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Karst geosites at risk of collapse: the sinkholes at Nociglia (Apulia, SE Italy)

S. Margiotta[1], S. Negri[1], M. Parise[2], T.A.M.Quarta[1]

1 Dept. of Biological and Environmental Science and Technologie, Salento Univ., Lecce, Italy
2 CNR-IRPI, Bari, Italy; m.parise@ba.irpi.cnr.it

Abstract

This paper focuses on the impacts of contemporary geomorphological processes on fruition activities in a karst area of Salento (Apulia, SE Italy). The work illustrates the results of studies in a sinkhole field at Nociglia, in the Lecce province, recently recognized as geosite and where the shallow phreatic speleogenesis operates close to the water table level with formation of karst caves, successive roof collapse, formation of wide caverns and sinkhole development at the surface. All these features threaten the nearby infrastructures, including a province road. Salento has a great number of active sinkholes, related to natural and anthropogenic cavities. Their presence is at the origin of several problems to the built-up environment, due to the increasing population growth and development pressures. In such context, the detection of cavities, and the assessment of the sinkhole hazard present numerous difficulties. To assess the potential danger from sinkholes, it is important to identify and monitor the main factors contributing to the process. A multi-disciplinary approach, comprising geological, geomorphological and geophysical analyses, is necessary to obtain a comprehensive knowledge of these complex phenomena in karst areas. Geophysical methods can be of great help to monitor the processes identifying and mapping the features related to the underground voids, likely evolving to sinkholes, by detecting contrasts in physical properties such as density and electrical resistivity, with the surrounding sediments. At the same time, recognition of the presence of sinkholes by geophysical methods has to adapt to the different geological conditions, and to take advantage of the integration among the several methodologies available. The territory of Nociglia testifies that the monitoring is essential for the safe exploitation of these type of geomorphosites.

Keywords: sinkhole, karst, geosites, geophysics, cavity detection

1. Introduction

Geosites are objects that have a scientific value for an improved understanding of the Earth's history. They can be of historical, cultural, aesthetic or socio-economic importance, and constitute a form of the landscape with peculiar and significant geomorphological attributes, which qualify them as components of the cultural patrimony of a territory. There is no standard dimension for geosites, some of them being punctual, whilst others might occupy wide areas (Wimbledon 1996; Wimbledon et al. 2000). Geosites of geomorphological interest are defined as "geomorphosites" (Panizza 2001). The geological heritage of Apulia region (southern Italy) has recently strongly been supported by the promulgation of Regional Law no. 33/2009 *"Tutela e valorizzazione del patrimonio geologico e speleologico"* (Safeguard and promotion of the geological and speleological heritage) which promotes the compilation of inventories of sites of geological interest (geosites), allocates economic support and provides a number of measures for their exploitation and protection (Martimucci et al. 2012). These sites may constitute, in fact, the basis for building cultural attractions for tourists during the off-season periods (Margiotta and Sansò 2014; Sansò et al. 2015).

However, the management of geomorphosites at risk of collapse requires an adequate knowledge of the spatial extension of the sinkhole systems in order to mitigate the related risk, as concerns both the likely exploitation of the site, and the nearby infrastructures. Sinkhole formation often causes public safety problems in karst environments (Parise and Gunn 2007; De Waele et al. 2011; Gutierrez et al. 2014).

Apulia region, due to the wide presence of soluble rocks, is actually well known since a long time for the occurrence of such events (Parise and Lollino 2011); therefore, the possibility of occurrence of sinkholes is not unexpected for the area. However, starting since the first years of the present century, the frequency of events had a definite increase, which reached a peak during 2009 and 2010. It has to be noted that, in any case, the documented events represent only a small part of what is actually occurring, since many others (likely, the majority) are not registered due to lack of information, or to rapid infilling of sinkholes by the landowners (Fiore and Parise, 2013).

Identification of the areas potentially interested by the sinkhole hazard presents numerous difficulties, which force to adopt a multi-disciplinary approach, comprising geological, geomorphological and geophysical analyses. To obtain high-resolution results, an important role is played by geophysical surveys. Geophysical methods are efficient for locating karst cavities (van Schoor 2002; Leucci et al. 2004; Ezersky et al. 2009; Nuzzo et al. 2007; Margiotta et al. 2012). However, due to availability nowadays of many techniques, and since each technique is generally considered individually in a specific context, it is difficult to compare and integrate the results coming from different methodologies (Leucci et al. 2004; Kaufmann et al. 2011). Nevertheless, integrated methods are needed to obtain comprehensive knowledge of complex phenomena in karst areas. Geological and geomorphological analyses provided the basic data necessary to constitute a framework to understand the mechanism of sinkholes formation and to guide the choice of the most suitable geophysical techniques, and the interpretation of the measurements as well.

In this work we focus on the ability to monitor the karst phenomena both in depth and spatially through non-destructive and fast methods in an area (Nociglia, southern Salento) characterized by sinkholes and inserted in the Apulian Regional list of the sites of geological interest. Further, the site is part of a landscape of environmental importance resting in a regional park. At this aim, we illustrate the advantages of integrating geological and morphological surveys with surface geophysical techniques such as seismic reflection, geoelectric tomography and ground penetrating radar methods for the identification of sinkhole-prone areas.

