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DIRECT AND INDIRECT PROSPECTING TO DETECT AND CHARACTERISE SINKHOLE FEATURES IN URBAN EVAPORITIC ENVIRONMENTS

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EXTENDED ABSTRACT

I *sinkholes* di origine naturale possono essere riconosciuti in aree caratterizzate da un substrato carsificabile, sia esso carbonatico o evaporitico. Geomorfologicamente, si possono trovare in cresta, in versante, ma anche in conche intramontane, terrazzi alluvionali e in corrispondenza degli altopiani carsici. Il Friuli Venezia Giulia (FVG) racchiude in sé tutti questi contesti rendendo il territorio regionale un sito ideale per lo sviluppo di queste forme. Su 20000 depressioni mappate, la maggior parte è dovuta a processi di dissoluzione, anche se numerosi sono i fenomeni di subsidenza. La pericolosità e l'attualità legata a questi ultimi è testimoniata dal recente *sinkhole* (collasso avente 18 m di diametro e 15 m di profondità) verificatosi nel 2022 a soli 150 m da un centro abitato.

In aree urbanizzate, piuttosto che in contesti extraurbani, la presenza di *sinkhole* costituisce un rischio maggiore in quanto i segni premonitori tendono ad essere obliterati dalle infrastrutture e dagli interventi di ripristino.

Negli ultimi vent'anni, grazie anche al supporto del Servizio geologico della Regione FVG, i ricercatori del Dipartimento di Matematica, Informatica e Geoscienze dell'Università di Trieste hanno lavorato alla predisposizione di un protocollo metodologico per lo studio e la caratterizzazione dei sinkhole in ambiente evaporitico urbano.

L'area dell'abitato di Quinis (comune di Enemonzo, UD), in cui sono documentati fenomeni di *sinkhole*, anche catastrofici, fin dalla fine del 1800, è stata scelta come area test nella quale mettere a confronto diverse tecniche di indagine valutando quelle più idonee ed efficaci. Quinis si trova in un'area intravalliva, in sinistra idrografica del Fiume Tagliamento, in cui i depositi eluvio-colluviali e alluvionali giacciono su un substrato roccioso evaporitico. Nel corso dell'ultimo secolo, numerosi sono gli sprofondamenti che hanno interessato questo territorio come pure gli interventi di manutenzione o demolizione degli edifici e di ripristino della rete viaria. Diverse abitazioni sono state abbattute ed alcune presentano ancor oggi significative lesioni. Lo stesso campanile della frazione è visibilmente pendente, mentre la chiesa è stata demolita a causa delle lesioni non sanabili.

Gli studi effettuati nell'area ricoprono una vasta gamma di indagini e tecniche che hanno messo in luce l'importanza e l'efficacia di un approccio multidisciplinare e integrato. In primis, un'ampia ricerca bibliografica ha fatto emergere la presenza e la storicità di questi fenomeni, alcuni dei quali documentati anche fotograficamente. Le segnalazioni degli abitanti e le successive analisi geologiche e geomorfologiche hanno confermato l'avanzato e continuo stato di criticità dell'abitato. Partendo da una scala d'indagine più ampia, sono stati analizzati i dati interferometrici e LiDAR nell'intero Comune. Questi hanno permesso di delineare e circoscrivere un'area più ristretta, in evidente stato di subsidenza, sulla quale ci si è focalizzati successivamente con indagini via, via di maggior dettaglio. In quest'area sono state impiegate non solo tecniche investigative geofisiche tradizionali come la tomografia elettrica (ERT), la sismica a rifrazione e riflessione (REFR, REFL), ma anche approcci più moderni quali ad esempio l'utilizzo del Ground Penetrating Radar 3D e, in alcuni ambienti specifici, dell'elettromagnetometro multi-frequenza (FDEM).

Dagli studi è emerso che, in un ambiente antropizzato dove le indagini dirette non sempre sono applicabili a causa della presenza di infrastrutture e sottoservizi, l'utilizzo di tecniche geofisiche integrate risulta quello più appropriato, anche perché permette di investigare ampie aree in tempi relativamente brevi. Nei contesti evaporitici come quello di Quinis, dove le caratteristiche petrofisiche dei materiali (sedimenti, roccia alterata e sana) sono molto simili, l'ERT e la REFR, non si sono dimostrate sempre efficaci, anche quando supportate da indagini dirette. La REFL, al contrario, ha fornito ottimi risultati permettendo di individuare i rapporti spaziali e le geometrie dei depositi di copertura e del substrato. Il 3D GPR avendo grande risoluzione, ma bassa profondità di investigazione, non permette di osservare direttamente i fenomeni di *sinkhole* nel substrato, ma consente di distinguere le zone con maggior deformazione e le varie fasi di ripristino (ripetuti riempimenti di avvallamenti e buche) del manto stradale succedutesi nel corso degli anni. Questa tecnica, ripetuta nel tempo, riesce non solo a delineare le aree in subsidenza, ma anche a monitorarne l'evoluzione. L'esperienza maturata a Quinis è stata poi applicata proficuamente anche in altri contesti regionali, ottenendo risultati apprezzabili e dimostrando come quanto suggerito possa essere utilmente utilizzato anche in altre zone affette da problematiche simili.

