Modelling of karst structures by geophysical methods. An example: the doline of S. Pietro dei Monti (Western Liguria)

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Abstract
Integrated geophysical investigations of karst structures were carried out in Liguria and Piedmont (NW Italy); this paper refers to the S. Pietro dei Monti doline, in the karst area of Mt. Carmo (Savona). The techniques used in the integrated study were magnetics, electromagnetics and seismic refraction. The target was to identify, without drilling, the nature of the doline, for example if it is of dissolution or collapse type. A preliminary susceptibility sampling of the outcrop and topsoil and the diffuse fractures with a probable water seepage suggested magnetics and VLF electromagnetics. Such methods applied in an area with an extremely low cultural noise allowed modelling of the buried structure of the doline.

Key words *karst environment – doline – magnetics – VLF – geophysical modelling*

1. Introduction

Location and structural investigation of fractures and cavities within soil and rock involve problems in the engineering and hydrologic fields. They can assume great relevance in karst environments, where complex geologic conditions, due to partial rock dissolution and underwater seepage phenomena, make projects of building and pile foundations, tunnelling and dams, a difficult task. Also hydrologic studies in these areas for development or protection of ground water resources need tools for accurate investigations of subsurface geology. Because traditional investigation by drilling or excavation (borings and wells) may be inadequate to produce a reasonable level of spatial sampling at an acceptable cost and time lag, geophysical methods assume great importance in this context (*e.g.* Benson and Yuhr, 1992; Yuhr *et al.*, 1993). In order to test the possibility of modelling karst features by geophysical data, ground surveys were carried out in Northwestern Italy. The first target regards the geophysical signature of one of the main features of karst environment: the doline.

In the Slavonic languages «dolina» means a valley, but also small, closed karst hollows. The term was introduced into geomorphology by Austrian geologists to indicate «simple, funnel-, howl- or kettle-shaped, closed karst cavities with underground drainage and a diameter which is greater than their depth» (Bögli, 1980).

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A genetic classification differentiates between solution dolines and collapse dolines (fig. 2). Solution dolines are formed when the limestone is dissolved away under a soil covering by a widening of the interstices, while the collapse doline is due to a crash, usually a single occurrence, of a cavity underlying the surface (Bögli, 1980).

2. Geological outline and preliminary ground investigation

From a regional point of view, the Ligurian Brianzonese characterizes the geology of the area (fig. 1). The basement, formed by porphyrite, dates back to 350 Ma; almost at the end of Ercynic orogeny (Late Permian), the erosion of this basement produced massive clastic (continental) deposits (Verrucano Brianzonese). The Lower Trias marine ingression is evidenced by the quartzites on the top of which a thick carbonatic sequence forms the Ceno-Mesozoic cover. Within this sedimentary sequence the formation of «Dolomite di S. Pietro dei Monti» is the most representative in the area.

Looking at the Mt. Carmo Massif, the tectonic evolution led to a «domes and basins» structure which is typical of the Ligurian Brianzonese (Menardi Noguera, 1984).

Karstic evolution and hydrology of the area have been strongly controlled by the tectonic