2. Geology and morphology

Salento is the terminal portion of Apulia, the heel of the Italian boot, and is an entirely karst land. It is characterized by diffuse karst morphologies, among which there are numerous collapse sinkholes, locally named *"vore"*, or *"spunnulate"* when they are in the proximity of the coastline (as for the origin of local karst terms, see Parise et al. 2003). Locally, sinkholes reach notable extension because of the coalescence of many individual features (Delle Rose and Parise 2002).

The geological setting of this region (Margiotta and Negri 2005; Giudici et al. 2012) comprises a Mesozoic carbonate sequence (hosting the deep aquifer) overlain by thin deposits of Paleogene, Neogene and Quaternary age, with a number of shallow water tables. The mid-southern part of Salento is marked by a wide endorheic area, bounded to the E and the W by degraded fault scarps which are the flanks of two NNW-SSE narrow ridges.

The study area is located at about 100 m a.s.l., at the border of one of the two elongated depressions characterizing the margins of the endorheic area. The geological map (Fig. 1) shows that the depression presents Lower Pleistocene calcareous sandstones (Gravina Calcarenite), Lower Pleistocene clays (Subapennine Clays, not outcropping but present in the subsoil) and Middle-Upper Pleistocene clayey sands (Terraced Deposits). Two main faults separate it from the Miocene fine calcarenites (Andrano Calcarenite) to the NE and the pre-Neogene limestones (Altamura Limestone, out of the geologic map in Fig.1) to the SW. The sinkholes are located in correspondence of the core of a NNW-SSE oriented syncline in the Lower Pleistocene formation.

The Gravina Calcarenite consists of yellowish coarse-grained calcarenites, with abundant fossils, and sandy or bio-limestones layers varying in thickness from a few to 15 cm; this unit unconformably overlies the carbonate Miocene bedrock. The thickness of the formation varies considerably, with a maximum of over 30 m.

The poorly developed surficial hydrography is conditioned by tectonics. Both the endorheic drainage network (about 14 km wide) and the sinkholes were markedly altered by man since the end of 1800 with the construction of channels flowing into the sinkholes. In the 70's the Fontanelle channel walls were cemented and at their end a settling tank was built (20 m x 10 m, depth 4 m; Fig. 2). Sinkholes formation has been responsible for the breaking out of the hydrographic network. This area was, as many other sectors of Salento, originally marshlands, that were subject to reclamation works in the first half of the 20th century; however, many swallow holes and active ponor remained at the sites, as testified by several documents and scientific articles (for instance, Anelli 1964).

The karst complex consists of five cavities, listed in Table 1, which also includes the main morphometric parameters of the caves, as well as the references to the register of natural caves in Apulia, managed by the Apulian Speleological Federation (Martimucci et al. 2012).

As a whole, the study area represents a sinkhole field (named *Vore Spedicaturo*), further complicated by the presence of the man-made channel that altered in some way the original groundwater circulation. Poor management of the area, in addition, repeatedly was in the recent past at the origin of degradation episodes in the area, with solid waste deposits dumped in the dolines, as unfortunately very common in the Apulian karst (Parise and Pascali 2003). From the south, the first cave encountered moving along the Fontanelle channel is *Inghiottitoio Leptospira*, that begins exactly from the end of the channel. From this point, mostly narrow passages bring to the western side of the main sinkhole in the area, where, at the northern wall, the *Vora Grande* system starts. This is a clear collapse sinkhole, which originated an opening in the ground of a few meters, despite its internal dimensions are far more impressive (at least 20 m in depth for a diameter of 15 m). It represents the longest cave in the area, reaching over 110 m of development. Continuing along the axis of the fold to the NW, there is the sinkhole called *Vora piccola* (Fig. 4), masked by thick vegetation and directly connected with the nearby *Vora nuova* (Fig. 4). A catastrophic subsidence event occurred on March 13, 1996, revealing the presence of this latter cave, about 19 m deep and 20 m wide. In the area there were already two large sinkholes from which it is possible to enter the *Vore Spedicaturo* karst system (Beccarisi et al. 1999; Selleri et al. 2003; Parise 2008, and references therein).

Recently, *Vora Grande* was affected by a recovery project for its exploitation: the sinkhole is bounded by a dry stone wall and an overlying wooden fence (Fig. 3a). A path leads in proximity of its bottom (at about 20 m depth; Fig. 3b) where there is a platform that allows to have a general view of the sinkhole (Fig. 3c).

The phenomena are presently active as suggested by the recent development of a new, albeit minor, collapse sinkhole (Fig. 5). A significant drainage from shallow water tables to the deep aquifer is most likely to occur along sub-vertical planes of higher hydraulic conductivity. The underground flow in the sinkhole system is conditioned by the rainfall regime: during intense rainfall events the water quickly reaches the most important sinkholes through the man-made channel and at the NE edge of the settling tank. The galleries forming the explored part of the system are filled by water during the major rainfall events, commonly in autumn and spring.