ABSTRACT

Natural subsidence sinkholes (according to Gutiérrez *et alii*, 2008, 2014; Parise 2019, 2022), both in carbonates and evaporites, represent a severe threat to man-made structures. Especially when bedrock is mantled and in urban areas, the identification and characterization of these phenomena is always challenging. For this reason, multidisciplinary and multi-technique approaches are recommended and in detail, the integrated use of geophysical techniques (Electrical Resistivity Tomography, Reflection and Refraction Seismic, Electromagnetometers and 2D Ground Penetrating Radar - GPR) and most recently developed 3D GPR is strongly suggested. Thanks to the Agreements signed between the University of Trieste and the Geological survey of the Friuli Venezia Giulia Region (NE Italy), since 2007 the researchers approached these issues in specific test site areas. From the studies in urban mantled evaporitic bedrock areas, emerged the supremacy of the 3D GPR jointly with reflection seismic, being the former able to identify with high accuracy and detail shallow deformations, and the latter the best approach to identify the thickness of cover materials, the morphology of the bedrock and the sinkhole location.

Keywords: *sinkholes, geophysical investigations, evaporites.*

INTRODUCTION

Numerous European regions experience ground subsidence issues caused by the existence of soluble rocks. Their dissolution and surface or subsurface deposits, coupled with internal erosion and deformational processes, can give rise to depressions known as sinkholes. This poses a significant geological hazard, as witnessed in various instances such as in France (Thierry *et alii*, 2009), Germany (Dahm *et alii*, 2010; Krawczyk *et alii*, 2012), Lithuania (Paukstys *et alii*, 1999), Russia (Koutepov *et alii*, 2008), Spain (Gutiérrez *et alii*, 2008a; Sevil *et alii*, 2020), United Kingdom (Cooper *et alii*, 2011), Albania (Parise *et alii*, 2004), USA (Kuniansky *et alii*, 2016), South Africa (Buttrick *et alii*, 1998), Iran (Taheri *et alii*, 2015) and Italy as well (De Waele *et alii*, 2017; Calligaris *et alii*, 2017, 2020 and references therein).

More precisely, these phenomena can affect and affected urban areas causing impressive damages to the infrastructures and posing risks to the inhabitants. Among the others, the most recent events captured by the web, can be summarized as follows:

1. The Guardian reported about a sinkhole the size of a car that opened up on a street in south-east London (UK) on the 11th September 2023. The feature took up almost an entire lane of the road and run alongside the kerb next to a postbox (https://www.theguardian.com/world/2023/sep/12/sinkhole-size-of-a-car-appears-on-street-in-south-east-london);
2. Fox News reported a sinkhole, 15-meter wide, formed on 8th September 2023 in same Florida area (Lakeland, USA) as 23-meter sinkhole formed in June of the same year; (https://nypost.com/2023/09/11/florida-sinkhole-50-feet-wide-forms-in-same-area-as-75-foot-sinkhole-months-earlier/);
3. On 25th February 2023, the Meteored Italia, reported about a new sinkhole appearance on the day before, 37 meters in diameter and 12 meters in depth. The catastrophic event occurred in the Karapınar district of Konya, in Turkey probably induced by an earthquake of 4.3 Magnitude (https://www.ilmeteo.net/notizie/attualita/gigantesca-voragine-appare-in-turchia-terremoto-video.html);
4. The NBC New York reported a sinkhole occurrence in Long Island (New York, USA) homeowner's backyard on 26th September 2023. It was about 3 m wide and 2 deep; (https://www.nbcnewyork.com/news/local/large-sinkhole-opens-up-in-long-island-homeowners-backyard/4714215/);
5. The ABC Eyewitness news documented a giant sinkhole which swallowed a van in New York City's Bronx borough (USA). The event happened on 19th July 2022; (https://abc7.com/bronx-sinkhole-swallows-van-new-york-city-video-nyc-falls-into-ground-weather/12060809/);
6. The Guardian on 8th January 2021 published a news regarding a giant sinkhole opened in hospital car park in Naples (ITA). The local hospital district said the 20-metre-deep 2,000 sq meter sinkhole opened at dawn. The implosion could have been caused by an infiltration of water underground from the recent heavy rains; (https://www.theguardian.com/world/2021/jan/08/giant-sinkhole-hospital-car-park-in-naples-italy);
7. The Messaggero Veneto, reported about a sinkhole occurred on 21st April 2022 at Raveo (Esemon di Sopra, ITA). The feature was 18 m wide and 15 m deep; (https://messaggeroveneto.gelocal.it/udine/cronaca/2022/04/22/news/sondaggi-nei-terreni-dopo-la-voragine-nel-frutteto-profonda-15-metri-1.41391985).

