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ORIGINAL ARTICLE

Evaporite karst in Sicily

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Abstract Karst areas are distributed over most of Sicily. The most widespread karst rocks are carbonates, particularly limestones, but karst phenomena can also be seen in evaporites and particularly in salt mines. This report provides an overview of evaporite karst in Sicily, along with a ''case history'' that shows some of the evaporite karst risks to the environment. In the centre and south of Sicily, a thick sequence of Messinian evaporite rocks are subject to dissolution from meteoric and formation waters. In areas where potassium salts and rock salts are being mined, some geomorphologic changes result from the drilling of boreholes and the collapse of underground mines, thus lowering or collapsing the land surface. An example is the old salt mine ''Muti-Coffari'', situated in the commune of Cammarata, where there is a modification of the surface flow of the River Platani. Meteoric waters and runoff flow down through a borehole, enter the underground mine cavity and dissolve the salts, and then the resulting brine flows into a branch of the river, making it salty. Field investigations showed the presence of salt along the edges and on the bed of the stream where it comes out of the cave. Therefore, interventions for risk mitigation are necessary since the old mine constitutes a serious danger for damage or collapse of nearby infrastructures, and can lead to degradation of the river ecosystem and the natural environment.

Keywords Karst phenomena · Evaporite karst · Salt mining

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Introduction

The geology of Sicily is favourable for the formation of major karst and speleogenetic phenomena. The presence of both carbonate and evaporite rocks on the island has caused the development of important surface and subsurface karst features resulting from dissolution of limestone and dolomitic limestone (karst morphologies), and from dissolution of chalky rocks and those containing gypsum (parakarst morphologies).

This paper also shows an example of karst phenomena in evaporite rocks that are related to mining activity. The ''Muti-Coffari'' Mine, situated in the area of Cammarata, in the provinces of the Agrigento, shows enlargement of the shallowest galleries because of repeated collapses of the mined-out rooms, and resulting subsidence of the overlying land surface. In addition, the mine has resulted in chemical degradation of water in the River Platani; meteoric waters and runoff enter through a borehole and a swallow hole formed on the land surface, are stored there and fill the mine, where they dissolve the salts and then flow into the river, making it salty.

This mine is an example of the risk to the natural environment that comes from pre-existing anthropic cavities (deserted mines).

Karst in Sicilian evaporite deposits (Gessoso–Solfifera Series)

In Sicily, the succession of evaporite rocks deposited in Messinian times is widespread, as a result of isolation of the Mediterranean basin from the open oceans. This was caused by continental collision between Spain and Africa, with consequent closing of the Gibraltar Strait (Bommarito and Catalano 1973). Isolation of the Mediterranean Sea during the Messinian produced a hydrologic deficit, a lowering of sea level, the emergence of vast areas, and the formation of restricted circulation basins in the deepest regions, where the evaporite rocks were deposited. From the lithostratigraphic point of view, in central-southern Sicily the Gessoso–Solfifera Series is divided in two great evaporite units (Decima and Wezel 1971):

- Lower evaporite unit
  - Tripoli: alternation of white diatomite, full of fish remains, with more or less dolomitic limestone marls
  - Evaporitic limestones
  - Gypsum, with interbedded marl
  - Salt, grading laterally and upwards into clays and gypsum.
- Upper evaporite unit
  - Gypsums, containing clayey, sandy, and calcareous gypsum layers
  - Bioclastic limestones, grading upwards and laterally into gypsum
  - Clayey sands (''Arenazzolo'') that envelop the evaporite rocks.

Most of the mines for extraction of potassium salts and/or rock salt are located in central-southern Sicily, in the provinces of Enna, Caltanissetta, and Agrigento; these mineral deposits are widespread in the graben located in the central-western side of Sicily.

Evaporite deposits (rocks of chemical origin, including carbonates, sulfates, and chlorides which are produced through precipitation of such salts from aqueous solutions with elevated concentration) and the gypsum rock contain karst features that develop quickly, compared to the rate of karst development in carbonates. Evaporite rocks are extremely soluble and are easily sculpted by rain and infiltrating waters (Sauro 1986). In particular, gypsum ($CaSO_4 \cdot 2H_2O$) and the alkaline chlorides, such as sodium chloride ($NaCl$) and potassium chloride (KCl), undergo extremely rapid dissolution. The process of dissolution in such lithologies is a chemical–physical phenomenon. In fact, dissolution of such salts is influenced by many factors, such as temperature, pressure, granulometry, and the presence of dissolved salts and carbon dioxide in the circulating waters.