3. Geophysical methods

Recently in the literature an increasing interest for the use of geophysical methods for applications in karst environments has been observed, typically integrating different geophysical methods and techniques of data acquisition and processing (Samyn et al. 2014; Kaufmann 2014). A geophysical survey was carried out in the study area to identify karst cavities and understand the karst system, with the goal to provide useful information for management of geomorphosites at risk of collapse. At this aim, an adequate knowledge of the spatial extension of the underground cave systems is required in order to mitigate the risk to visitors.

All the geophysical methods are potentially suitable to detect cavities, faults, aquifers, etc, provided that there are high contrasts of physical parameters between these features and the hosting rocks. However, the techniques are strongly influenced by the field conditions. In the Nociglia area quite difficult subsoil conditions are present, due to complex geology at the site, with the presence of tectonic features (joint systems, faults), karst landforms (sinkholes), and different lithotypes (calcarenite, clay) in peculiar hydrogeological conditions. In this case we decided to carried out and to compare three geophysical techniques: the Electrical Resistivity Tomography (ERT), the Ground Penetrating Radar (GPR) and the Seismic Reflection (SR), this latter being the most expensive method. The choice of using different techniques was dictated by the difficulty in obtaining clear information on the subsoil from a single method, and the need to integrate the outcomes from multiple techniques in order to get a more reliable model of the investigated site. Moreover, if a good performance is reached, you can get 2D and 3D models of the study area in a relatively short time. Often, to avoid high costs of the survey, 2D techniques are implemented through the use of profiles. In this case one obtains quite detailed information on the structures of the subsoil intersected by a vertical plane passing through the profile, but no information is obtained in a direction perpendicular to the profile.

In the specific case at Nociglia, conductive materials such as silt clayey layers at the surface and/or in the first meters of depth, and locally soil cover are present. In this context, one of the most suitable methods is represented by the Electrical Resistivity Tomography (ERT; Reynolds 1997; Loke 2012). ERT allows a good depth investigation also in the presence of conductive materials; furthermore, it has a good resolution, and is a fast method.

The ERT method analyses the materials in the subsoil on the basis of their electrical behaviour and can provide two and even three-dimensional high-resolution electrical images of the subsurface (Reynolds 1997; Loke 2015). ERT method uses numerous electrodes, with the distance between the electrodes depending upon the resolution and depth of the particular targets being sought. ERT survey can be carried out using different electrode arrays (dipole-dipole, Wenner, Schlumberger). The electric current is injected into the ground and the voltage signals are measured. From the configuration of the array it is then possible to calculate the apparent electrical resistivity. We used for calculation of the true resistivity the least-square method with an enforced smoothness constraint using the RES2DINV software (Geotomo Software). The inversion method constructs a model of the subsoil using rectangular cells and determines the resistivity value for each of them, minimizing the differences between the observed and the calculated apparent resistivity values (Loke 2015). We also corrected the effect of the topography on the measurements, incorporating the topography into the inversion model. The RES2DINV program has three different methods that can be used to incorporate the topography into the inversion model. The three methods are similar in that they use a distorted finite-element mesh. In all these methods, the surface nodes of the mesh are shifted up or down so that they match the actual topography. In this case, the topography becomes part of the mesh and is automatically incorporated into the inversion model. The difference between these three methods is the way the subsurface nodes are shifted. The simplest approach, used by the first finite-element method, is to shift all the subsurface nodes by the same amount as the surface node along the same vertical mesh line. This is probably acceptable for cases with a small to moderate topographic variation, as in the present case study.

The ground penetrating radar (GPR; Jol 2009) performs very well in resistive environments, but suffers in the presence of conductive materials due to the absorption of the electromagnetic waves. Nevertheless, in favourable conditions it has also been used successfully in karst (Leucci et al. 2004; Nuzzo et al. 2007; Margiotta et al. 2012).

The GPR technique uses high frequency electromagnetic waves to explore the subsurface and is similar in principle to reflection seismic and sonar techniques. A pulse of radar energy is generated on a dipole transmitting antenna that is placed on the ground. The resulting wave of electromagnetic energy propagates downward, where portions of it are reflected (or diffracted) back to the surface when a discontinuity in dielectric permittivity is encountered. Such discontinuities, where reflections occur, are usually created by lithological passages, presence of cavity, faults, joints, etc.

The main limitation of the GPR method is due to the attenuation of the radar signal in the subsoil, which substantially reduces the depth of investigation. Radar signal attenuation with depth is influenced by the electrical conductivity, the relative dielectric permittivity, and the magnetic permeability of the material through which the radar energy propagates. Absorptive attenuation losses of electromagnetic energy increase with the soil humidity and vary with the amount and types of salts present in the medium and in presence of conductive material. Under the very unfavourable condition of wet, clay-rich soils, the maximum depth of GPR penetration can be lower than a meter.

Another suitable method is the seismic reflection, very sensitive to the acoustical contrasts in either the mass density and/or the seismic velocity (Reynolds 1997). In many cases these contrasts occur at the boundaries among geological layers, and/or in presence of a cavity. The seismic reflection and GPR methods are similar in concept, but almost mutually exclusive in terms of where they work well.