The above-mentioned examples represent a tiny part of the phenomenon. In all cases, also listening to the direct witnesses, what is shocking, is the lack of premonitory signs: often sinkholes just occur promptly in natural environments as well as in urban areas. In the latter, the presence of man-made structures (e.g. asphalt roads, cement buildings, etc…) and the restoration activities (e.g. hole fillings, building cracks renovation) do not allow to observe (or they mask) the starting phases of the sinking phenomena sometimes up to the catastrophic events, thus representing still more hazardous situations. In addition, direct investigations as geological and geomorphological survey, trenches and drilling are not always possible to be realized. Therefore, the use of indirect investigations as PS-InSAR technologies (Persistent Scatterer Interferometric Synthetic Aperture Radar) and geophysical approaches, are the best choice to evaluate the hazard and the risk. But a single method is not enough to identify a sinkhole in a complex mantled karst environment. A multidisciplinary and multi-technique approach is thus recommended (Gutiérrez 2016; Calligaris *et alii*, 2023).

From the experience gained, it resulted that the integration between traditional geophysical techniques as the Electrical Resistivity Tomography (ERT), Reflection (REFL) and Refraction (REFR) seismic, the most recent 3D Ground Penetrating Radar (GPR) and in some specific contexts the low frequency Electromagnetometer (FDEM), allow to identify those premonitory signs which otherwise could not be recognized. These non-invasive investigative techniques have been applied in the village of Quinis (NE Italy) for the first time, allowing the specific investigation of the subsurface around damaged buildings and in particularly urbanized areas where other investigative approaches cannot achieve such a high level of both vertical and areal resolution.

THE STUDY AREA: GEOLOGICAL, STRUCTURAL AND GEOMORPHOLOGICAL SETTINGS

The FVG region (Fig. 1a and 1b) which covers an area of approximately 8,000 km², is unique for its geological diversity, with outcropping rocks spanning from the Paleozoic to the Present. In the northern sector bordering Austria, older rocks from the Ordovician to Triassic period outcrop. Moving south, the Carnian and Julian Alps and Prealps exhibit mainly Triassic rocks, fostering a myriad of karst landforms (nearly 40% of the region). Cretaceous and Paleogene outcrops appear south of the Alpine Chain. Geomorphologically, the northern Alps gradually diminish their altitude southward, with the Prealps bordering the northern part of an extensive alluvial plain with relevant moraine evidences. The evaporite sequences acted as tectonic lubricant facilitating the detachment of Permian or Permo-Triassic units from overlying Triassic-Jurassic ones. These evaporites, constituting around 1% of the regional territory, are identifiable in E–W-oriented valleys, corresponding to major Alpine thrusts (CR Comeglians-Ravascletto thrust, SA Sauris thrust and AT Alto Tagliamento thrust) (Fig. 1b). Of this, 25% is Permian, and 75% is Triassic. Notably, evaporite outcrops are partially concealed by alluvial, glacial deposits, or non-karst rocks. The Tagliamento Valley exemplifies this, showing phenomena due to mantled Upper Triassic gypsum and other evaporites. The latter (Raibl Formation) are part of a transgressive sequence, marking a global climatic event at the end of the Upper Carnian. The litho-facies, as described by Carulli (2006) and Venturini (2009), include grey marly dolostones and light grey vacuolar dolostones with centimeter-thick marly layers. The total thickness of the sequence is approximately 600 meters (Fig. 1b, pink color).

In this geological context fits the area of Quinis hamlet (Enemonzo municipality) where Quaternary deposits as glacial till, alluvial and colluvial levels mantle the evaporitic bedrock. The complexity of the depositional and tectonic patterns reflects on the heterogeneity of the area. The thickness of the sediments varies from few meters to the North, deepening towards the South up to more than 60 m in correspondence with the Tagliamento River terraces.

