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# Integrated geophysical survey in a sinkhole-prone area: Microgravity, electrical resistivity tomographies, and seismic noise measurements to delimit its extension

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ABSTRACT

Detection, forecasting, early warning, and effective monitoring are key aspects for the delimitation of sinkhole-prone areas and for susceptibility assessment and risk mitigation. To attain these goals, direct and indirect techniques can be employed, and the integration of different indirect/non-invasive geophysical methods including 2D- and 3D-electrical resistivity tomography, microgravity, and single-station seismic noise measures was carried out at "Il Piano" (Elba Island – Italy), where at least nine sinkholes occurred between 2008 and 2014. The most likely origin for these sinkholes had been considered related to net erosion of sediment from the alluvium, caused by downward water circulation between the aquifer hosted in the upper layer (Quaternary alluvial deposits) and that in the lower (Triassic brecciated dolomitic limestone and Cretaceous slate). The integrated geophysical survey, therefore, was carried out a) to differentiate shallower from deeper geological layers, b) to detect possible cavities that could evolve into sinkholes, c) to suggest possible triggers, and d) to delimit the sinkhole-prone area. The results of the integrated geophysical surveys suggest that the study area is mainly characterised by paleochannels, and that the sinkhole-prone area boundaries correspond to these paleochannels.

## 1. Introduction

The term "sinkhole" was first introduced in the late sixties to indicate the subcircular surface depressions or collapse structures formed by the collapse of small subterranean karst cavities. Currently, sinkholes are related to subterranean cavities propagating up to the surface, regardless of their trigger and shape. According to the USGS (http://water.usgs.gov/edu/sinkholes.html) and the scientific literature (Guerrero et al., 2004; Waltham et al., 2005; Kaufmann, 2014; Argentieri et al., 2015; Sevil et al., 2017), sinkholes can be classified according to a large variety of schemes depending on the dominant process of formation and on the geological scenario behind the development of the phenomenon. Specifically, three main factors can be identified: i) predisposing causes, such as the nature of the sub-superficial geology and the bedrock and the presence of sub-superficial anthropogenic structures; ii) triggering causes, such as rain or the superficial drainage of water infiltrating into the soil; and iii) concurrent causes, such as the anthropic effect on the continuity of the superficial drainage network and the extraction of superficial water.

Sinkholes can cause spatially dispersed damage. In particular, related losses are direct (e.g., human casualties and damage to property), indirect (e.g., interruption to businesses, transport infrastructure and communication networks) and intangible, especially if they occur in urban areas (Galve et al., 2012; Intrieri et al., 2015; Sevil et al., 2017). Knowing the formation mechanism, some general actions may be identified as countermeasures to mitigate the sinkhole susceptibility of the area and to overcome the environmental and infrastructure problems. In addition, considering that in general, sinkholes are densely clustered in "sinkhole-prone areas" while completely absent in others, key aspects of sinkhole risk mitigation are setting up early warning systems on the basis of effective monitoring programmes (to predict where and when new phenomena will occur) and assessing how

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existing systems will evolve (Guerrero et al., 2004; Kaufmann, 2014). However, techniques developed specifically for sinkhole detection, forecasting and monitoring are missing, probably because of a general lack of sinkhole risk awareness and of the intrinsic difficulties involved in detecting precursory sinkhole deformations before collapse (Intrieri et al., 2015). Therefore, direct and indirect techniques able at least to detect existing subterranean cavities are important. Among the direct methods, blind drillings in sinkhole-prone areas and electric cone penetration tests (CPT) are common applications; nevertheless, these methods puncture the surface, may be disadvantageous in urban areas and may exacerbate sinkhole development (Zhou et al., 2002; Krawczyk et al., 2012; Samyn et al., 2014; Lee et al., 2016; Sevil et al., 2017). On the other hand, indirect techniques allow for the extrapolation of data concerning sinkhole location and risk by means of a) the back-analysis of past events, b) the stratigraphy of the sediments filling existing sinkholes, and c) the susceptibility models generated by analysing the statistical relationship between the spatial distribution of sinkholes and that of specific conditioning factors (Pueyo Anchuela et al., 2013; Kaufmann, 2014; Zini et al., 2015).

Currently, non-invasive high-resolution geophysical methods for shallow exploration and imaging of local subsurface heterogeneities are recognised as the best practice approaches to identify and map sinkholes, especially if they are actively developing (Smith, 1986; Zhou et al., 2002; Ezersky, 2008; Krawczyk et al., 2012; Martinez-Moreno et al., 2013; Pueyo Anchuela et al., 2013; Cardarelli et al., 2014; Kaufmann, 2014; Samyn et al., 2014; Argentieri et al., 2015; Zini et al., 2015). Natural cavities, in fact, can be filled with air, water, or collapsed/unconsolidated material, resulting in variations in the ground physical properties and therefore providing fairly distinct geophysical contrasts, which may be detected (Bishop et al., 1997). Moreover, since the rock surrounding the cavity is often disturbed, the associated fracturing may extend up to two or more diameters away from the cavity.