Results of the survey

The geophysical surveys were performed in an area with presence of a known sinkhole (Fig. 6). The GPR was carried out near the southern margin of the sinkhole, whilst the ERT and seismic profiles at approximately 3 m from its northern entrance. To evaluate the effectiveness of the GPR technique, some test-profiles (with different ranges of antennae and parameters) were tried, and after careful analysis of the data we decided to use a 500 MHz and 200MHz antennas with 70 ns, sample/scan 512 by means of a Sir 3000 GSSI. R1 and R2 profiles overlapped and their origin coincided; length was, respectively, 19 m for R1 and 14 m for R2. Figure 7 shows the section after processing (horizontal normalization at 0.2 m/scan), clearly indicating two strong signal reflections in its central part, due to the top (about 25 ns) of the sinkhole, highlighting its shape. The electromagnetic (EM) wave velocity plays an important role in defining the depth of the object, in this case a sinkhole. Electromagnetic wave velocity can be estimated from GPR data in several ways (Jol 2009). We chose the quicker method to determine EM wave velocity from the reflection profiles acquired in continuous mode, using the characteristic hyperbolic shape of reflection from a point source (diffraction hyperbola). In our case the estimated velocity is 0.10 m/ns, therefore the top of the sinkhole is at about 1.20 m of depth. Furthermore, in the section relative to 500 MHz some reflected signals up to about 10 ns (approximately 0.5 m in depth) is clearly visible; these reflections are due to fractures of the sinkhole, and were identified because the 500 MHz antenna is at higher resolution than the 200 MHz one. This result suggests to use for further investigation the 500 MHz antenna.

Unfortunately, in other profiles near the zone of interest where there was the presence of clays the electromagnetic signal was absorbed, and GPR resulted not suitable to detect the sinkholes. ERT measurements using both the Wenner and dipole-dipole arrays were performed to obtain information about the local stratigraphy and the karst features. The profiles were collected by means of a Iris Syscal R1. The dipole-dipole array is very sensitive to horizontal changes in resistivity values, and good for mapping vertical structures. The Wenner array is very sensitive to vertical changes in resistivity values and is suitable to map horizontal structures. Forty-eight electrodes were used at a 5 m inter-electrode distance. The subsoil model related to the dipole-dipole array measurements (Fig. 8) shows changes in resistivity in both the horizontal and vertical directions. Therefore, ERT is suitable to discriminate the stratigraphy and, in the central area, to detect two strong resistivity areas corresponding, respectively, to a known and an unknown sinkhole. Interpretation of the model is associated to the following lithologies: a) clay and sandy silts, b) sands with calcarenite levels, c) silts and silty sands, d) calcareous sands. Moreover, it also highlights the presence of a fault.

The two seismic profiles (6 m overlap) were carried out partially covering the same area of the ERT (Fig. 6), by means of a Geometrics Strataview Seismograph (model Nimbus 1220) with 24 active channels, using 100 Hz vertical geophones at 3 m spacing and 23 shot points placed between the geophones. This geometry of acquisition allows processing different CMP (common Mid point). By using several CMP-velocity-analyses the calculation of a one-dimensional velocity- depth-distribution from CMP was obtained. The different models 1D were interpolated to obtain a 2D velocity model (Fig. 9). The qualitative model discriminates the stratigraphy between b (sands with calcarenite levels) and c-d (silts and silty sands, calcareous sands). The imperfect coincidence with the resistivity model is due to lack of data in the 2D CMP-velocity-analysis and to noises. There is, however, a good agreement with the presence of the sinkholes (C in Fig. 9), which indicates that the shallow seismic reflection is potentially suitable to detect these features.

4. Conclusions

Our researches have underlined the importance of monitoring in areas characterized by the presence of karst geosites in order to mitigate the risk for exploitation of the site. The relationship between human activities and geomorphological heritage should lead to further evaluation and protection strategies.

Geological and geomorphological analyses provided the basic data necessary to constitute a framework to understand the mechanism of sinkhole formation and at the same time to guide the choice of the most suitable geophysical techniques, and the interpretation of the measurements as well. Different geophysical methods (GPR, seismic and ERT) were applied in order to point out their ability to locate the main karst conduits and caves. Even though it appears that all three methods can detect the cavities, GPR method appears as the most resolute, while the method producing the best compromise between resolution and investigation depth is the ERT that, even in presence of conductive materials, allows identification of the sinkhole features.

From the analyses of the outcomes of the geophysical surveys it can be noted that the quicker methods are ERT and GPR. Both can be used to locate unknown sinkholes, and also for monitoring such features. As for monitoring actions, a possibility might be to delimit the areas affected by sinkholes, creating a network of electrical sensors to perform continuous measurements in order to evaluate any lowering of the ground. In alternative, repeated measurements on the critical areas could be carried out on a monthly basis.

In the case of absence of conductive material at the surface, use of GPR could be preferable, as the evolution of the sinkhole could be estimated with more precision by means of this technique, as evidenced by the results obtained with the 500 MHz antenna.

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FIGURE CAPTIONS

Figure 1 – Geological map of the Nociglia area (Salento, Apulia, SE Italy). The lower right inset shows location of the area. The lower left inset indicates the distribution of the caves discussed in the text.

Figure 2 – Cemented channel walls leading to the tank built in the 70's.