Environmental conditions being equal, the speed of the dissolution process (and therefore the evolution of the karst forms) is at a maximum in the salts ($NaCl$, KCl), is elevated in the gypsums, and is relatively slow in the carbonate rocks. Thus, it can be generally stated that the speed of karst development is about one order of magnitude faster in gypsum, compared to limestone, and within two and three orders of magnitude faster in salt, compared to limestone (Agnesi and Macaluso 1989; Agnesi et al. 1987).

Evaporite rocks are widely distributed in Sicily, and are most abundant in the western part of the island; in the eastern part they are present and crop out only in limited areas. Some of the principal evaporite karst areas in Sicily are located in Belice, Nisseno-Agrigentino, and the Erei Mountains.

From the morphostructural, topographical, and environmental point of view, the karst landscapes in evaporite rocks of Sicily are varied, especially with reference to the complex evolutionary history of the evaporite basins and to the following orogenic, morphogenetic, and climatic-environmental events. The most common types are:

- plateaus corresponding to tabular complexes, derived from uplift and exhumation of the sediments deposited in evaporite basins; the evaporite series result in a sort of ''inversion of relief'';
- monocline dorsal constituted from evaporitic rocks;
- concordant folds with alternation of anticlinal uplifts and synclinal depressions. They are found mainly where the evaporite formations are more plastic, often with marly and clayey interbeds.

Dissolution of evaporite rocks, acting over many millennia, causes regions to develop peculiar morphologies (Ruggieri 1987; Macaluso et al. 2001). The prevailing forms of dissolution on the emerging surfaces of hilly landscapes (superficial or shallow-subsurface forms) are those related to the superficial outflow of water. On the other hand, larger landforms, such as dolines and blind valleys, are produced by ''accelerated dissolution'' and by mechanical erosion at points of surface-water infiltration and/or groundwater outflow.

River landscapes are characterized by valleys formed by flowing water that cuts into, and sometimes cuts beneath, the ground; this favours the collapse of blocks of overlying rocks. The resultant landforms are often valleys with subvertical walls in the lower part of the slopes.

Lake landscapes are characterized by a closed basin, including a lake in the lowest part of the basin; for example, the Soprano Lake, in the province of Caltanissetta, is produced by dissolution of the underlying gypsum and sinking of the land surface (Agnesi et al. 1986).

In sea-coast landscapes, the karst-producing agent is sea water; waves and ocean spray can, as is the case in Agrigento, undercut the coast to sometimes produce a high coast with ''furrow of leaf'' features due to chemical dissolution.

The action of the sea generates frequent landslides that produce an accumulation of blocks on the coast. These blocks undergo accelerated dissolution because of the action of the water.

Hypogeum or subsurface features that are found within cavities below the subsoil result from the infiltration of waters that penetrate up and down in the rock fractures and result in dissolution. Examples of karst cavities in gypsum are: the Cave of Santa Ninfa, the Cave of Sant'Angelo Muxaro, and the swallow-hole of Mount Conca (Bertolani 1975; Chiesi et al. 1987; Agnesi and Macaluso 1989).

Karst phenomena in evaporite areas (''Muti-Coffari'' Mine)

Geologic features

The Spina Mine (Fig. 1) is situated along national road 189 (Palermo–Agrigento), and more precisely near the marker for Km 26. Surface lithologies are typical of the rocks belonging to the Gessoso–Solfifera Series. The area is described in the tablets I.G.M. (1:25,000), Sheet 267 IV NE Cammarata; Sheet 267 IV SE Casteltermini; Sheet 267 I SW Mussomeli; Sheet 267 I NW Peak Ficuzza. Stratigraphic terms used in the area belong to the ''Gessoso–Solfifera Series'', and show an age involving an interval of time (Messinian) between the Late Tortonian and the Early Pliocene (Catalano and D'Argenio 1982; Catalano 1986). These rocks were deposited during a sharp increase in water salinity; in fact during the Messinian (about 5.6 million years ago) there was an interruption of the normal connection between the Mediterranean Sea and the Atlantic Ocean. Two paleogeographic zones are distinguished: a ''marginal'' zone that developed SE of the line between Agrigento and Caltanissetta, and NW of the Sciacca-Nicolosi alignment; and the zone of ''Bacino'', or of Cattolica Eraclea.

