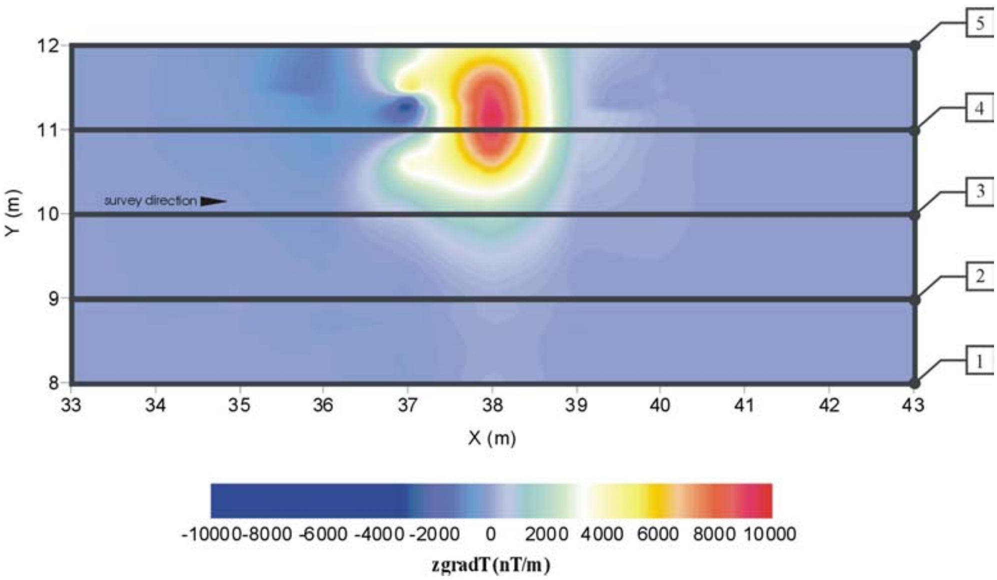

Fig. 14 Detailed magnetic map carried out inside the map of Fig. 13. A very intense magnetic anomaly is present in the upper central part of the area, with gradiometric values greater than 9,000 nT/m in modulus. Location of the five radargrams carried out by means of the 200 MHz antenna at site 3 of Fig. 9

plotting the position of the hyperbolas onto the magnetic map (stars in Fig. 10), no relationship between GPR data and magnetic anomaly can be drawn. Surprisingly, even radargram 20, which falls on a strong and oblong magnetic anomaly, does not provide any significant information. This could be due to the insufficient resolution of the used antenna in comparison to the dimensions of the buried objects. Unfortunately, the roughness of the ground surface prevented the use of higher frequencies antennas.

To obtain information about a possible pollution of the areas close to site 1, two magnetic map surveys, located in sites 2 and 3 of Fig. 9, respectively, were carried out. The magnetic map related to site 2 with dimensions of 36×21 m^2 did not give any significant result, allowing to infer that no soil pollution originating from site 1 was present. However, in order to have a complete picture of the investigated soil, a third magnetic map was carried out at site 3, with dimensions of 48×12 m^2 and a sampling step of 3 m (Fig. 13). As it can be observed, there is a well-defined dipolar magnetic anomaly in the upper right part of the map, with magnetic gradient values greater than 1,000 nT/m in module. Starting from this occurrence, a better investigation was carried out on a more detailed series of magnetic measurements with dimensions of 4×10 m^2 and sampling step of 1 m, from 33 to 43 m in the x direction and from 8 to 12 m in the y direction (Fig. 14). This map shows a very intense magnetic anomaly concentrated in the upper central part of the area with gradiometric values greater than 9,000 nT/m in modulus, probably due to the presence of buried metallic drums in the subsoil, as in the case of Ferrandina.

Inside this area, 50 magnetic susceptibility measurements were successively carried out by means of both the MS2D and MS2F probes, which put in evidence the greatest values in correspondence to the center of the magnetic anomaly with values of 681.9×10^{-5} SI for the MS2D and 705.1×10^{-5} SI for the MS2F. Furthermore, the measures made by means of the two susceptibility

