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Hidden sinkholes and karst cavities in the travertine plateau of a highly-populated geothermal seismic territory (Tivoli, central Italy)

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ABSTRACT

Sinkholes and other karst structures in settled carbonate lands can be a significant source of hazard for humans and human works. Acque Albule, the study area of this work, is a Plio-Pleistocene basin near Rome, central Italy, superficially filled by a large and thick deposit of late Pleistocene thermogene travertine. Human activities blanket large portions of the flat territory covering most evidence from geological surface processes and potentially inducing scientists and public officials to underestimate some natural hazards including those connected with sinkholes. To contribute to the proper assessment of these hazards, a geomorphologic study of the basin was performed using digital elevation models (DEMs), recent aerial photographs, and field surveys. Historical material such as old aerial photographs and past geomorphologic studies both pre-dating the most part of quarrying and village building was also used together with memories of the elderly population. This preliminary study pointed out the presence of numerous potentially active sinkholes that are at present largely masked by either quarrying or overbuilding. Where this first study pointed out the apparent absence of sinkholes in areas characterized by high density of buildings, a detailed subsurface study was performed using properly-calibrated electrical resistivity tomography (ERT) and dynamic penetration measurements (DPSH), together with some borehole logs made available from the local municipality. This second study highlighted the presence of sinkholes and caves that are, this time, substantially hidden to the resolution of standard methods and materials such as aerial photographs, DEMs, and field surveys. Active sinkhole subsidence in the Acque Albule Basin may explain, at least in part, the frequent damages that affect numerous buildings in the area. The main conclusion from this study is that the mitigation of sinkhole hazard in highly populated areas has to pass through a thorough search of (hidden) sinkholes that can be masked by the Anthropocenic molding and blanketing of the territory. For these purposes, data from historical (pre-Anthropocene) documents as well as, where possible, subsurface investigations are fundamental.

1. Introduction

Sinkholes (or dolines) are depressions or holes in the ground generated by some form of slow subsidence or sudden collapse induced by physical–chemical erosion of rocks in the shallow subsurface (Fig. 1). Most sinkholes are caused by carbonate karst processes (i.e., chemical dissolution of carbonate rocks), but these structures can similarly form also in other rocks and minerals such as salt and gypsum. Sinkholes may vary in size from a few to hundreds of meters both in diameter and depth, and, as mentioned above, may form gradually or, more often, through a sudden collapse. The formation of these latter sinkholes can be dramatic, as the surface land usually stays intact until there is not enough support. At this time, a sudden collapse of the land surface can occur with possible dramatic consequences for humans, buildings, and infrastructures (Jennings, 1985; Gillieson, 1987; Ford and Williams, 1989; Faccenna et al., 1993; Salvati and Sasowsky, 2002; van Schoor, 2002; Waltham and Fookes, 2003; Williams, 2004; Beck, 2005; Waltham et al., 2005; Yechieli et al., 2006; Ford, 2006; Gutiérrez et al., 2007, 2009, 2014; Bruno et al., 2008; Faulkner, 2009; Valois et al., 2011; Brinkmann, 2013; Ezersky and Frumkin, 2013; Gulley et al., 2013; Siart et al., 2013; Carbonel et al., 2014a; Simón et al., 2014; Poppe et al., 2015). Hence, populated sinkhole-prone areas necessitate specific prevention and management measures (Sowers, 1996; Ford, 2006; Epting et al., 2009; Hao et al., 2009; Song et al., 2012; Siart et al., 2013; Carbonel et al., 2014a,b; Gill and Malamud, 2014).

In central Italy, which is the carbonate sinkhole-prone study area of this paper (Fig. 2), sudden occurrences of sinkholes have happened on several occasions in recent and historical times (Faccenna et al., 1993;

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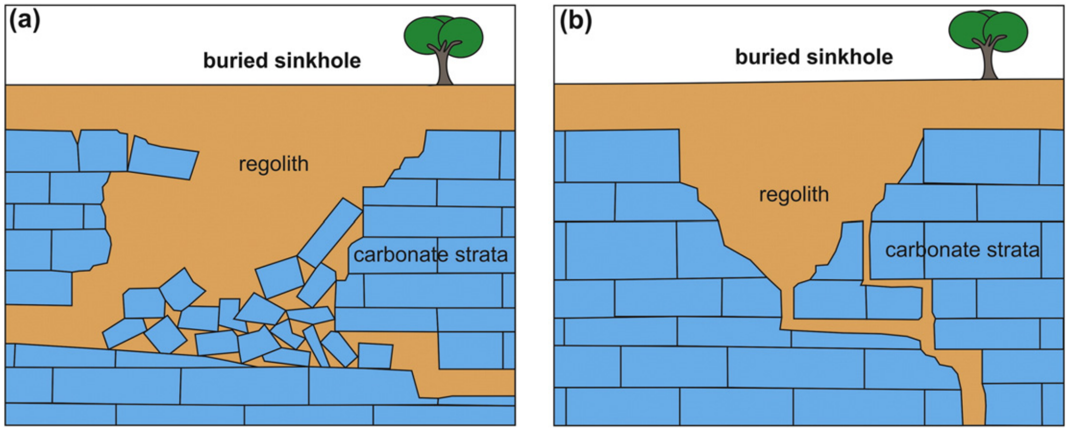

Fig. 1. Conceptual sketches of two types of buried (hidden) sinkholes (modified from and inspired by Ford and Williams, 1989, Gunn, 2004, Waltham et al., 2005, and Nisio et al., 2007). These types of sinkholes are common in the travertine substratum of the Acque Albule Basin and visible along the travertine quarry walls (Figs. 2–5). (a) Buried (hidden) cave-collapse sinkhole filled by soil and regolith after (and partly before) the collapse of the carbonate vault. (b) Buried (hidden) solution sinkhole (also commonly known as doline) filled by soil and regolith after the chemical (and partly physical) erosion of the carbonate substratum. Both sinkholes in (a) and (b) are drawn as apparently inactive (i.e., no surface depression).