Figure 3 – Exploitation works at Vora Grande: a) entrance of the site exploited for tourists; b) vegetated walls of the sinkhole, seen from within, showing the entrance to the cave in its lower part; c) pathway leading to the bottom of the sinkhole.

Figure 4 – Vora Nuova, the sinkhole that opened on March 13, 1996. In the background, masked by vegetation, Vora Piccola is visible.

Figure 5 – The most recent sinkhole, with opening about one meter-wide, located nearby Vora Grande: a) picture taken few months after the opening, in 2007; b) the situation today (the sign says "Warning! Imminent collapse risk".

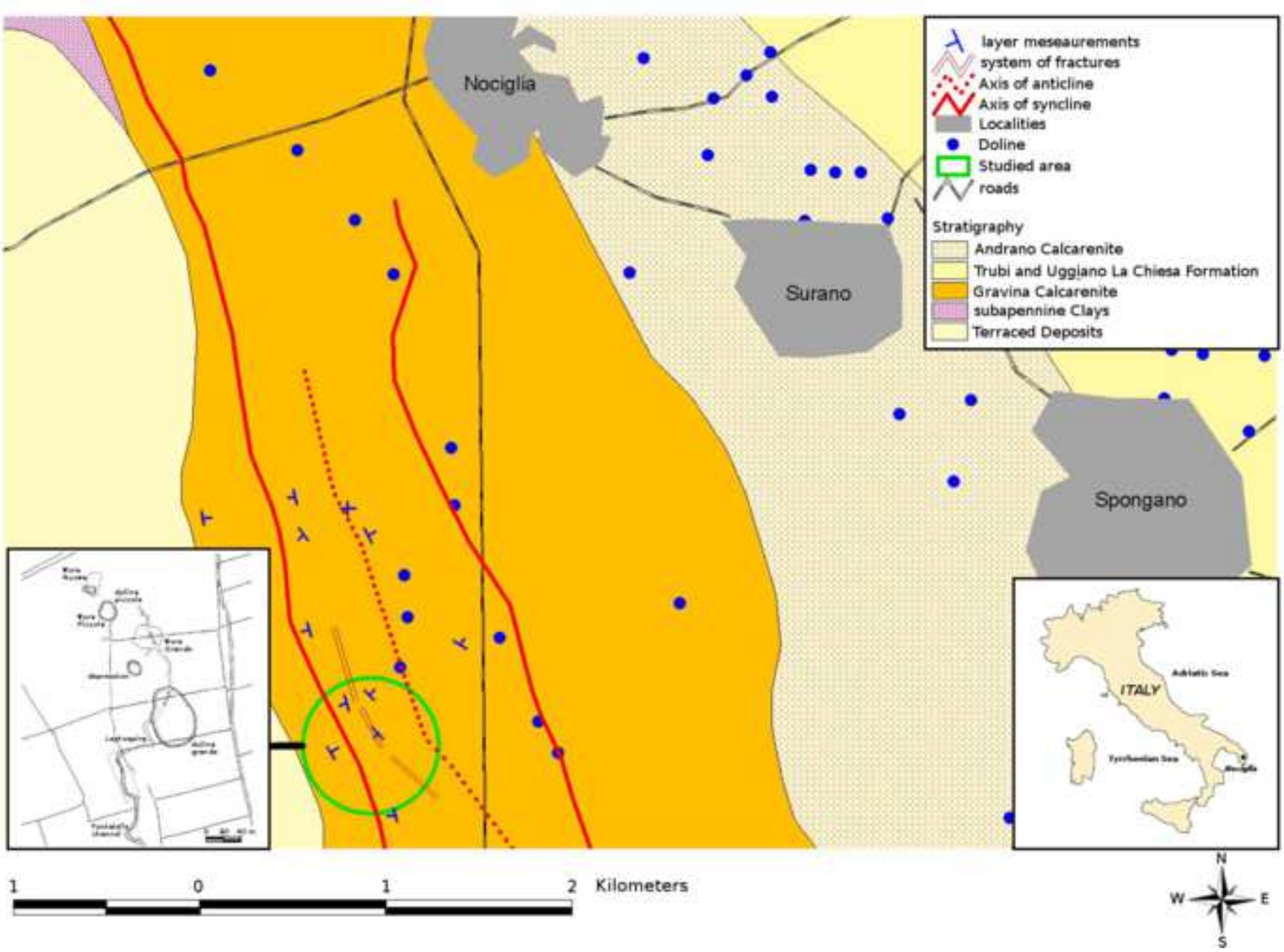
Figure 6 - Location of the geophysical surveys.

Figure 7 - a) Radar section relative to the R1 profile, acquired with the 500 MHz antenna; b) radar section relative to the R2 profile, acquired with the 200 MHz antenna.

Figure 8 - Electrical Resistivity Tomography (ERT), using forty-eight electrodes at a 5 m inter-electrode distance and with the dipole-dipole array measurements. Key: a) clay and sandy silts, b) sands with calcarenite levels, c) silts and silty sands, d) calcareous sands, B,C) cavity F) fault.

Figure 9 - 2D seismic velocity model. Letters B and C indicate the cavities.