In the Quinis area, already Marinelli (1898) described subsidence phenomena which have been confirmed by Cosano (1947) who noted geostatic instabilities attributed to the presence of chalks in the bedrock. Historical phenomena were documented by Gortani (1965) who described a significant cover-collapse sinkhole occurred in 1964 near the Tagliamento River (Busetti *et alii*, 2020). In the last 20 years, there has been a surge in similar phenomena. In the entire Enemonzo municipality, 208 sinkholes have been inventoried, of which 46 cover-suffosion, 40 cover-collapse (Busetti *et alii*, 2020), and the remaining with complex/undefined typology. They vary in size from a few tens of centimeters up to 75 meters, with depths ranging from a few centimeters to over 15 meters. In the Quinis hamlet, 32 sinkholes are present and cause significant damages to infrastructures.

MATERIALS AND METHODS

Several geophysical surveys have been carried out in the Quinis hamlet and its surroundings since 2007 to present. Both potentials (ERT and FDEM) and wave fields geophysical methods (REFL, REFR seismic and GPR) have been exploited at different survey locations, resolution scales and penetration depths. ERT surveys encompassed up to 72 electrodes (Syscal Pro – IRIS) with a spacing within the range 1-10 m. Wenner, Wenner-Schlumberger, Dipole-Dipole and Pole-Dipole configurations were tested. FDEM surveys were recorded with different instruments (CMD Explorer - GF Instruments and GEM-2 Geophex with frequency range from 4.1 up to 20 KHz) to get variable penetration depths (spatial sampling 1s). GPR Profiles were collected using different equipment and antennas: ProEx (Malå Geoscience) and the Zond-12 (Radar System) instruments have been used for 2D (and 2.5D surveys) while Minimira (Malå Geoscience) was exploited for full 3D data collection. Several shielded antennas were tested within the range between 250 and 800 MHz, in order to obtain different resolution levels and penetration depths (Spatial sampling interval 5 to 10 cm). Seismic reflection surveys were conducted using both a sledgehammer and a vibrating source (IVI Minivib T-2500 operated with 2,500 lbs peak force spread configuration) with up to 96 channel arrays (2 m long, 6 vertical 10 Hz geophones); the former source was also exploited for refraction seismic in which vertical 14 Hz geophones have been used.

Some of the acquisitions have been repeated through time, making possible to highlight eventual occurred time variations. All the data have been accurately positioned using RTK GPS devices, thus allowing to combine all the data into the same GIS project and to integrate/compare the different measurements.