Salvati and Sasowsky, 2002; Nisio et al., 2007; Nisio, 2008; Caramanna et al., 2008; Centamore et al., 2009; Guarino and Nisio, 2012; Amanti and Nisio, 2013; Billi et al., 2014; Ciotoli et al., in press). Sinkholes, however, are dangerous and harmful for humans and human works not only when the collapse abruptly occurs, but also after the collapse when they are totally filled, apparently extinct, and de facto hidden (Fig. 1). The filling, in fact, can be made of unconsolidated soft clay-to-sand allogenic deposits and soil (regolith) that may easily be compacted and depressed under the load of a construction or may be the locus of a new sudden collapse through the slow process of suffosion or, more in general, through sinkhole rejuvenation processes (i.e., cover-collapse sinkhole and cover-subsidence sinkhole; Waltham et al., 2005; Ford, 2006; Koutepov, 2008; Zhou and Beck, 2008; Billi et al., 2014). Suffosion, in particular, occurs when loose soil or other non-cohesive material that lies on top of a karst-carved limestone substratum containing fissures and joints is gradually washed downward through the fissures and into the caves beneath, thus creating a depression on the landscape of varying depth and diameter.

All the above-mentioned phenomena leading to sinkhole formation can be highly favored by geothermal and seismic processes leading to, for instance, pressurized geothermal circulation or seismic shaking (Heidari et al., 2011; Santo et al., 2011; Sella et al., 2014). The case of slow compaction and subsidence on top of sinkholes filled by ground and regolith under the load of multi-story buildings in a geothermal-seismic area seems to be the case of the densely-populated and (in places) overbuilt Acque Albule Basin, Tivoli, central Italy (Fig. 2). This is a Plio-Pleistocene basin near Rome, partly filled by a late Pleistocene travertine large deposit that is a few tens of meters thick and on the order of 1 km^3 in volume (Maxia, 1950; Faccenna et al., 1994, 2008; De Filippis et al., 2013a,b). The travertine originated by the subsurface circulation through the Meso-Cenozoic marine carbonates of groundwater enriched in CO_2 and other endogenic elements by the nearby quiescent and degassing Colli Albani volcano (Manfra et al., 1976; Minissale et al., 2002; Vignaroli et al., 2015). The geothermal circulation is still active and inverse erosion (bottom-up) is one of the causes of carbonate chemical dissolution

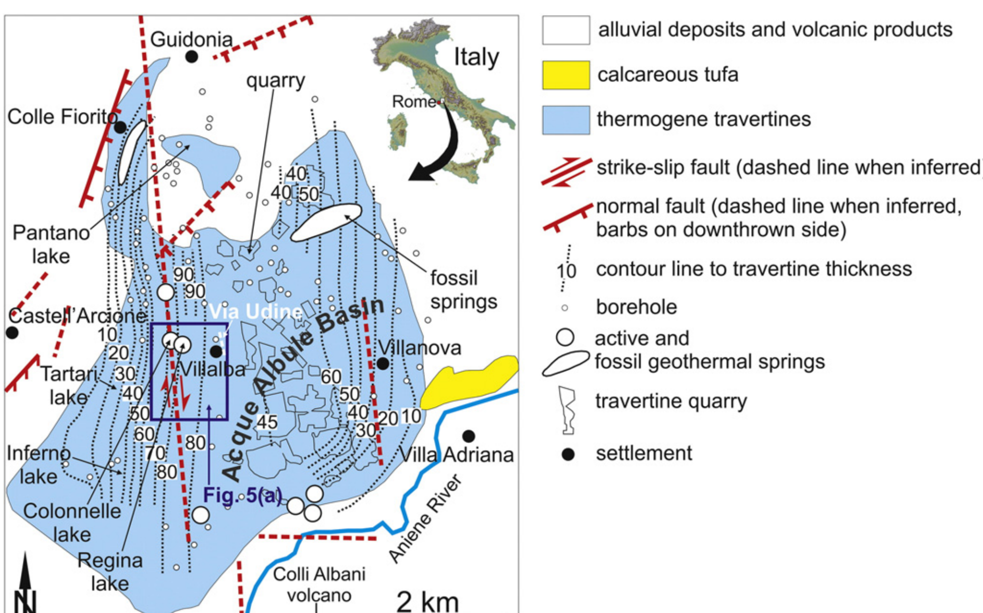

Fig. 2. Geological setting of the geothermally- and seismically-active Acque Albule Basin close to Rome (c. 25 km distant), central Italy. In its upper section, the basin is largely filled by a late Pleistocene thick (maximum thickness: c. 90 m) thermogene travertine deposit (Faccenna et al., 2008), which is rich in various karst features and sinkholes (Figs. 3–5).