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KARST SINKHOLES FORMATION AND SPATIAL DISTRIBUTION: CLUES FROM THE SOUTHERN APENNINES (ITALY)

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ABSTRACT: Sinkholes that affect both carbonate rocks and alluvial plain deposits are widely distributed in the southern Apennines. Karst sinkholes, in particular, are generally clustered within High Sinkhole Concentration Area (HSCA). A geological and geomorphological study of some, selected HSCA, has been carried out, aimed at constraining hypotheses on both factors that control sinkhole spatial distribution and causative mechanisms of karst collapses. Based on independent evidence on the active tectonic framework and deep fluid rising in the HSCA, karst sinkhole phenomena appear related the hypogenic karst controlled by the rise of acidic fluids along active faults.

KEYWORDS: Sinkholes, karst sinkholes, active faults, southern Apennines

1. INTRODUCTION

The term sinkhole broadly indicates any medium-sized, sub-circular depression without considering its origin (Beck, 1984). The same term is adopted for both karst related and anthropogenic collapses (Santo et al., 2011; Scotto di Santolo et al., 2018). Regarding karst sinkholes, a genetic classification has been recently proposed by Gutierrez et al. (2008). Karst sinkholes occur in the entire southern Apennines, however they are densely distributed in specific areas labelled High Sinkhole Concentration Area - HSCA, *sensu* Santo et al. (2011). Recent studies highlight the occurrence of some peculiar geological and geomorphological features in the HSCA, such as the occurrence of active faults that are inferred as acting as pathways for the rise of deep fluids (Santo et al., 2011, 2017). Karst collapse sinkholes are also often associated with gas vents and mineral springs.

We have carried out a study aimed at the characterisation of the main geological and geomorphological features of some of the HSCA. Selected areas are (from the NW to the SE) the Pratella area, the Telese - Solopaca area and the Contursi area (Fig. 1). The investigated areas are characterised by the occurrence of mineral and/or thermal springs. Furthermore, in all of the investigated areas deep fluid inputs are either testified by gas vents, or inferred from mineralogy and geochemistry of precipitated minerals (Ascione et al., 2018; Santo et al., unpublished data). We have combined geological and geomorphological investigations aimed at reconstructing local geological setting and at detecting evidence for active faulting in the study areas. The aim of our study is to constrain hypotheses on causative mechanisms of karst sinkhole formation and factors that control karst sinkhole spatial distribution.

2. MATERIAL AND METHODS

The study areas are located in the axial portion of the Southern Apennines and include the Telese - Solopaca and the Contursi area already identified by Santo et al. (2011). In addition, the Pratella area has been investigated on the basis of the recent paper of Ascione et al. (2018). Detailed geological and geomorphological investigations have been carried out. The geological analysis was based on the combination of field surveys with stratigraphical data of both published and unpublished boreholes. The latter ones, in particular, provided useful constraints on the spatial distribution and features of both outcropping and buried Quaternary deposits. The geomorphological investigation has been based on the analysis of detailed topographic maps (1:5000 scale technical map of the Regione Campania) and has been addressed to the recognition and mapping of fault controlled features such as fault scarps, triangular facets, river bends, wind gaps, water gaps, beheaded valleys, besides sinkholes. The latter have been classified as either karst collapse sinkholes or alluvial plain sinkholes. Mineral, sulphurous and hot springs have been also mapped. Mineralogical and geochemical data within study areas have been derived from the literature.

All of such information has been plotted on a simplified geological map of the southern Apennines, in which information on active and capable faults (derived from detailed, local scale, and the Ithaca database, http://sgi.isprambiente.it/geoportal/catalog/content/project/ithaca.page) and epicentres of moderate to strong earth-