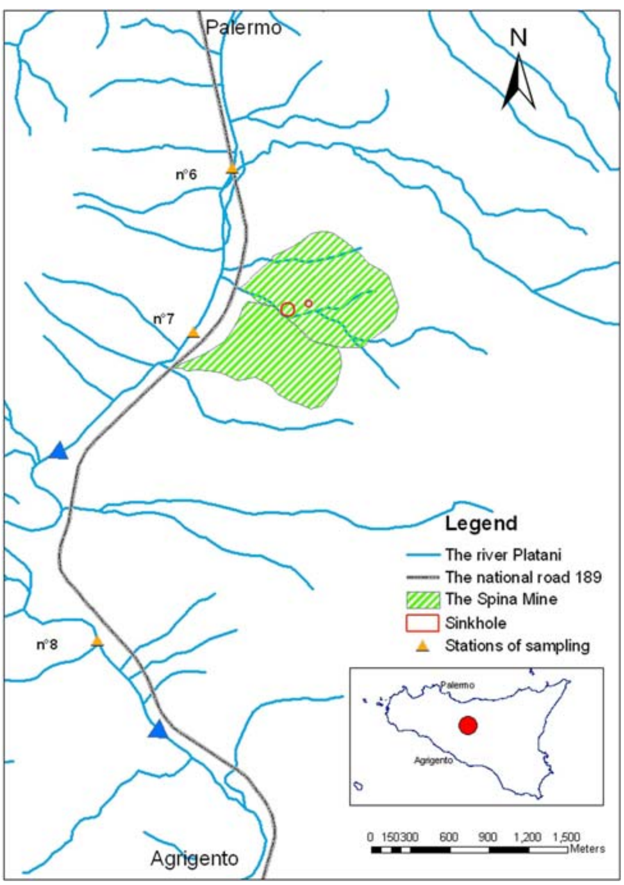

Fig. 1 Geographic location of the ''Muti-Coffari'' Mine in Sicily

The Sicilian ''Gessoso–Solfifera Series'' is characterized by a lithologic succession of diatomites, evaporitic limestones, gypsums, salts, and interbeds of clays, marls, and carbonates. This succession of strata lies discordantly on the pre-evaporite deposits of siliciclastics of the Terravecchia Formation (Upper Tortonian–Lower Messinian), and it is overlain by pelagic limestones of the ''Trubi'' (Lower Pliocene).

The mine and the surrounding environment

The old salt mine is located in the ''Contrada Spina'', in the territory of Cammarata in the province of Agrigento, and the overlying rocks are gypsums and clays. Originally the mine was separated into two parts: one run by the firm ''Coffari'' and the other run by the firm ''Muti''. The salt layer occurs in a SW–NE trending monocline that dips to the SE. The thickness of the salt is 30–40 m in the mine ''Coffari'' and 100 m in the mine ''Muti''. The mine ''Coffari'' is about 300 m from Spina railway station, located on the Palermo–Agrigento line and bordered on the South by the concession of the ''Muti'' mine. Previously, the mine was divided into two sections, referred to as ''Stazione Vallone'' and ''Vecchia Salina''. The latter was extensively developed and the mine reached depths of 308.3 m below the land surface. The mine was operated at six levels, starting at a depth of 96 m below the land surface.

The third level contains a horizontal gallery, which is the principal haul way located at an elevation of 263 m. Mining was done by the room-and-pillar method. On June 26, 1956, the companies then running the mines entered into a partnership that unified all the operations. The last concessionaire seems to have been the company Italkali, but at present the mine is closed because mineable salt has been exhausted.

Some years ago the mine, after being filled with flood waters that have not stopped, caused subsidence and sinkoles in the surrounding area. Mud, water, and salt came out of the mine, but luckily they didn't overwhelm the nearby bridge of highway 189, and were channelized into the river bed.

