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Recognition and classification of evaporite karst phenomena: examples of outstanding sinkholes from Sauris (NE Italy)

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ABSTRACT
Sinkholes are one of the most hazardous phenomena due to their occurrence and unpredictability. In the Friuli Venezia Giulia Region (northeast Italy), the presence of outcropping, mantled or capped evaporites is the main predisposing factor for these phenomena. Even if evaporites do not exceed 1% of the entire regional territory, their presence causes catastrophic events mainly in the Carnian alpine valleys. Chalks are included in the Bellerophon Formation (Late Permian) and in the Raibl one (Upper Carnian). These weak rocks are mainly located in the valley bottoms and not at the top of the mountains. Even if, in correspondence of the northern ridges of Sauris municipality, several sinkholes have been observed. In detail, north of Sauris, quartz sandstones and mica-siltstones belonging to the Werfen Formation (Triassic) are widely present. These rocks, capping evaporitic ones, belonging to the Bellerophon Formation, are jointed and characterized by a secondary permeability. Over time, water infiltration and weathering led to the solution of the Permian evaporites and to the progressive failure of the overlying terrigenous rocks, less soluble but more plastic. The result is the genesis and evolution of depressed landforms classifiable as sinkholes. On the grassy meadows stretching from Sauris di Sopra to Sella Festons at 1800 m a.s.l., outstanding sinkholes can be observed at the top as well as on the slope. Since now, almost 80 sinkhole phenomena were recognized and classified in the Sauris Municipality; most of them are aligned along approximately E-W oriented faults. All the data were added and stored in a GIS, which represents the first sinkhole inventory related to the evaporite karst environment in Friuli Venezia Giulia Region.

INTRODUCTION
Even if evaporate rocks are not abundant in the Friuli Venezia Giulia Region, they cause the occurrence of sinkhole phenomena creating a peculiar and at the same time hazardous karst landscape.
A spectacular example of evaporitic karst area is represented by the surroundings of Sauris Municipality (42 km^2), which is located in the NW portion of the Friuli Venezia Giulia Region.
In the study area, evaporites are mainly mantled by Quaternary deposits or are capped by other rocky types. Tens of sinkholes are recognized on the valley bottoms, over the top of the ridges and in the middle of the slopes. The presence of these phenomena in a so beautiful landscape partially compromise the urban sprawl and consequently affect the territorial availability. In the villages and settlements present in the valleys, this situation is even more pronounced, becoming for the mountain areas, a real huge problem. The scarcity of labour supply, but also the difficulty to cohabit with the cruelty of the mountain territory itself do not facilitate the mountain life. It is although crucial to protect the territories, to know the

potentialities and the weaknesses avoiding the abandonment facilitating the ones who remain to live in safer areas being conscious of the existing risks. A deep knowledge of the territory assist the inhabitants and the local authorities to be more conscious of the problems and to cohabit with these difficulties. Geological, geomorphological and hydrogeological features of karst landscapes make them highly vulnerable to a variety of degradation problems (Williams, 1983; Parise and Pascali, 2003). Without thoroughly entering the social, economical and historical matters, this paper aims to investigate the sinkhole hazards in the evaporate karst located in the Sauris Municipality.
The possibility to live in a safer territory and to provide to the stakeholders a detailed territorial analysis, leads the researchers, supported by a project funded by the Geological Survey of the Friuli Venezia Giulia Region, to inventory and catalog the main karst features.
As reported by Ford and Williams (2007), a sinkhole is a depressed feature with an internal drainage. According to the different genetical classifications, sinkholes can be roughly divided in two main groups: the *solution sinkholes* and the *subsidence sinkholes* (Gutierrez et al., 2014). To the first group belong the phenomena result of a different corrosional lowering of the ground. They generate in places where rocks are exposed or poorly mantled. In this case, sinkhole genesis is due to a centripetal flow towards higher permeability zones with a resulting concentrated dissolution (Ford and Williams, 2007).
The subsidence sinkholes are included in the second group, mainly caused by a subsurface dissolution and drawdown gravitational movement of the overlying material (Gutierrez et al., 2014).
These two macro groups represent only a simplified classification based on a genetical criterion and here described only to frame the problem. Several papers such as Beck (2005), Waltham et al. (2005) and Gutierrez et al. (2008) focused on sinkhole classification. For this paper, the Authors used the genetical methodology proposed by Gutierrez et al. (2008) in the classification process of each single phenomena
But why this macro distinction. The necessity derives from the needs to be able to explain the readers that the phenomena that took place on soluble rocks as the solution sinkholes or dolines, represent a real problem only when these sinkholes are underlined by dissolutional features as conduits or shafts of a certain dimension that could take to the occurrence of a sudden collapse. The subsidence sinkholes instead, from a hazard point of view, are the most important because more dangerous. After a detailed field survey, in the area of Sauris municipality, the researchers identified and classified more than 70 phenomena the most part of them belonging to the subsidence sinkholes.