Figure 1


Nociglia
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Axis of syncline
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Stratigraphy
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Trubi and Uggiano La Chiesa Formation
Gravina Calcarenite
subapennine Clays
Terraced Deposits
ITALY
Adriatic Sea
Tyrrhenian Sea
Nociglia
1
0
1
2
Kilometers
N
W
E
S

Figure 2

Figure 3

Figure 4

Click here to download Figure: figure4.jpg

Figure 5

Figure 6

Click here to download Figure: figure6.tif

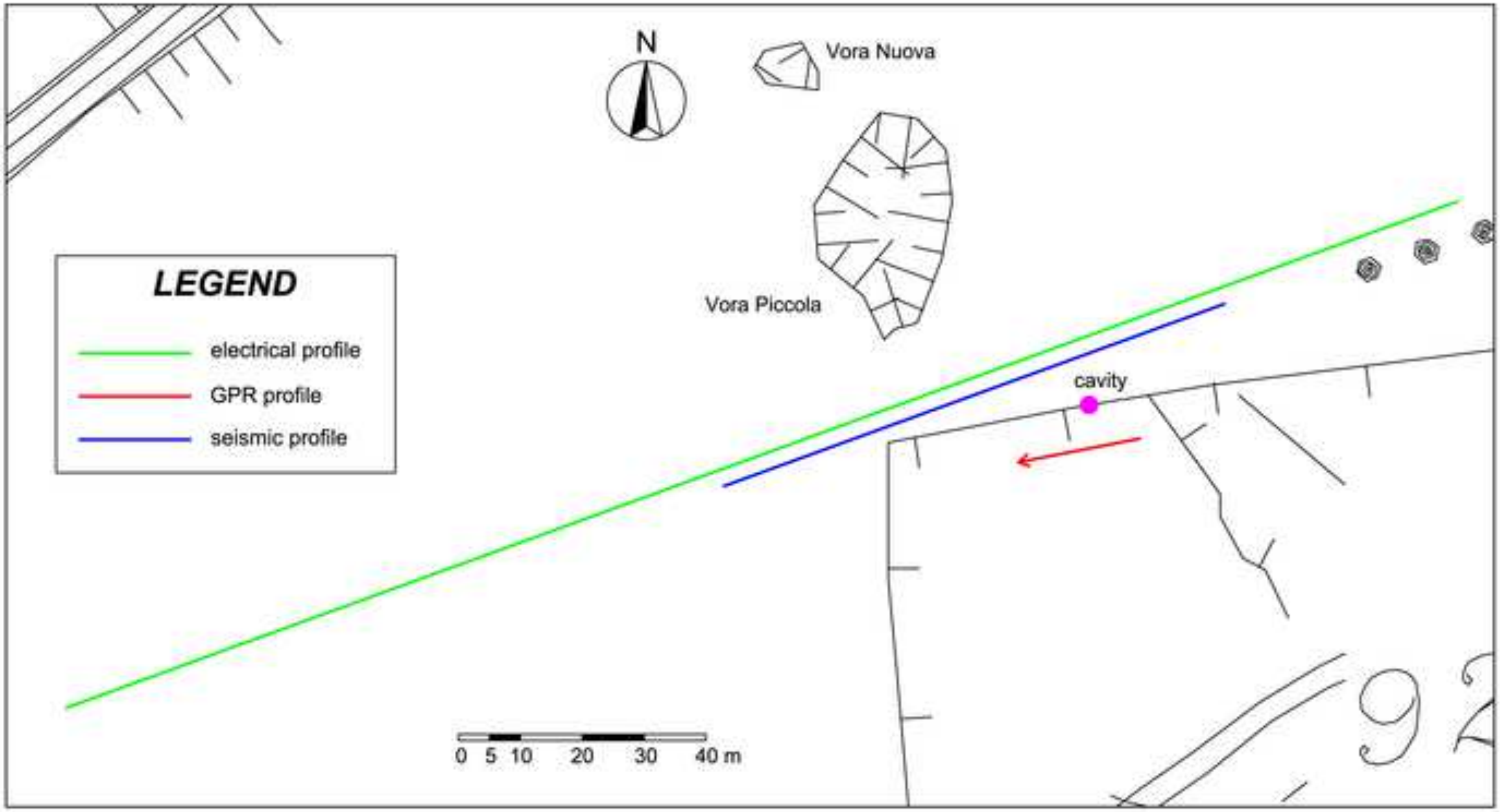

Figure 7

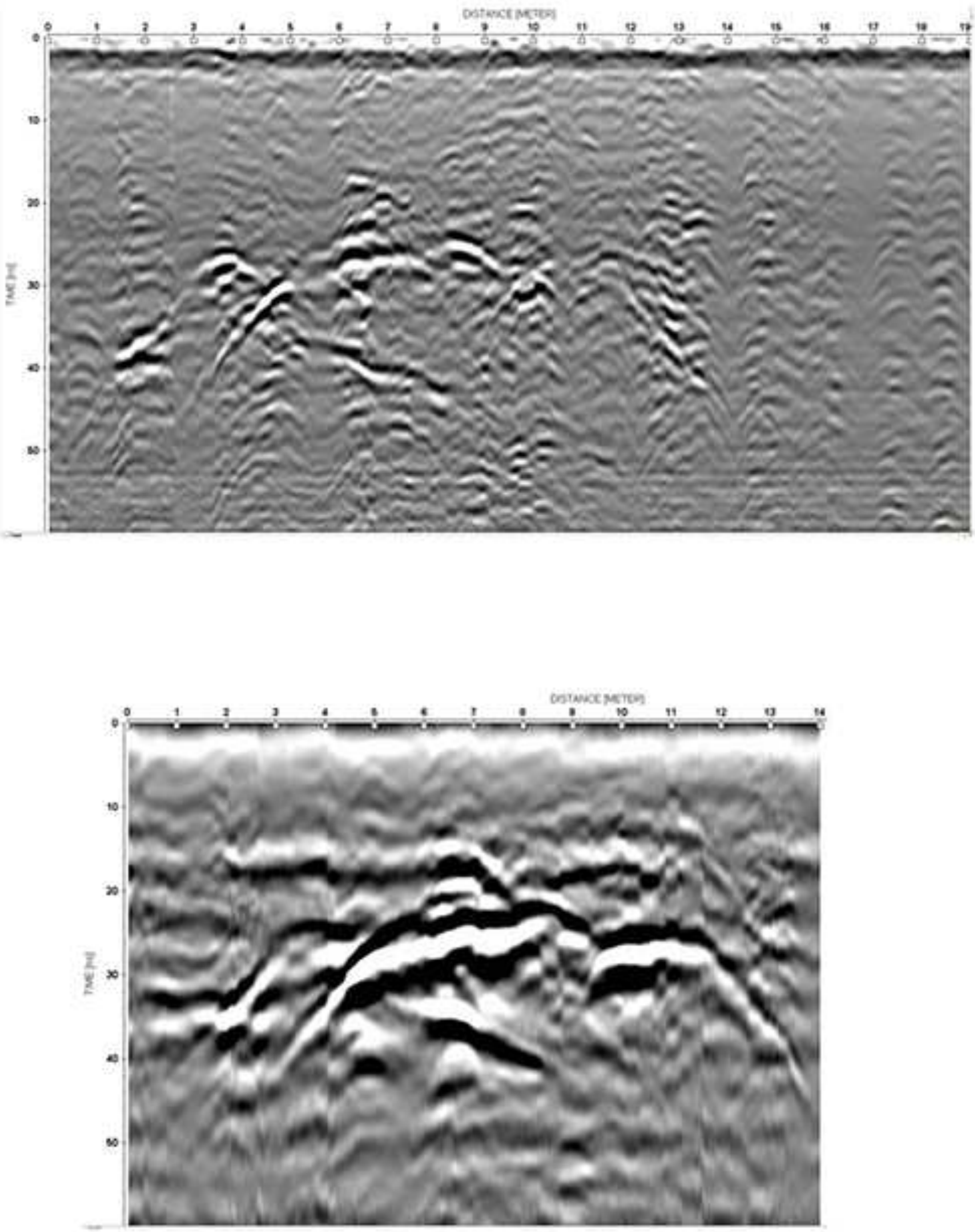
DISTANCE [METER]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
TIME [ns]
0
10
20
30
40
50
DISTANCE [METER]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
TIME [ns]
0
10
20
30
40
50