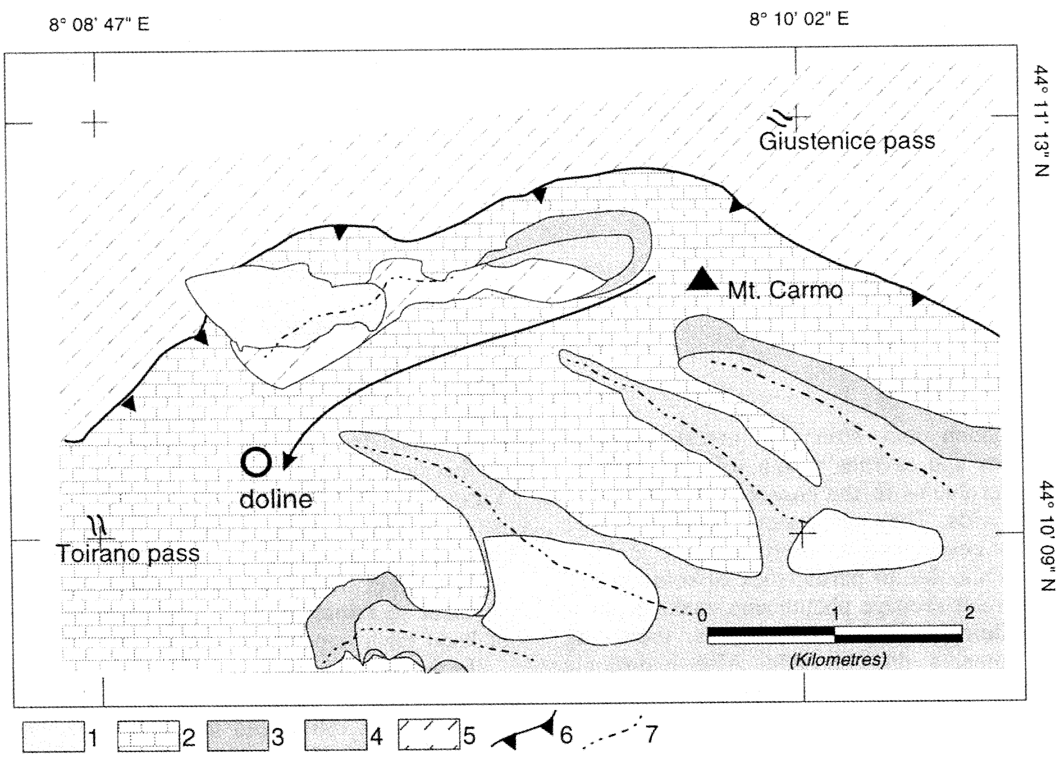

Fig. 1. Geological sketch of the area and location of the S. Pietro dei Monti doline. 1) Alluvial deposits; 2) San Pietro dei Monti 1 dolomite (Middle Trias); 3) San Pietro dei Monti 2 dolomite (Anisico); 4) Ponte di Nava quartzite; 5) Melogno porphyrite; 6) overslip line; 7) anticlinal folds axis. With the curve arrow is indicated the underground water flow direction.

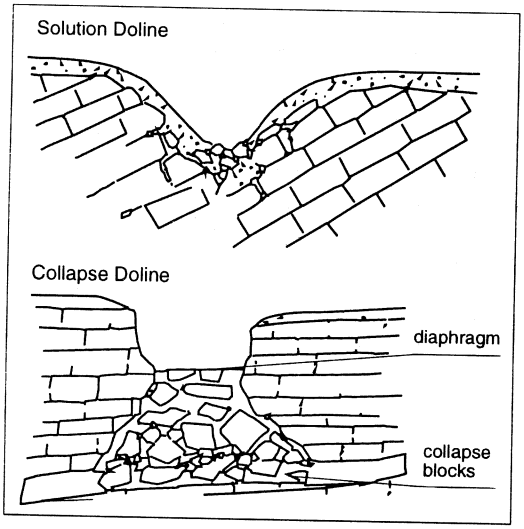

Fig. 2. Examples of morphological types of dolines (redrawn, Bögli, 1980).

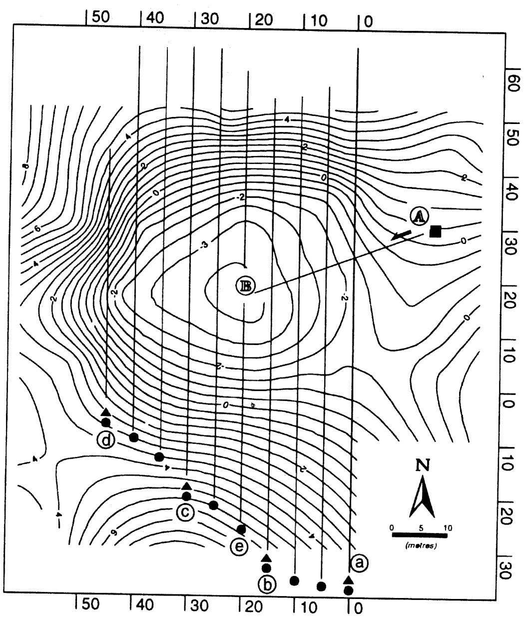

Fig. 3. Topography and geophysical array. Black circles and lines indicate the magnetic profiles; the black triangles (*a*, *b*, *c*, *d*) the VLF-EM profiles; *AB* is the refraction seismic line. Along line (*e*) the inversion model was calculated.

set-up. A big anticlinal fold (with axis ENE-SWS), corresponding with the Ligurian-Po watershed, brings up the impermeable basement. Some minor folds, located on the right flank of the major one, force the karstic water to flow from east to west along preferential ways. Concerning with shallow karst, the huge dolomitic outcrop shows some caverns and abysses located roughly parallel to the main watershed (Regione Liguria *et al.*, 1992).