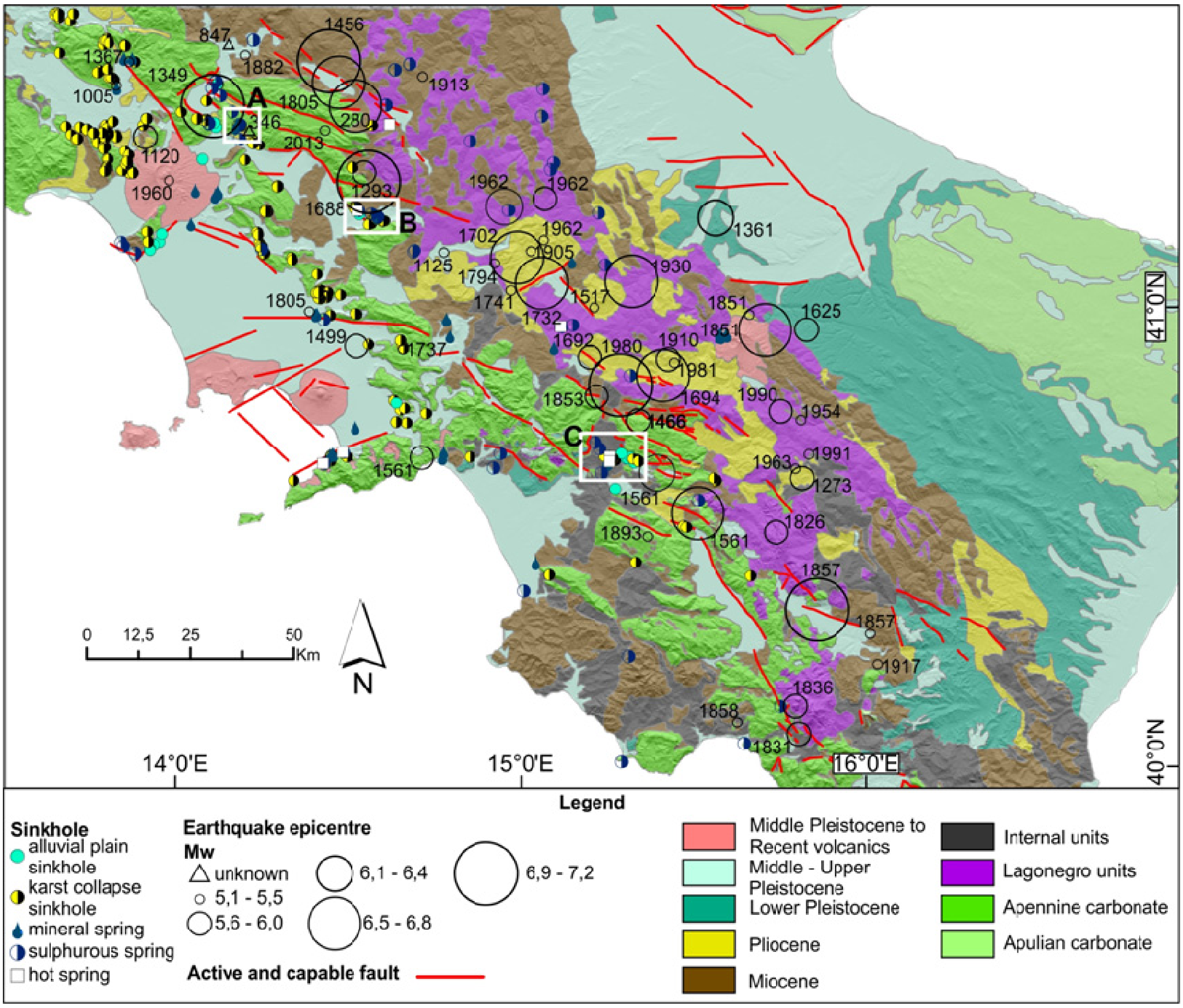

Fig. 1 - Spatial distribution of sinkholes in the southern Apennines plotted on a simplified geological map (modified from Santo et al., 2011 and Ascione et al., 2013). White boxes indicate HSCA investigated in this study. A: Pratella area; B: Telese - Solopaca area; C: Contursi area.

quakes has been included. Locations of epicentres has been extracted from the Parametric Catalogue of Italian Earthquakes (Rovida et al., 2016), with the exception of the 280 B.C., 346, 847, 1349, 1456 and 1805 earthquakes, whose locations are from Galli & Naso (2009).

3. RESULTS

3.1 Pratella area

The Pratella area (box A in Fig. 1) is located to the southwest of the Matese ridge. The Pratella area is characterised by carbonate hills, whose elevations range between 300 and 500 m a.s.l., which are dissected by the Lete river valley. In the Pratella area, the Lete mineral spring is located. The carbonate hills of the Pratella area are interposed between Quaternary lacustrine deposits that crop out in the Ciorlano area, to the north, and Ailano area, to the south. Quaternary lacustrine deposits in the areas of Ailano and Ciorlano form terraces that are dissected and eroded at variable degrees, whose elevation ranges between 230 and 280 m a.s.l. Geological, geomorphological and stratigraphical data allowed the recognition of several extensional fault strands with evidence of activity in the late Quaternary, with prevailing E-W and N-S orientations that affect both the carbonates and the alluvial deposits (Ascione et al., 2018). Karst sinkholes in the Pratella area are clustered along the carbonate hills. They are mainly distributed along an E-W direction, and are aligned with some active fault strand.