Figure 8

Click here to download Figure: figure8.tif

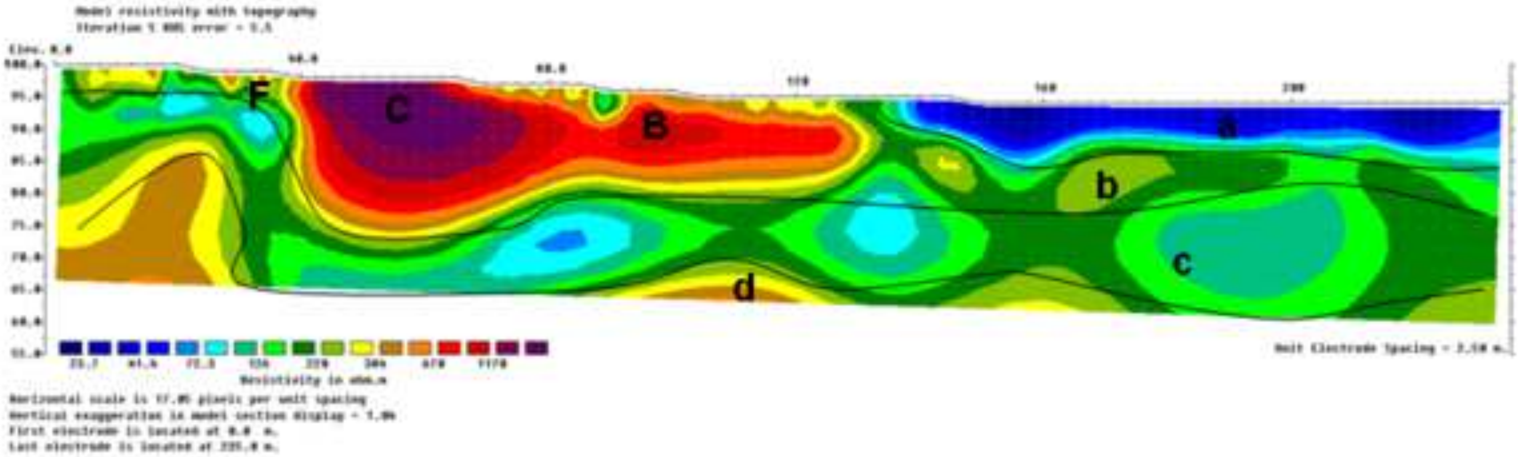

Figure 9

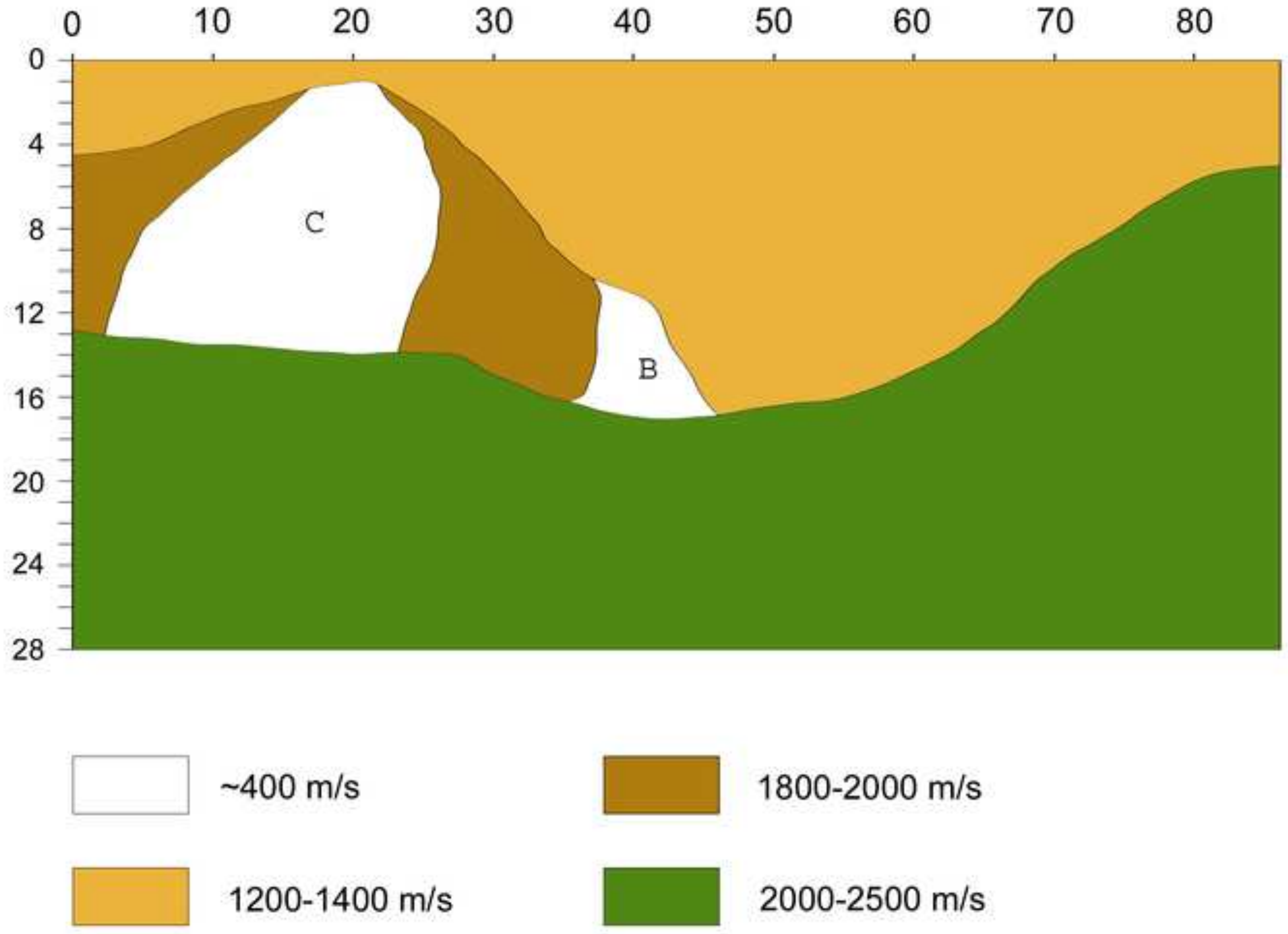
0
10
20
30
40
50
60
70
80
0
4
8
12
16
20
24
28
C
B
~400 m/s
1800-2000 m/s
1200-1400 m/s
2000-2500 m/s

Table 1 – List of caves in the Nociglia area. The cadastral number refers to the Register of Natural Caves in Apulia, managed by the Apulian Speleological Federation (http://www.fspuglia.it/).

name(s)	*cadastral number*	*depth (m)*	*development (m)*	*diameter (m)*
Vora Grande di Surano (Vora dello Stige; Vora di Spedicaturo)	PU 192	27	121	20
Inghiottitoio Leptospira	PU 1557	7	90	
Vora Nuova	PU 1558	19	25	23
Vora Piccola	PU 1559	14	52	21
unnamed sinkhole	not in the register	5	n.a.	1