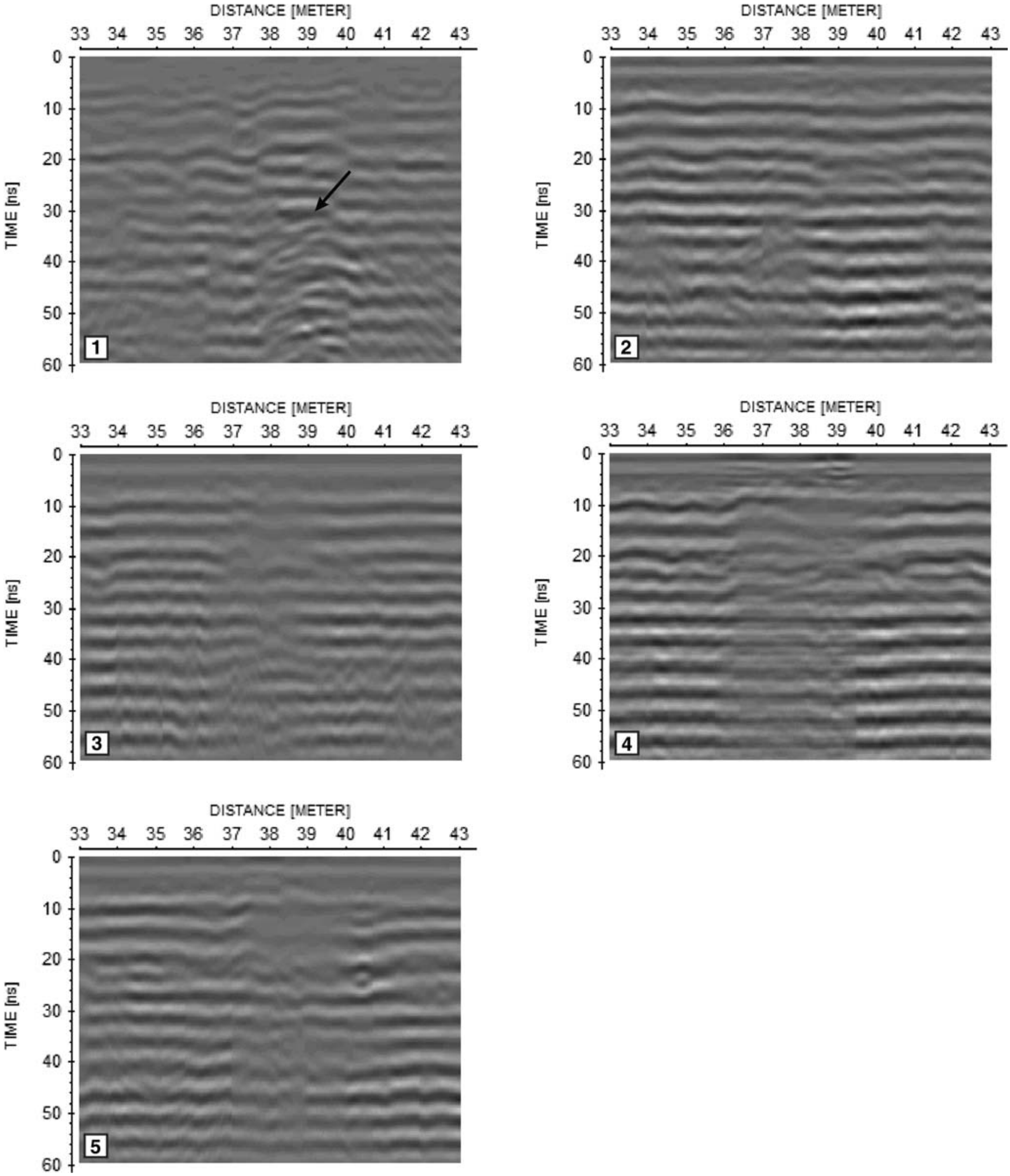

Fig. 15 Results of the five of GPR profiles carried out by means of the 200 MHz antenna in the magnetic map at site 3 of Fig. 9. They show many diffractions at great depths and an attenuation band between 36 and 40 m

meters are in good agreement, with a correlation coefficient of 0.8.

Finally, to get information on the depth of the magnetic sources of anomalies, in the area related to Fig. 14 five GPR profiles were carried out by means of the 200 MHz antenna, with dimensions of 10 m×60 ns and 1 m spaced.

Five radargrams are very noisy even after the processing (Fig. 15). However, a weak reflection can be appreciated in radargram no.1 at about 30 ns, between 39 and 40 m. The radargram no.2 provides no useful information. Other radargrams (3 and 5 of Fig. 15) show an attenuation zone between 36 and 40 m. This could be the effect of the antenna coupling to the ground or alternatively, an effect of a change of the composition of the soil. In fact, the position of this zone fall perfectly on the strong magnetic anomaly (Fig. 14), which could be caused by conductive material dispersed into the subsoil.

Conclusions

In this work the main results of a field geophysical survey carried out in two industrial sites of the Basilicata Region (Southern Italy) were shown. The aim was to obtain a quick characterization of the soil pollution level of the investigated area. The field survey has been divided in two different phases:

1. A preliminary phase during which, 75 magnetic susceptibility measurements across the Basentana freeway, from Salandra to Pisticci were carried out. The aim of this field survey was to obtain a first screening of the most sensible sites from an environmental point of view. In these sites a detailed investigation was successively carried out.
2. A second phase that was structured on the basis of the results gathered from the preliminary field survey, including magnetometric maps, magnetic susceptibility measurements and GPR profiles.The preliminary screening put in evidence that the most polluted areas seemed to be the industrial areas of Ferrandina and Pisticci. In addition, magnetic susceptibility measurements highlight the presence of areas that are suffering heavy metal pollution phenomena. So the second joint field survey was carried out in the industrial site of Liquichimica, at Ferrandina, and beside the Pisticci airstrip. At the Liquichimica area, a very intense gradiometric anomaly was found in a site, probably due to the presence of buried objects with a great magnetization value; the next GPR profiles carried out in the same area revealed some reflections in correspondence to the magnetic anomaly at a depth of approximately 0.8–2.0 m.

At the Pisticci airstrip area, a good agreement in site 1 was found between the three employed geophysical techniques because they evidenced the presence of near surface objects with a great magnetic susceptibility. Furthermore, in site 3 an intense magnetic anomaly together with high magnetic susceptibility values was found, while the GPR measurements put in evidence the presence of an attenuation zone probably due to a change in the composition of the soil.

In conclusion, the integrated geophysical survey conducted at Ferrandina and Pisticci industrial settlements provided many interesting results about the possibility to employ different geophysical methodologies for the mapping and characterization of broad polluted areas. Furthermore, the joint application of geophysical techniques based on different magnetic and electromagnetic sources allows to obtain detailed information about the presence of buried objects in the subsoil and to give estimation about their shape, dimensions, and depth.

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