The S. Pietro dei Monti doline (fig. 1) is located close to Toirano Pass (Mt. Carmo area – Ligurian Alps). A preliminary geomorphological survey of the area has shown the S. Pietro dei Monti dolomite (Ladynic-Anysic) outcropping in the SSE-NW area. In particular the doline shows steep walls where dolomite is sticking out, while it is flatter in the eastern sector. In its central part, where temporary surficial water traces were recognized, the clay infill might be massive.

The doline surface morphology was pointed out by a 51 station-points topographic survey by a self-reducing tacheometer. The resultant topographic map (fig. 3) reveals an elliptic shape with an EW elongation, an areal extension of about 80×60 m^2 and an altimetric difference, between the center and the edges, of about 10 m decreasing in the SE sector.

3. Methods, data acquisition and processing

Magnetic, VLF (Very Low Frequency) electromagnetic and seismic methods were used to investigate the S. Pietro dei Monti doline structure. The magnetic method is appropriate to detect fractures or cavity when the investigated subsurface body shows a good susceptibility contrast with respect to background conditions (Benson and Yuhr, 1992). Then magnetic susceptibility measurements were carried out by a portable susceptibility meter on the outcropping dolomite and the doline infill in order to determine their induced magnetization features. The subsequent total magnetic field survey was performed by proton precession magnetometers with a resolution of 0.1 nT and absolute accuracy of ± 1 nT. The profile line separation was 5 m and the sampling rate along each line 1 m (fig. 3).

The VLF electromagnetic method is widely used in detection and delineation of shallow conductors as well as in groundwater exploration and in engineering geophysical studies. It is based on the recording of the vertical magnetic field induced by a horizontal primary field coming from communication transmitters in the frequency range 15-30 kHz (*e.g.* Tabbagh *et al.*, 1991). Data were collected by means of a portable instrument with a three component sensor recording the magnetic field at a selected VLF frequency; instrument outputs the in-phase and in-quadrature vertical magnetic component values as percent of the horizontal one. VLF line interval was 15 m with a sampling spacing of 2 m (fig. 3).

Refraction seismics can be successfully adopted when a good contrast in the elastic properties of the investigated media can be supposed, as in the case of the doline infill and the hosting dolomite.

A seismic profile was carried out by a 12 channel seismograph. The seismic line (38 m long with geophones every 1 m and multiple shots) is reported in fig. 3.