GEOLOGICAL OVERVIEW OF THE STUDY AREA

From a geological point of view, in the study area the Bellerophon and Werfen Formations are dominant. The Bellerophon Formation is a regionally extensive unit, outcropping from Slovenia to Adige River valley. The intensity of the alpine tectonic deformations strongly affected its stratigraphic continuity that never has comprehensive sections and often appears, at least in part, cataclastic (Venturini et al., 2006). The original thickness of this unit is difficult to define because it is crossed by numerous overthrusts and altered by the gypsum dissolution (Buggisch and Noè, 1986). Most of the outcrops of this unit is focused in a wide belt coincident with the valley bottoms mainly E-W oriented. A further but smaller outcropping belt is driven by the alpine tectonic compression and is aligned along the Sauris fault (SF), an important overthrust E-W oriented (Figure 1). This stately structure is persistent for about 40 km from west to the east of the Region till the Tagliamento River where is present its further eastern portion. It takes the Permian units to overlap the Triassic ones. The presence of gypsum at the base of the northern overthrusted units facilitated the process. The main structure is also complicated by transverse faults.
The Bellerophon Formation is constituted from two members: gypsum and black dolostone (thickness of about 60 m) capped by dolostones and black limestones (200 m). In the study area, the two members are always in a direct stratigraphic overlap. The strong deformation

behaviour of the evaporite member means that only seldom it outcrops. Conversely, the upper Member is well represented in correspondence of the right tributary of Plotnpoch torrent, where, within the dark limestones are present limy horizons, strongly vacuolar with a spongy aspect named *Rawacke* (Venturini et al., 2006).
In the northern part of the study area the Bellerophon Formation is capped by the Werfen rocks (Lower Triassic), subdivided in six members according to the lithological content and depositional environment. The lower Member is the Tesero Horizon (oolitic limestone, <7 m), followed by the Mazzin Member (limestone and marls, 80 m) and the Andraz Member (dolomitic limestones and marls, 8-12 m). More recent is the Siusi Member (limestone, marls and pelite,125 m), overlyed by the Gasteropod Oolite Member (marly mudstone and alternating calcareous sand and mud, 5-10 m). The Formation end up with the Campil Member (fine-grained violet sandstones and pelites, 200 m) outcropping at the top of the Pieltinis Mt. and in its surrounding (Venturini et al., 2006).
Moraine deposits partially hidden the valley bottoms and the flatten areas located on the peaks.

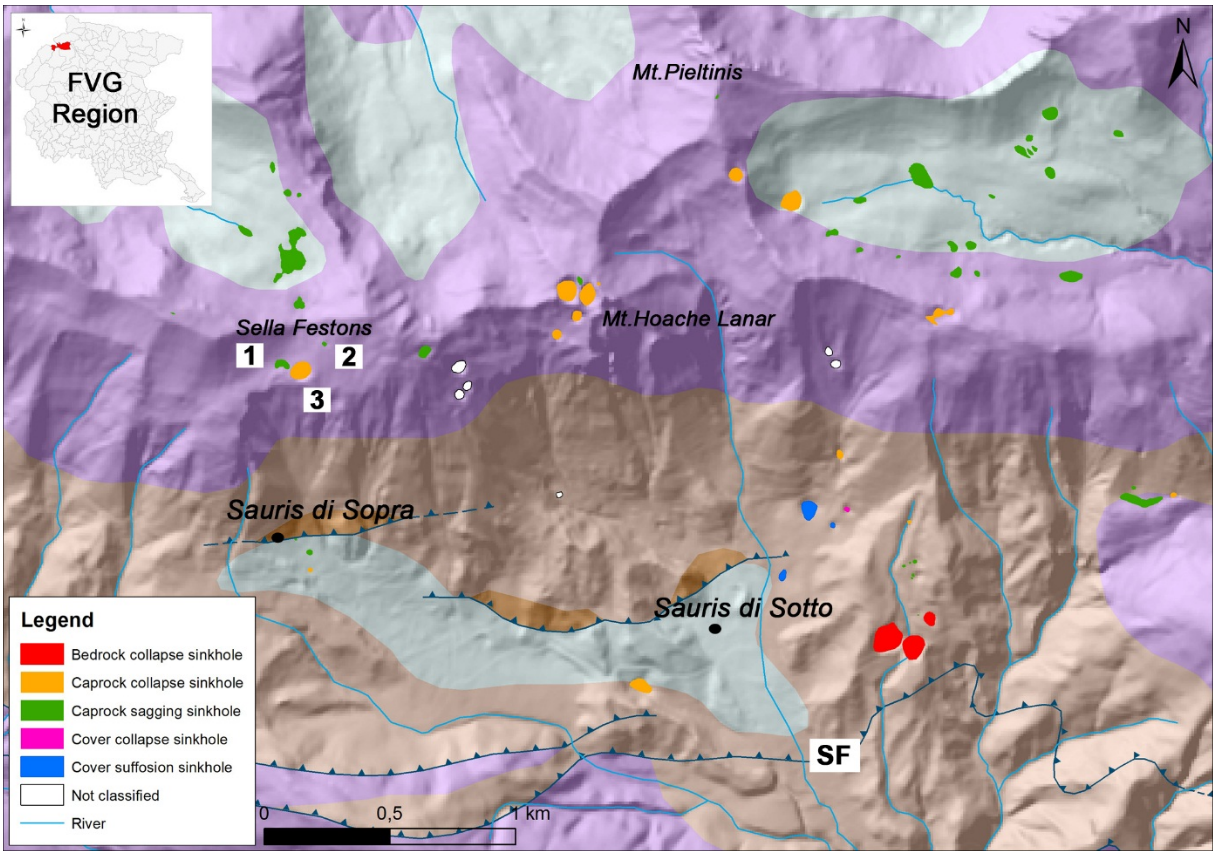

Figure 1. Geological map of the study area and sinkholes. Pink areas correspond to Werfen Formation, whereas light brown areas correspond to the 2 members of the Bellerophon Formation.