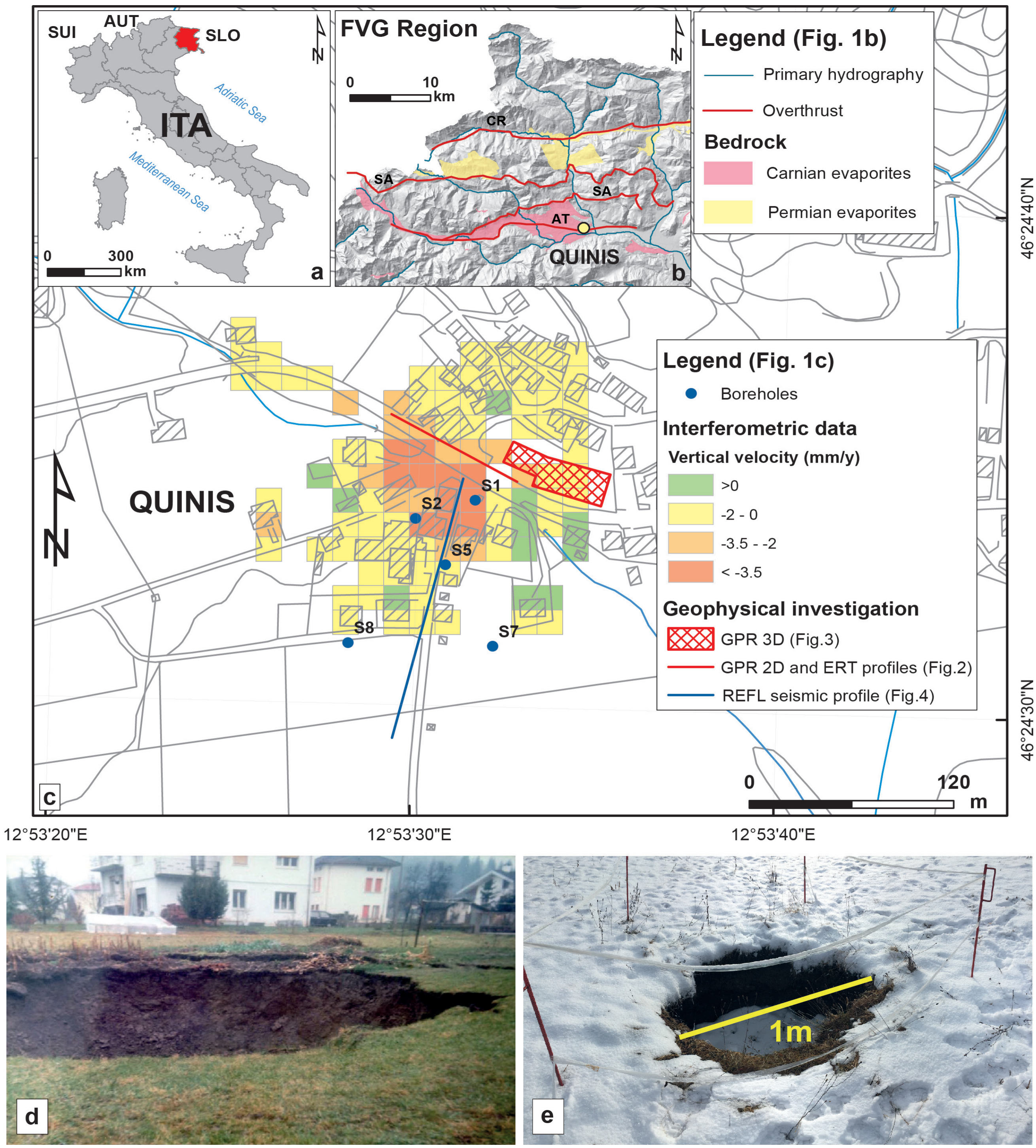

Fig. 1 - Study area. a) The Italian peninsula with in red the Friuli Venezia Giulia Region (FVG); b) North-western side of the FVG, in yellow the Permian evaporites (Fm. Bellerophon), in pink the Carnian (Fm. Raibl) ones. Red lines identify the main overthrusts, blue lines, the rivers; c) focus on the Quinis study area with evidences of downward displacements got from PS-InSAR data (Busetti et alii, 2020) and the traces of the geophysical investigations; d) cover collapse sinkhole in 1977 occurred in a grassy area westerly of Quinis; e) small cover collapse sinkhole in the NE of Quinis, occurred in 2017

RESULTS AND DISCUSSION

Quinis area and its surroundings were used as test site to set up different protocols to identify and characterize sinkholes in urban mantled evaporitic environments. In more than 15 years of studies, direct and indirect approaches were applied. Geomorphological surveys as well as remote sensing (PS-InSAR) data analyses, allowed to identify subsidence areas (Fig. 1c) but not to outline their precise extension and volume.

In urban areas, direct investigations are often not applicable and being punctual do not allow to outline the geometry of the phenomena. On the contrary, indirect investigations, allow 2D and 3D reconstructions without interfering with the existing infrastructures. Therefore, integrated approaches are crucial to image the subsurface geometries at different scales and exploiting different, and often only partially correlated, physical parameters.

In Figure 2 we provide an example of results obtained with different GPR antennas (Fig. 2a, b, c) and with ERT data (Fig. 2d), all collected along the same 84 m long linear profile (Fig. 1c, red line).

2D GPR is able to highlight interesting geometries related to depocenters in which the sedimentary (and anthropic) stratigraphic sequence is more and more deformed for increasing depths. This is typically related to the fact that abrupt or slow vertical deformations in paved zones within urban areas are periodically filled with new asphalt layers or even other filling materials especially for the largest and deepest cases. Also, such newer levels are later deformed thus producing the typical "U" shape structures (see labels d1 to d4 in Fig. 2). Abrupt lateral movements are also often imaged in such a geological context (dotted white lines in Fig. 2). Highest resistive areas are often correlated with such a depocenters due to the periodic re-filling, but from Fig. 2 it is apparent that the overall resolution of GPR data is indeed higher that the ERT one from which the actual geometry of the subsurface structures cannot be evidenced. On the other hand, higher GPR frequencies often do not allow to reach depths higher that 1 or 2 meters, especially when high conductive materials are presents.