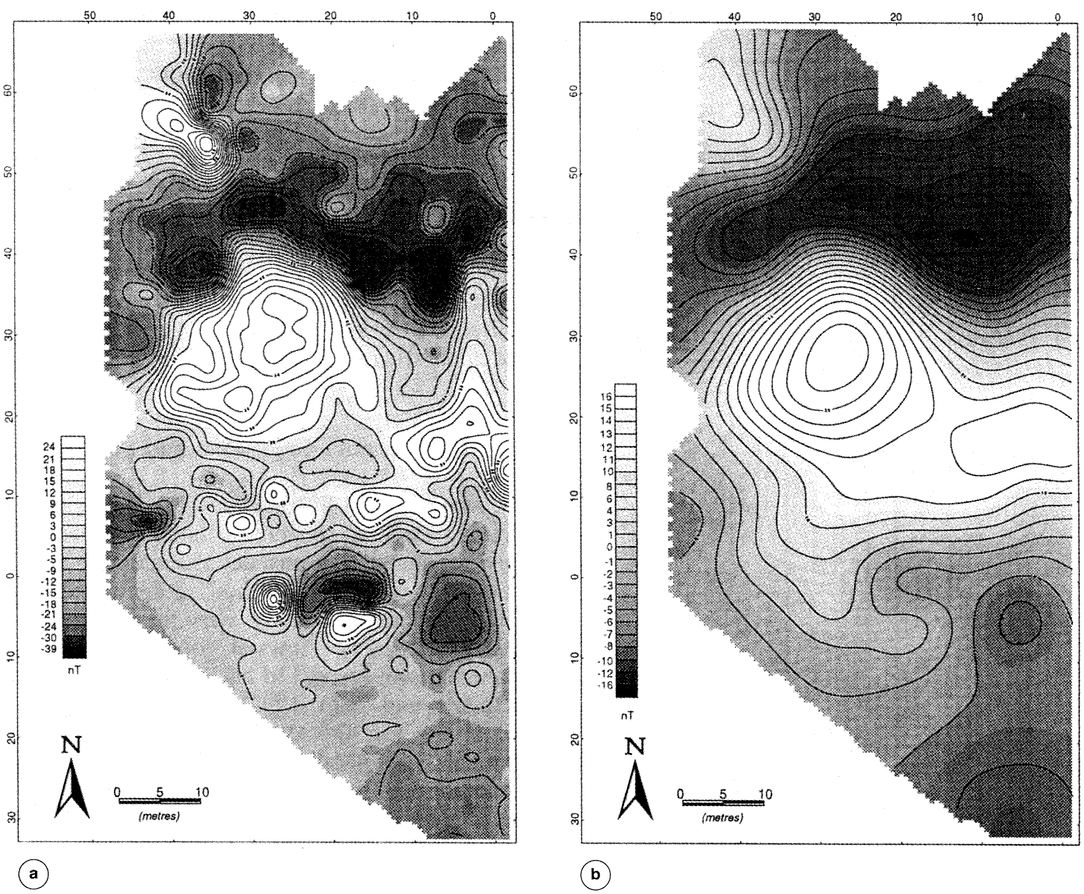

Fig. 4a,b. a) Total magnetic anomaly field map grid (nT); b) upward continuation (5 m) magnetic anomaly map (nT).

Mean susceptibility values of 30×10^{-6} SI were measured on the dolomite outcrop while 1800×10^{-6} SI on the surface of the clay infill. Such observed susceptibility features assure a good resolution to the magnetic investigation.

Total magnetic field data were corrected for time variations and residual levelling errors were removed by filtering as described in Minty (1991). The magnetic anomalies $\Delta F = Fc\text{-}Fm$ were computed (by subtracting the mean value Fm from the corrected data Fc) and reduced to the pole (fig. 4a). A relative magnetic high is located in the middle of the doline while high frequency anomalies are evident in the NNW and S sectors; in the latter they have a clear EW elongation. An upward continuation to 5 m (fig. 4b) was applied to the ΔF data in order to minimize the effects of soil magnetic sources and noise. The central anomaly is still in evidence while anomalies in the southern sector disappear, revealing their shallower nature.

Topographic correction of VLF data was computed following Karous (1979). Because the terrain relief effect due to the doline was found to be of the order of instrumental errors, it was not applied. On the contrary, the topographic effect of the regional relief certainly affects normal field values, but it can be considered constant throughout the survey area causing a vertical data shift which does not affect the interpretation. Along the line «c», in-phase and in-quadrature values of the VLF magnetic vertical component (frequency 19.6 kHz, transmitter station azimuth N330°E) as percentage of the primary field are shown in fig. 5. Along this profile, at 15 m, in-phase response shows a typical crossover type of anomaly (*e.g.* Sinha, 1990). After 28 m, in-quadrature values are higher and decrease more slowly than the in-phase ones, with a typical behaviour which can be correlated with changes in thickness of the conductive overburden (Bozzo *et al.*, 1996).

Seismic refraction data were processed and interpreted by the generalized reciprocal method of Palmer (1981). The obtained three layer seismic stratigraphy is shown in fig. 6.

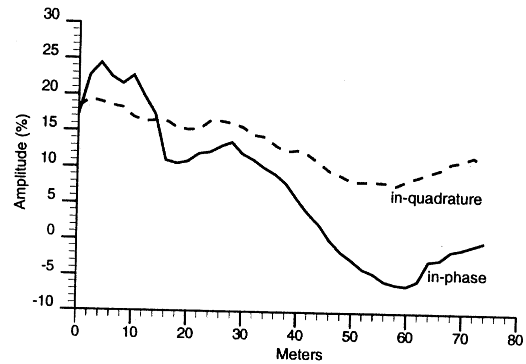

Fig. 5. In-phase (solid line) and in-quadrature (dashed line) values of the vertical VLF magnetic field component along profile «c» (see fig. 3).