SINKHOLE RECOGNITION AND CLASSIFICATION
In order to inventory sinkhole phenomena, field surveys and aerial-photo interpretation were carried out. The Authors recognized and classified 77 sinkholes.
The Figure 2 summarizes the outputs of above-cited activities.

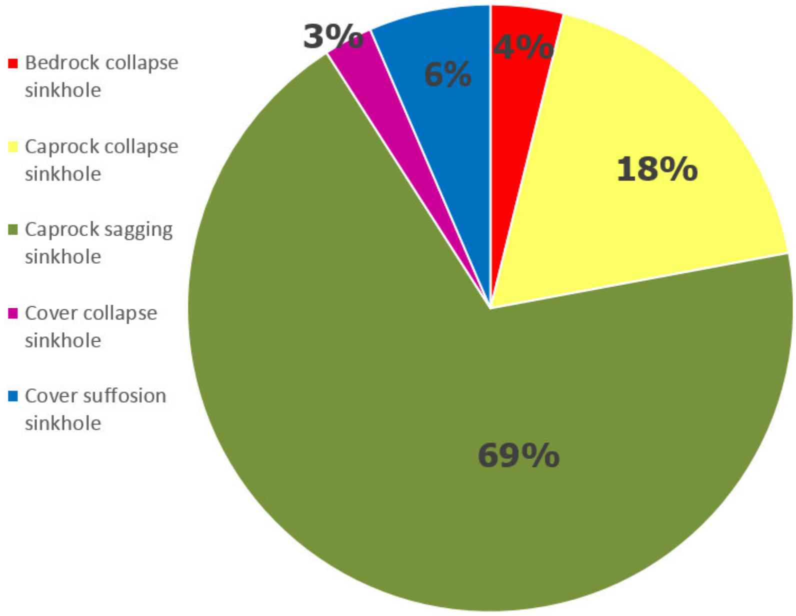

Figure 2. Graph of the different types of sinkholes affecting Sauris Municipality.

The most part of them (53 phenomena) are *caprock sagging sinkholes*, which are abundant in the northern part of the study area.
According to the classification used, caprock is referred to the uppermost layer that has to be made up by non-karst rocks that, in this case, are terrigenous rocks of the Werfen Formation.
The progressive downward bending due to the lack of basal support can be appreciated in Figure 3 where sinkhole 1 and 2 represent the early stages of a later sudden collapse evolving in a *caprock collapse sinkhole* (3) where the slopes are quite steep.
The majority of caprock sagging sinkholes are areally characterized by a circular or sub-circular shape.

Figure 3. Panoramic view of a spectacular caprock collapse sinkhole and two caprock sagging sinkholes located closed to Morganlaite Mt (northern part of the study area).

Although the *bedrock collapse sinkholes* are scarce (only 3 phenomena identified in the whole area), we observed two spectacular sinkholes lying 500 meters east of Sauris di Sotto Village. These phenomena involve the Bellerophon rocks and are limited by steep slopes affected by abundant fall of trees and debris (Figure 4). These cylindrical karst depressions are originated by the presence of a torrent, which accelerates the dissolution processes of gypsum and causes the piping effect.
The *cover suffusion sinkholes* (5) and *cover collapse sinkholes* (2) are mainly located near Sauris di Sotto and involves the Quaternary glacial deposits.

Figure 4. The view shows an impressive bedrock collapse sinkhole characterised by vertical slopes. The sinkhole bottom is hidden by a pond.

CONCLUSIONS

The outputs of the traditional field surveys permitted to recognize and classify 77 sinkholes in the Sauris Municipality. This work is part of a wider project supported and funded by the Geological Survey of the Friuli Venezia Giulia Region having as aim the inventory of evaporite sinkholes and the assessment of the related geohazard.
In the study area, different types of phenomena were observed. The majority of the sinkhole, about 80%, involves the Werfen Formation, which is dominant in the northern side.
The sinkholes located in the surroundings of the top of Mt. Festons, Malins and Pieltinis display that their occurrence can affect areas where the evaporites are located at 250m deep. This is related to the different behaviour of Werfen Formation with respect to Bellerophon Formation.
Conversely, the 4 recognized bedrock collapse sinkholes involve only Bellerophon Formation.
They are spectacular reaching diameter of about 110m and depth which can exceeds 35m.
The spatial distribution of sinkholes does not highlight any particular alignment even if the investigated area is crossed by a regional overthrust and other faults.

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