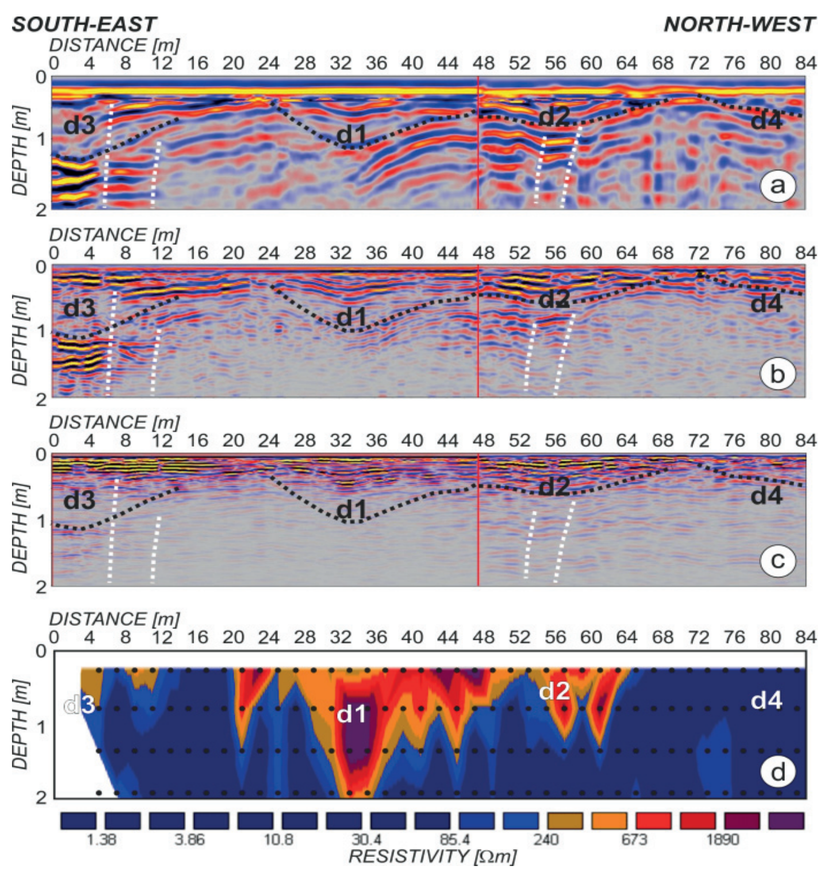

Fig. 2 - Processed and interpreted GPR profiles acquired with different antennas: a) 250 MHz; b) 500 MHz; c) 800 MHz, compared with an ERT (d) acquired along the same path (inverted data). d1, d2, d3 and d4 highlight the positions of 4 depocenters marked by black dotted lines. White dotted lines mark the main lateral variations. Red vertical segments on the GPR profiles depict the transition between two different road pavements (modified after Zini et alii, 2015)

For the study of subsidence phenomena, commonly used GPR techniques are actually 2D or 2.5D (i.e. pseudo-3D), surveys (see e.g. Forte *et alii*, 2021 for further details), with data collected as a set of independent profiles using traditional GPR equipment (Fig. 2). Both the solutions demonstrated the capability to detect shallow deformations related to subsidence (see Fig. 2), but with strong limitations in determining their actual extension.

In recent years, full 3D GPR equipments exploiting antennas arrays have been extensively applied especially for engineering and archaeological purposes (Forte *et alii*, 2021), but only seldom for geological applications. As far as we know, this new technique was never applied specifically for sinkhole detection and monitoring.

In Fig. 3 an example of results obtained with a full 3D GPR acquisition is provided. Data processing and imaging is performed in a data cube volume with bins (i.e. cells) 8 by 8 cm wide and about 10 to 13 cm high, depending by the velocity of the EM waves propagating in the subsurface. It is therefore possible to slice the data volume both to get vertical sections (i.e. the typical GPR profiles) with any direction, or depth slices which are very helpful to identify and interpret the structures at various depths. This allows to identify not only the 2D shape of deformations (Fig. 3c) but also their spatial extension and 3D morphology (Fig. 3a, b). In the example provided, even though several pipes are present and partially mask the target of the survey related to subsidence phenomena, it is clearly possible to highlight two depocenters having irregular shape and deforming the subsurface starting from a depth of a few decimetres (H0). In the 2D profile (Fig. 3c) it is interesting to remark that even below the high-reflective horizon H1, interpreted as the contact between the landfill material (above) and the natural sediments (below), the deformation can be still recognized (see e.g. horizon H2).