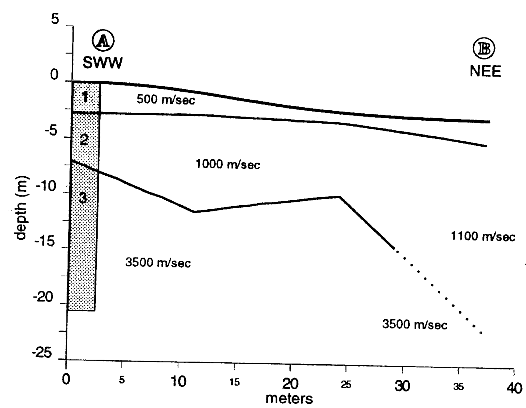

Fig. 6. Refraction seismic profile (*AB*) along SWW-NEE axis. 1) Alluvial cover; 2) clay layer; 3) dolomite bedrock.

4. Discussion

The seismic model (fig. 6) shows a shallow layer, with low velocity, which could be associated with aerated soil. The second layer, dipping towards the centre of the doline, with a seismic velocity of about 1000 m/s, seems to be formed by water soaked, clay infill. The deeper refractor should point out the dolomite bedrock.

Interpretation of VLF in phase data by equivalent electric current density pseudosections (Karous and Hjelt, 1983; Ogilvy and Lee, 1991) is shown in fig. 7. This technique provides a semiquantitative analysis by representing high conductivity zones as high density current layers. In the middle of the sections «b» and «c», a conductive high with a horizontal extension of about 20 m is clearly visible, while it seems to vanish in sections «a» and «d» (note that the VLF «d» profile is 50 m longer than the corresponding magnetic one). This higher conductive zone can be related to the main clay-infill detected also by magnetic data. However, no interpretations on shape, dip and dimension of the infill are inferred from the VLF pseudosections because of pattern distortions which affect the complex structural