Ground subsidence has extended so as to involve new areas adjacent to the principal sinkholes (at elevations of 350 m above sea level). Such sinking has originated from collapse of the vault in the shallowest mine level, despite having about 50 m of overburden. The volume of material that sank into the principal sinkhole was about 800,000 m^3, and about 50,000 m^3 sank into a later sinkhole. The first sink also caused a debris slide from an adjacent hill slope, while at the other sink there are many systems of radial cracks that precede new collapses (Figs. 2, 3).

Infiltrating water enters through a borehole and through the sinkholes, whereupon it floods all the mine levels and dissolves the salt. Saturated brines that don't infiltrate to great depths escape to the land surface from the mine entrances and flow into the River Platani. Investigations carried out in the area show the presence of salt along the edges and on the bed of a stream that comes out of the mine which flows into the River Platani; the water coming from the mine is salty, and the salt crust present in the stream results from partial evaporation of the brine (Fig. 4). The mine discharge strongly influences the quality of surface waters because it contains brine that continues to pollute the River Platani, especially in winter. Brine that flows into the river coats the ground with salt, it causes the death of fish, it alters the ecosystem, and it leads to abandoning fertile areas that once yielded luxuriant crops. The areas most affected by hypersalinity of the river are those of Acquaviva Platani, Campofranco, and Sutera.

Fig. 2 One of the sinkholes formed above the ''Muti-Coffari'' Mine

Monitoring of surface waters of the River Platani has been carried out since December 2001, and some of the analyses allow us to characterize the waters. Along the principal course of the river, from its mouth up to Fanaco Lake, 13 sampling stations (Fig. 5) were selected for field measurements of dissolved O_2, temperature of the air, and temperature of the water.

The location of the stations was selected with regard to human activities, which clearly have an influence on water quality: presence of habitation centres, presence of urban and industrial emissions, and the presence of tributary streams. In some cases, the locations were changed because of difficulty in reaching the selected sites, but only after being sure that the distance of the sample points from the above-mentioned emissions was enough to guarantee full remixing of the waters: that assures assessing the quality of the water receptor, and not that of the mine-emission deposits. The station n°7 was located adjacent to the old salt mine.

During testing, the following parameters were monitored:

- air temperature and water temperature during the sampling, measured in °C;
- dissolved oxygen, measured in situ and expressed in mg/l;
- nitrogen, present in different forms;

Fig. 3 Additional sinkhole formed above the ''Muti-Coffari'' Mine

Fig. 4 Salt deposits formed by evaporation of brine flowing from the mine

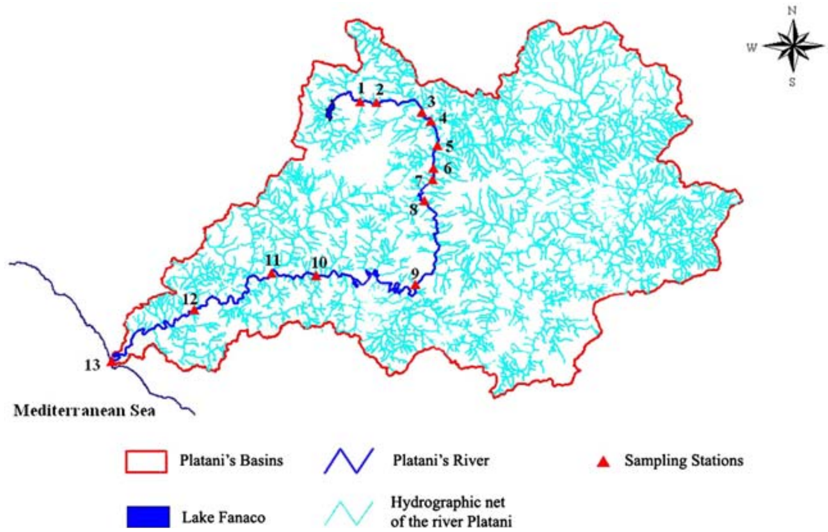

Fig. 5 Sampling stations along the River Platani

- phosphorus, an element essential for the growth of the organisms, and often the principal cause of eutrophic phenomena;
- conductivity, related to the presence of salts;
- chlorides, their presence in elevated concentrations can indicate that an emission has occurred;
- sulfates, their presence can produce bad odours (connected to the production of sulfides) and corrosion of manufactured articles (indirectly due to the hydrogen);
- sodium and potassium; calcium and magnesium.