In the Quinis area and its surroundings, REFR surveys did not allowed to clearly identify the evaporitic bedrock, possibly

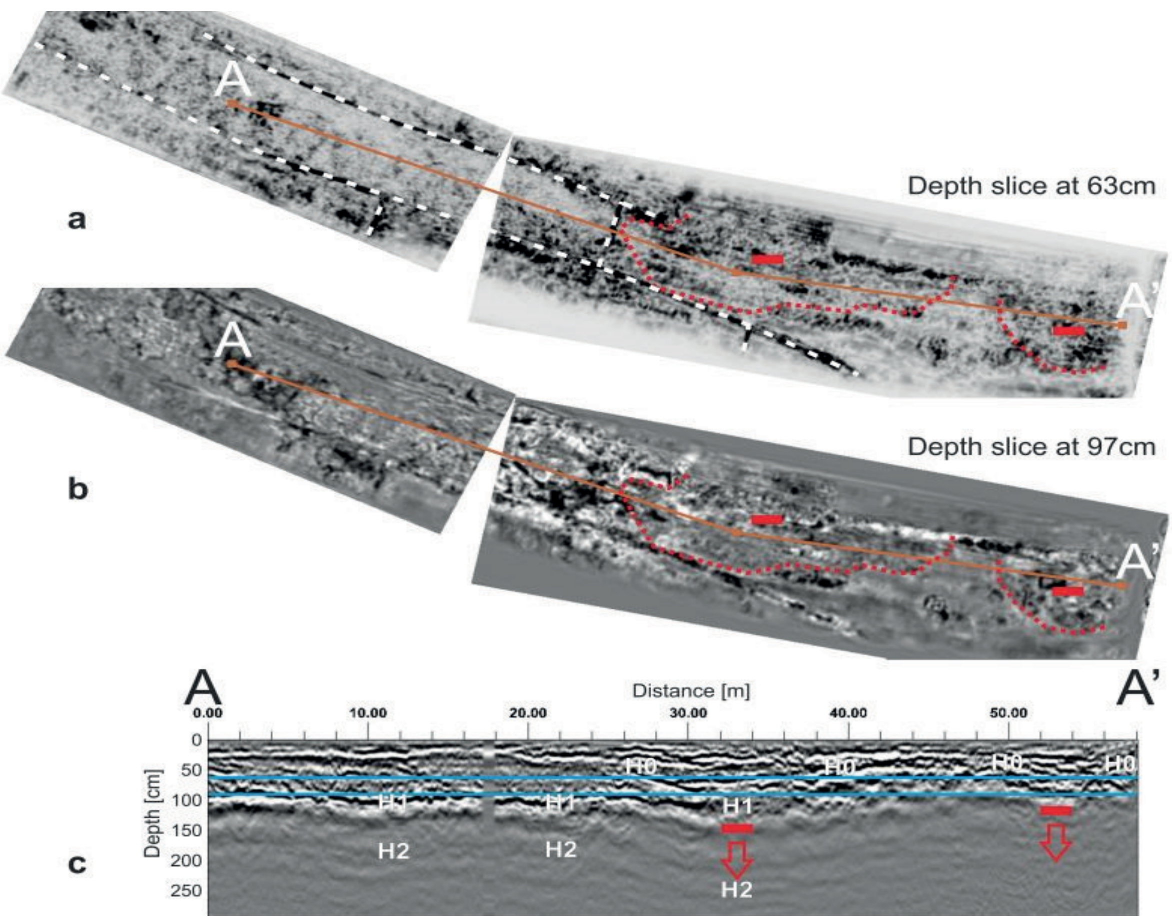

Fig. 3 - Example of results of full 3D GPR surveys. a) and b) are two exemplary depth slices at 63 and 97 cm below the topographic surface, respectively, while in c) a profile crossing the area is shown. All red features are related to two interpreted depocenters: dotted lines mark their lateral extension, while the arrows the maximum deformation. Dashed white lines highlight some of the various pipes present in the area. Blue lines in c) mark the depth of the two depth slices in a) and b). H0, H1, H2 are GPR horizons, see text for further details

due to velocity inversions and/or to gradual velocity changes, while such a target was clearly imaged by REFL (Fig. 4). In particular, the bedrock showing a not planar morphology was correctly imaged and its inferred depth was validated by the stratigraphy of available boreholes. The FDEM measurements collected within the urban area, as expected, are very noisy and suffer the presence of metals both above and below the topographic surface, while the surveys performed to the south of the village (in a grassy area) both collecting single profiles and grids (here not shown) were able to detect low resistivity anomalies corresponding to still active or former sinkholes.