In this paper, we present the results of an integrated geophysical survey at “Il Piano” (meaning “Flat” in Italian, Elba Island – Italy), where at least nine sinkholes occurred between 2008 and 2014 (Intrieri et al., 2015), with the aims of a) obtaining a suitable geological and hydrogeological model of the area, b) detecting possible cavities that could evolve in sinkholes, c) suggesting possible triggers, and d) delimiting the sinkhole-prone area. The most likely origin for these sinkholes has been considered related to net erosion of sediment from the alluvium caused by downward water circulation between the superficial aquifer and the main karst aquifer represented by the local rock substratum (Intrieri et al., 2015). Therefore, to differentiate shallower (Quaternary alluvial deposits) from deeper (Triassic brecciated dolomitic limestone and Cretaceous slate) geological layers and to detect possible cavities in the karst bedrock, investigations by means of 2D- and 3D-electrical resistivity tomography (ERT), microgravity, and single-station seismic noise measurements (H/V) were carried out. This integrated geophysical approach is included in a wider project (Fig. 1) aimed at characterising the geomorphology and hydrogeology of the area (Intrieri et al., 2018). The key result of this study is that the hazards of the area are ascribable to shallow causes (i.e., water infiltrating into the soil and related fine material transport) instead of deeper ones (i.e., karst caves).

The paper is structured as follows: Section 2 provides a geological and geomorphological description of the study area; Section 3 details a brief overview of the employed techniques and methodology; Section 4 presents the results of the geophysical survey independently for each technique, while in Section 5, the overall data are integrated and discussed.

## 2. Study area

The complex Elba Island stack of nappes is identified as the westernmost part of the Northern Apennine chain (Bortolotti et al., 2001). From a geological point of view, the western part of the island is dominated by a large granodiorite pluton (Monte Capanne), whereas the eastern part is composed of a set of Ligurian and Tuscan tectonic units, mostly composed of sedimentary formations and Messinian-Pliocene intrusive magmatic bodies (Ferrara and Tonarini, 1985; Rocchi et al., 2002; Maineri et al., 2003). Bortolotti et al. (2001) provided an updated model of the structure of central and eastern Elba Island and defined nine, generally east-vergent, different tectonic complexes.

The study area is located in the northeastern part of the island (Fig. 2a) and corresponds to the mostly flat terrain separating the municipalities of Rio nell'Elba and Rio Marina. The most recent 1:25000 geologic map by ISPRA (http://sgi1.isprambiente.it/website/isolaelbageo/carta_geologica_isola_elba.htm) is dated 2015 and shows that the Cavo Formation (FCV in Fig. 2c, d) and the Rialbano Breccia (RBC in Fig. 2c, d), previously known as Calcare Cavernoso (Bortolotti et al., 2001; Intrieri et al., 2015), constitute the rock substrata herein. The Cavo Formation, a metamorphosed siltstone characterised by polyschistose calc-schists and varicoloured slates, tectonically overlies, by means of a N−S oriented, W-dipping fault, the Rialbano Breccia, a brecciated dolomitic limestone (Bortolotti et al., 2001). In the easternmost portion of the study area, the substratum consists of the Verrucano sequence, a HP-LT metamorphic sedimentary sequence. This substratum is extensively covered by approximately 20–30 m of alluvial (b in Fig. 2c, d) and erosional (a in Fig. 2c) deposits (Quaternary alluvium) composed of lenticular gravel and sand bodies within a sandy silt matrix. For a detailed lithologic description of these formations, see Bortolotti et al. (2001).

From a hydrogeological point of view, the outcropping formations are quite different: the Rialbano Breccia shows high permeability, mainly owing to tectonic fracturing and karst phenomena, while the permeability of the Cavo Formation metasiltstone is very low. The hydrographic basin is characterised by a narrow topography that separates “Il Piano” by means of the downhill end section from the outlet into the sea. This topography is the result of the geological and geomorphological evolution of the area, which reached its present appearance because of the fluctuations in sea level and the alternation of depositional and erosional events that occurred in the late Pleistocene and Holocene epochs (Bortolotti et al., 2001). Consequently, the area was gradually filled with continental deposits (i.e., of lacustrine, fluvial, hillslope, and mass transport origin). In the study area, two main aquifers can be recognised: a superficial one hosted by the Quaternary alluvium and the main one of karst origin hosted in the fractured limestone and deeply exploited for industrial, agricultural, and drinking purposes (Intrieri et al., 2015). The presence of water in the area is also witnessed by the past presence of at least 22 watermills, many millponds, and ditches for their hydraulic energy supply, the ruins of which are still largely visible (although in different states of preservation).

## 3. Material and methods

To detect caves, gravity and/or electrical methods were mainly employed and combined with other techniques (Martinez-Moreno et al., 2013). The integration of microgravity, ERT, and H/V technique was performed to characterise the study area and delineate the sinkhole-prone area (Fig. 3). Direct information about the subsoil properties was obtained from the Lefranc permeability test, SPTs, and stratigraphy boreholes carried out along the road SP26 (Fig. 2b, c) after the sinkholes developed in 2013. The microgravity surveys were conducted mostly in the inhabited areas around houses and along the two main roadways (Fig. 3). On the other hand, H/V measurements and ERT were carried out to characterise a wider area, although their distribution was influenced by field accessibility.

### 3.1. 2D- and 3D-ERT

To achieve the aims of this work, eight 2D- and seventeen 3D-ERT