The lacustrine basins of Ciorlano and Ailano are characterised by several gas vents and diffuse gas emission. The spatial distribution of the gas vents and gas emissions shows alignments that are consistent with orientation of active faults (Ascione et al., 2018). Geochemical data point to strong CO_2 emission, which is among the highest gas emissions in non-volcanic areas in the world (Ascione et al., 2018). Isotopic analyses of C in the CO_2 suggest a crustal origin of the emitted gas, probably due to thermo-metamorphism of buried Apulian carbonates triggered by buried magmatic bodies (Ascione et al., 2018).

3.2. Telese - Solopaca area

The Telese - Solopaca area (box B in Fig. 1) is located to the north of the Mt. Camposauro massif. The latter consists of carbonate rocks and is bounded to the north by a wide piedmont area made up of slope and alluvial fan deposits interbedded with tephra layers. The Calore river valley limits the Camposauro northern slope and its piedmont to the north (Amato et al., 2018). The Solopaca village falls in this area, whereas the Telese village is located at the base of Mt. Pugliano, an isolated carbonate hill located to the northeast of Solopaca. Amato et al. (2018) point to the occurrence of several normal faults with evidence of activity in the late Quaternary. Active fault strands affect the entire Camposauro piedmont and the Telese area, and are mainly E-W and NE-SW trending.

Sinkholes occur in the surrounding of both the Solopaca and Telese villages. Sinkholes in the Solopaca area affect the alluvial fan conglomerates. They are NE-SW aligned and placed close to some of the NE-SW trending active faults, while sinkholes in the Telese area affect the top surface of Mt. Pugliano, and are also aligned with fault strands. Here, thermal spring of Telese and large travertine bodies also occur, with $\delta^{13}C$ isotopic values of the carbonates indicating a crustal contribution (Santo et al., 2011; Ascione et al., 2014). Mineralogical and geochemical analyses of gypsum rich cursts/patina precipitated close to Telese hot springs and inside the sinkholes have been carried out by Santo et al. (2018). Isotopic analyses of $\delta^{34}S$ and $\delta^{18}O$ indicate a deep origin of sulphate leading the authors to hypothesize the presence of a deep-seated sulphur source.

3.3. Contursi area

The Contursi area (box C in Fig. 1) is dominated by the ~1600 m high Mt. Marzano carbonate massif which is bounded, to the south, by San Gregorio Magno and Buccino intramontane basins, filled by late Quaternary fluvio-lacustrine deposits. Several evidences of recent faulting have been identified in these area, resulting in few km long fault strands affecting both the Mt. Marzano and the adjoining intramontane basins (Ascione et al., 2013). Sinkholes have been identified along the carbonate southern slope of Mt. Marzano and related alluvial fans. In addition, sinkholes affect the top surface of Mt. Pruno close to Contursi village. Here, a thermal hot spring is also present. Their distribution is consistent with some of the active fault strands recognized by Ascione et al. (2013) and Santo et al. (2011). Santo et al. (unpublished data) carried out a detailed mineralogical investigation of limestones and related precipitates close to sinkhole and mineral spring. The author found isotopic composition of S and O compatible with a deep source.

4. DISCUSSION AND CONCLUSIONS

Karst sinkholes are widespread in the southern Apennines, and in several instances are found close to active faults. In some cases, such as the Pianelle sinkhole along the southern slope of Mt. Marzano, their formation is linked to seismic shaking related to high magnitude earthquakes (Santo et al., 2011; unpublished data). Independent mineralogical and geochemical evidence from the investigated HSCA highlights the occurrence, in the surroundings of the karst sinkholes, of both CO_2 emissions and strongly weathered carbonate rocks associated with diffuse precipitation of sulphure-rich minerals (Ascione et al., 2018; Santo et al., unpublished data). Gas vents are also found within or close to the HSCA (Ascione et al., 2018), even if their distribution is strongly controlled by the rock-type, being clustered where clayey rocks crop out. Isotopic composition of both gas emission and precipitates point to a crustal origin of rising fluids, triggered by the presence of buried magmatic bodies (Ascione et al., 2018; Santo et al., unpublished data). Overall scenario from the investigated HSCA suggests that enhanced dissolution that originates karst sinkholes is triggered by the presence of acidic (CO_2 and/or H_2S rich) fluids. Clustering of karst sinkhole phenomena appears related with localised hypogene karst controlled by the rise of acidic fluids conveyed towards the surface by active faults.

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