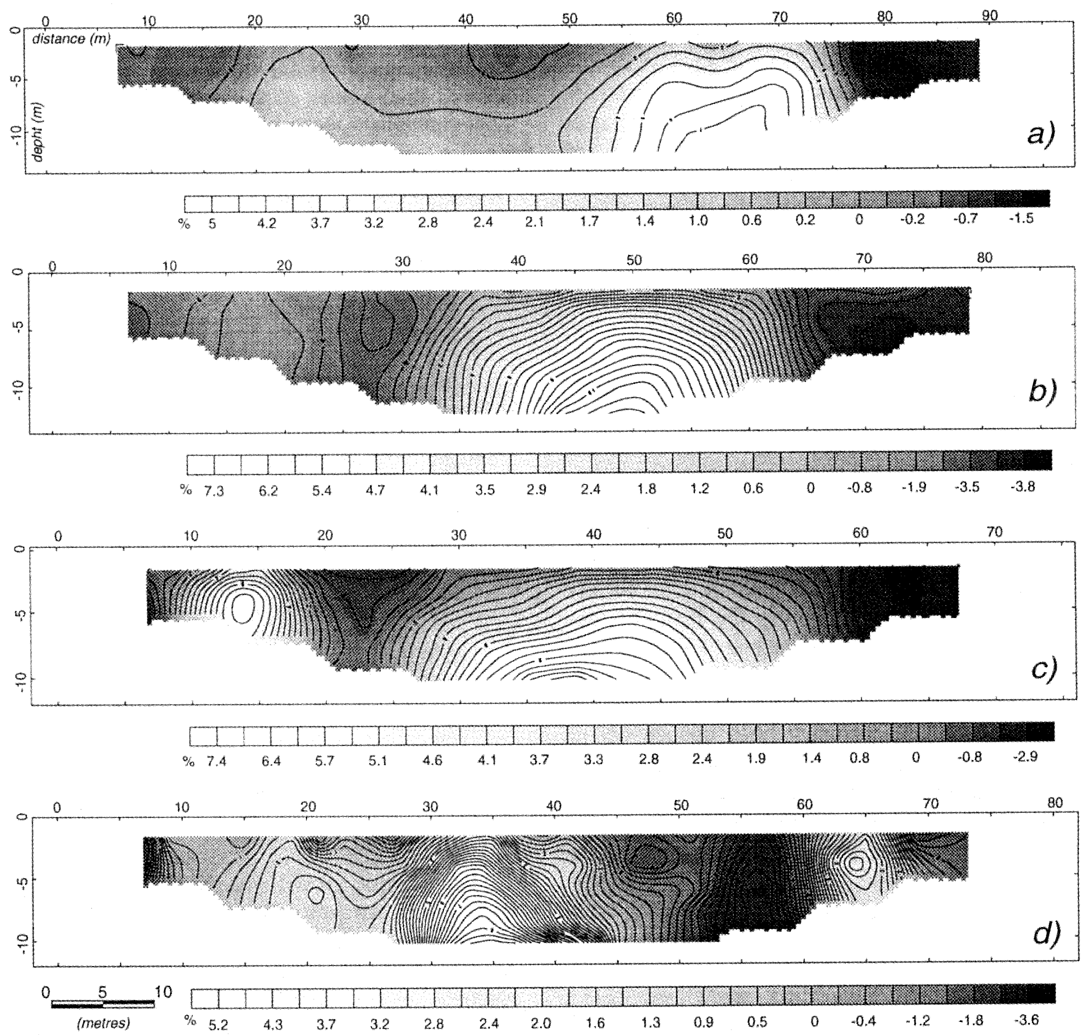

Fig. 7. EM-VLF density pseudosections (*a*, *b*, *c*, *d* indicate the EM-VLF profiles).