To show changes in concentrations along the principal river, and in proximity of the mine, graphs have been made to plot the salts, the conductivity, the sulfates, and the dissolved oxygen (Figs. 6, 7). Based on these graphs, especially those showing salts and conductivity, the river can be divided into two reaches. The first one is in the mountainous part of the river, from the salt mine up to Fanaco Lake. The second extends from the salt mine to the mouth of the river. Separation of the two reaches occurs where emissions of salt from the mine modifies the waters, making them salty and altering the river ecosystem.

The values of chlorides, sodium, and sulfates, and consequently the conductivity (Figs. 6, 7), increase remarkably downstream of the deep valley coming out of the mine (80 Km from the mouth). Calcium and magnesium gradually increase beginning at the same point of emissions from the salt mine. Dissolved oxygen values vary between 6.10 and 13.20. The only value that is outside of that range is the station of ''Ponte Vecchio'', where the measure is 3.10. This is due to the presence of the emissions at Castronovo.

In conclusion, the old salt mine causes a negative impact for the river ecosystem, for the natural environment, and for the nearby road system like the busy road S.S. 189 Pa-Ag.

It is necessary to intervene as soon as possible, also keeping in mind that the hill overhanging the mine poses a risk of slipping because of water infiltration into the subsoil.

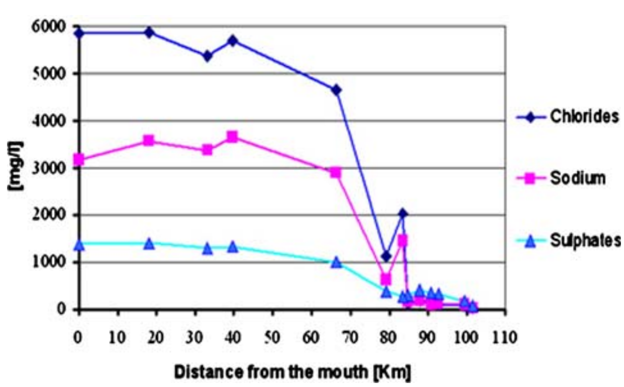

Fig. 6 Concentration of salts and sulfates along the main course of the River Platani

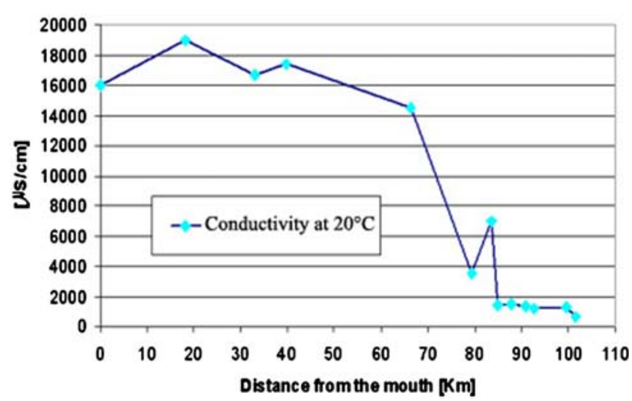

Fig. 7 Conductivity along the main course of the River Platani

In general, the negative effects linked to the mining activity are mainly connected to the following factors:

- mobilization of the dissolved waste material placed in the dumps with varying degrees of slopes;
- alteration of the surface and subsurface hydrology for the collection of meteoric waters in the galleries of the mine, which then are emitted as brackish waters, or for the interception of formation waters;
- potential instability of rocks and land on the border of the excavation fronts;
- erosion along the river bed that is related to the mining activities;
- modification of the land morphology and destruction of the vegetation, with remarkable effects on the landscape.

Conclusions

The current paper describes types of karst phenomena, both in the evaporite complexes and in cavities in the subsoil of Sicily, and includes a description of one case study that has caused environmental and infrastructure risks.

The ''Case History'' was a study of the old mine Muti-Coffari, that some years ago (after total flooding) caused subsidence of the surrounding area. Fortunately, the river of mud, water, and salt that ran out of the mine didn't overwhelm the nearby bridge of highway 189, because they were directed into the river bed.

Investigations showed the presence of salt along the edges and on the bed of the stream coming out of the mine and flowing into the River Platani, making it salty. Before reaching the old salt mine, water in the river was fresh. The presence of the mine causes a change in the state of the waters, altering the ecosystem of the River Platani.

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