CONCLUSIONS

Characterizing sinkholes in urban mantled evaporitic environments is always challenging. An integrated approach is mandatory and a single technique is often not sufficient to get reliable results. Thanks to a 20-years' experience in studying such features, we can make the following general considerations:

1. Geomorphological surveys, remote sensing data analyses, and direct investigations are essential to preliminary analyze also wide areas but they cannot be considered resolutive;
2. ERT can explore the shallower and deep subsurface, but with low overall resolution. Such a technique can be exploited as a preliminary approach at relative low price, to indicate where to focus for further investigations;
3. FDEM is useless in urban areas characterized by the presence of technological networks, but express interesting results in grassland or field areas;
4. 2D GPR (i.e. the typical GPR profiles) can provide reliable, high resolution information of the shallow subsurface depicting the presence of local depocenters and their 2D extension. 2.5D surveys (i.e. the integration of several profiles) allow to obtain a rough idea about the spatial extension of the subsiding areas with a low detail level.
5. 3D GPR, despite the limited penetration depths, demonstrated its effectiveness and versatility to locate and map deformations even when multiple infrastructures such water, sewerage and technological networks are present. In addition, being not time consuming and costly effective, it allows to survey also

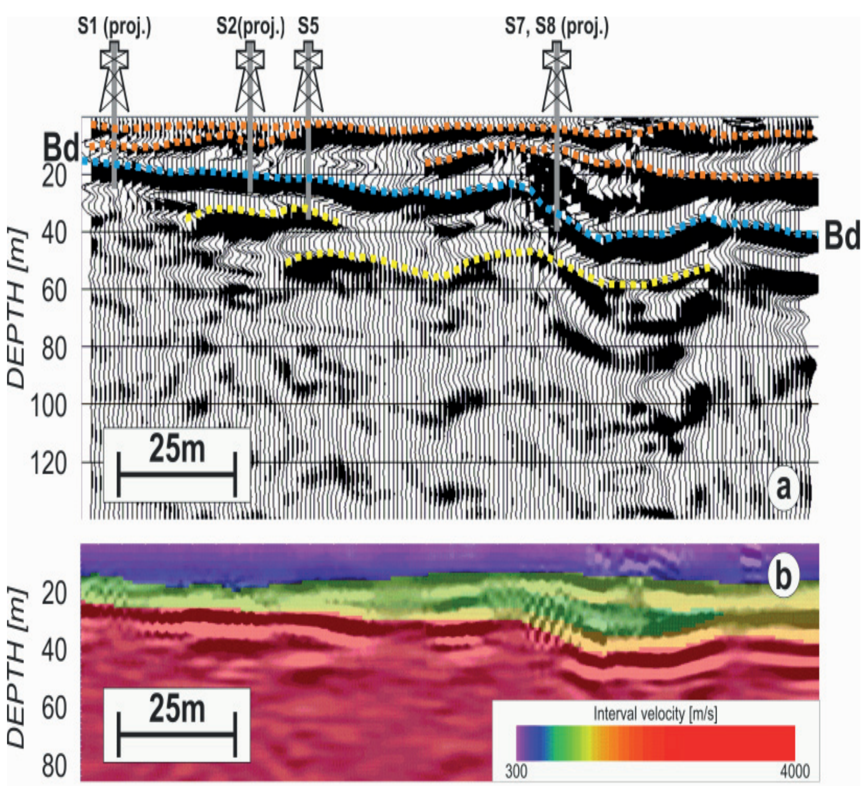

Fig. 4 - Exemplary reflection seismic section (modified after Busetti *et alii, 2020). a) Processed and interpreted section; b) seismic interval velocity field (P-waves) superimposed on the seismic section as in a). The evaporitic bedrock (Bd) is clearly imaged and shows a strong velocity increment up to values typical of evaporites. Other horizons can be recognized both above (in orange) and within (in yellow) the bedrock. Some boreholes validate the seismic results*

wide areas thus representing the best technique to image the 3D shallow deformations due to sinkholes;

6. REFR, possibly due to velocity inversions or to gradual velocity changes in mantled evaporitic bedrock environments, not always allows to clearly identify the bedrock and sediments above it;
7. REFL appears to be the best approach to identify the thickness of cover materials and to characterize the morphology of the bedrock. It is a quite expensive and logistically demanding technique, but from our experience the costs-benefits ratio is often favorable.

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(2) *Accordo attuativo di collaborazione per la definizione e quantificazione della pericolosità dei sinkhole nei litotipi evaporitici Carniani dell'alta valle del Tagliamento (prot. no. 877 del 06 October 2016);*
(3) *Accordo attuativo di collaborazione per la misurazione delle geometrie e delle deformazioni indotte dalla presenza di sinkhole (prot. no.1254 del 21 November 2018);*
(4) *Accordo attuativo di collaborazione per l'aggiornamento censimento e pericolosità dei sinkhole del territorio regionale (prot. no.0035220 del 27 July 2020);*
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