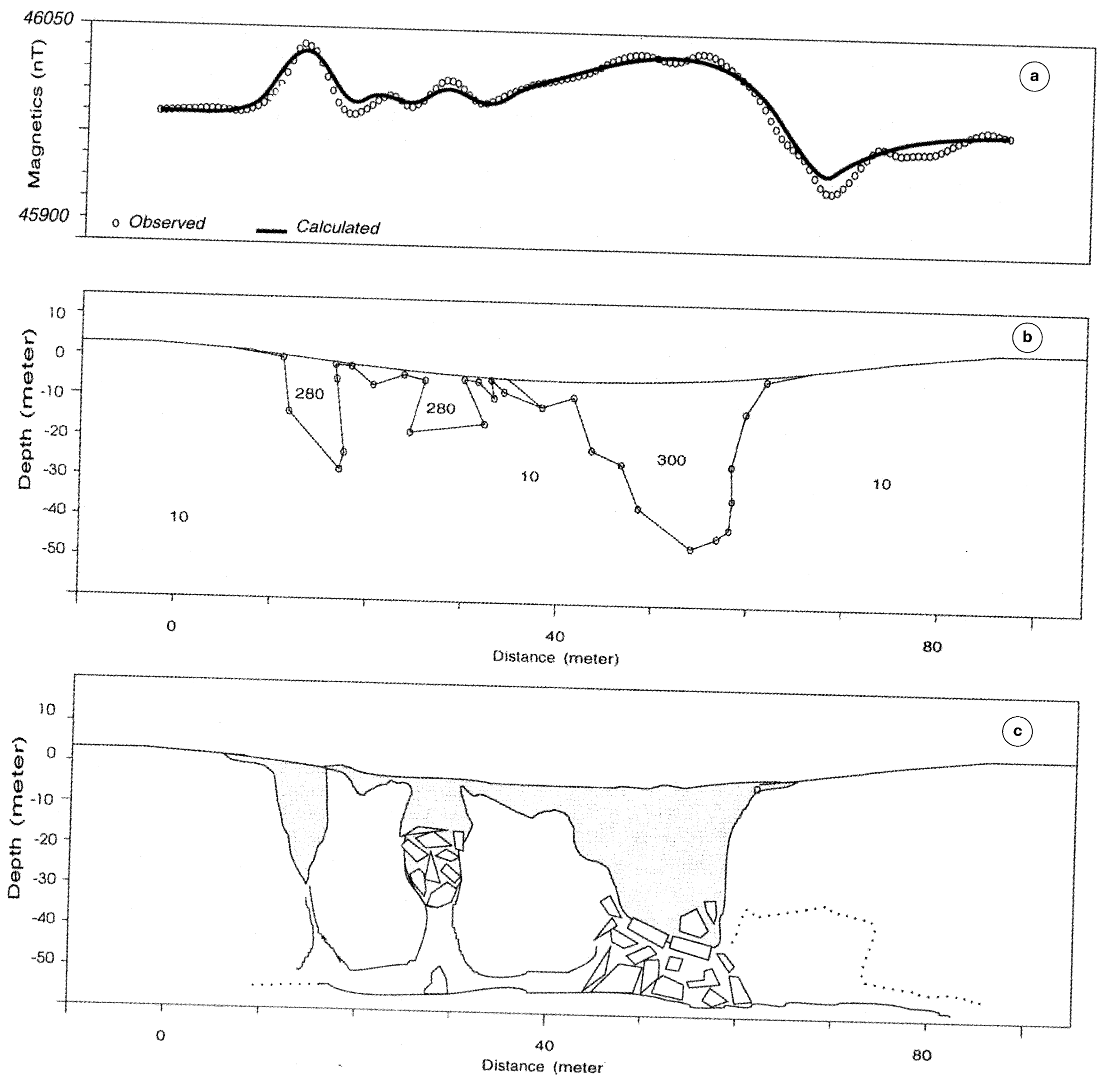

Fig. 8a-c. Magnetic and geological models: a) observed and calculated magnetic anomaly values along line (*e*) (see fig. 3); b) the inversion magnetic model; the numbers indicate the susceptibility values (10^{-6} SI); c) geological interpreted model.

setting (Ogilvy and Lee, 1991). In the pseudo-sections «c», at 15 m (see also fig. 5), and «d», at 65 m, there are also two shallower and localized higher conductive zones. These anomalies may have the same structural source as the corresponding magnetic anomalies (fig. 4a). Therefore the VLF evidence suggests that the cavity is probably filled with soaked clay.

A possible model of the subsurface structure (fig. 8a,b) was obtained by a 2D linear inversion program based on the Marquardt algorithm (Webring, 1985), applied to «e» magnetic data profile (fig. 3). In the proposed geological model (fig. 8c), high frequency anomalies in the southern part of the doline are linked to the presence of two clay filled secondary fractures in the host rock, while the main clay infill, which reaches about 40 m in depth, is localized in correspondence with the topographic minimum. Since southern high frequency anomalies are elongated in the EW direction (fig. 4a), it is possible that a system of fractures larger than expected exists. The southern side of the main body of the doline dips northward; this immersion is coherent with that of the dolomite layers, which may have acted as slide surface. Note that the value of the susceptibility contrast adopted in the model is lower than the observed one; indeed the superficial values of the infill can be enhanced by microcrystalline maghaemite or magnetite from weakly magnetic iron oxides and hydroxides via the reduction-oxidation cycles which occur under normal pedogenic conditions (Thompson and Oldfield, 1986).

All the geophysical data and models in this site agree with the detection of a collapse type doline; its most reliable structural setting, a suggestion about the probable secondary fracture system are also provided. This interpretation is also consistent with other similar structures existing in the surrounding area.

Finally some methodological considerations: two geophysical techniques, gravity and Ground Penetrating Radar (GPR) were not used in this study; they may be fundamental for prospection of buried caverns and valleys and surely they would be effective in integration of the geophysical investigations. In spite of this, GPR is usually quick and inexpensive if there is no clay and the groundwater content is low (Wolfe and Richard, 1992) while a gravimetric (or better microgravimetric) approach (*e.g.* Mirzaei and Bredewout, 1996) is recommended if the presence of a cavern is expected in a not-fractured media. In our case magnetic and electromagnetic data proved that a large volume of the investigated materials, namely infill of the doline, was conductive, magnetic, clay enriched and mostly wet. Also the gravity data, whose acquisition is very time consuming, would have been difficult to interpret because of ambiguity among the sources of the density contrasts. In fact these latter could be undifferentiatedly induced by the changes in porosity and thickness of the fill material and fracture pattern in the dolomite forming the doline framework. For all these considerations, the most cost effective geophysical techniques for these investigations, apart from any attempt to obtain a standard, are indeed those which better enhance the differences in the physical properties of local materials and their subsurface conditions.

This example demonstrated that the applied geophysics can hopefully delineate the buried karst structures like the dolines and can improve the fractures and cavity mapping and their vertical extension estimate.

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