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The gypsum mining area in the "Vena del Gesso" biodiversity landscapes (Monte Tondo quarry, Emilia-Romagna Region): quarrying and old mine tunnels environment impact on natural karsts systems and groundwater quality

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This environmental geology study develops and correlates different earth science subjects and investigation tools to evaluate the environment health of Borgo Rivola "Vena del Gesso" zone, known as an important naturalistic and characteristic landscape of Romagna's Northern Apennines, involved in the largest gypsum mining industry of the country. A particular focus is due to the assessment of groundwater drainage and quality, proposing operating and mining development guidelines in agreement with environment sustainable principles.

1 Introduction

The Monte Tondo quarry is located on the Vena del Gesso ridge of the eastern Senio valley (Figure 1), between the NE gentle clay hills of Riolo Terme and the SW mountain landscape of Casola Valsenio.

This productive gypsum site is the only legal mining area allowed in the Emilia-Romagna Region, as a result to reduce the historical intense exploitation along the Vena del Gesso outcrops. The existing Monte Tondo quarry is an open pit mine with traditional drilling & blasting excavation and mineral processing. The total annual gypsum production is about 350.000 ton. The quarry underground is characterized by 13 kilometres of galleries, carried out in the past since 1958, on 4 different surface levels, from 220 m to 100 m, coinciding with the Senio river edge.

Gypsum rock formed during Messinian events makes up an almost continuous and prominent belt (the so called, Vena del Gesso) along the Apennines foothills. This rock belt is characterized by peculiar morphology and ecosystems, has been attractive to man for different uses since ancient times, providing the natural resource for an important social, artistic and economic development [1]. Local community and authorities are sensitive to future mining developing scenarios because bordering to the Vena del Gesso Natural Park, one of the remarkable regional features, from the geological, karsts, naturalistic and archaeological point of view.

The aim of this study was to define the interaction process between the anthropogenic and the hydro-environment, with particular attention to the gypsum karsts protection and to the surface and groundwater pollution risks. The international speleology community have recognised this area, and in detail Re Tiberio karst system (linear development, 2120+ meters) as one of the longest gypsum caves in Italy, after Inghiottitoio Cà Siepe and Spigola-Aquafredda caves.

Fig. 1: Aerial overview of Monte Tondo open pit quarry and Vena del Gesso belt on the eastern Senio Valley.

2 Geological setting

The Romagna Apennines, extending from Sillaro Valley to the west, from Marecchia Valley to the east, are part of the Northern Apennines, an ENE-verging arc, characterized by compression along the external front and extension in the inner western part. The Romagna Apennine is split in two sectors (western and eastern) by the Forlì line, a complex fault zone oblique to the Apenninic trend. The two sectors defined by this feature have different structural arrangements at the surface; the foothills of the western sector (as the present study area) shows a gentle N-NE dipping monocline of Messinian to Pleistocene deposits, resting above the Marnoso-Arenacea Formation, while the same succession is deformed by several thrust-related anticlines with Apenninic trends in the eastern one.

The lithostratigraphy of Senio Valley consists of four main formations (from the bottom):

i) the *Marnoso-Arenacea Fm.* (MA, Langhian-Messinian), is a deep-water siliciclastic turbidites, in huge clastic wedge, up to 3000 meter thick, made up of slope mudstones which contains minor torbiditic sandstone and chaotic bodies (named *ghioli di letto*) and finely-interbedded organic and diatomite-rich laminites and mudstones (named *euxinic shales*);

ii) the *Gessoso-Solfifera Fm.* (GS, Messinian), is made up of both primary and clastic, resedimented evaporates, with interbedded organic-rich shales, put down during the evaporitic and post-evaporitic stages of the "Messinian salinity crisis" (between 7.2 to 5.3 million years ago);

iii) the *Colombacci Fm.* (CO, Upper Messinian), consisting of mainly siliciclastic sediments derived from Apenninic sources, characterized by coarser-grained lithology and by the occurrence of thin lacustrine micritic limestone beds;

iv) the *Argille Azzurre Fm.* (AA, Lower Pliocene), is made up of relatively deep marine mudstones.

The study area of Monte Tondo quarry and the adjoining Vena del Gesso outcrops (Figure 2), is in prevalence (70%) a Messinian Gessoso-Solfifera Formation; 80% of the gypsum lithology corresponds to natural and vegetated outcrops, and the remaining 20% is gypsum in anthropogenic surface. The west side of the quarry is marked up by various debris deposits and a huge mining sterile dumping area. The limit between the Marnosa-Arenacea and the Gessoso-Solfifera Formations, not visible from the field, is located under the mining sterile deposits, at about 15 meters of depth from the SW quarry floor.

The Gessoso-Solfifera Fm., of this area, is a monocline structure with uninterrupted belt up to 150 m thick in outcrop and a maximum thickness of 240.80 meters (S1/2001 borehole). The gypsum deposit has a

strong cycle organization, at first recognized by Vai and Ricci Lucchi [2] who counted up to 16 small-scale, decametric-thick, shallowing-upward cycles, recording the progressive evaporation of shallow lagoons. The Monte Tondo upper evaporitic cycles (informally, gypsum layers), thinner, in fine size gypsum crystals and more fractured, compared to the bottom evaporitic cycles, known as coarse size gypsum or selenitic crystals, thicker and less fractured. Gypsum beds are separated by thin bed of pelitic lithology varying in thickness between 0.2 m and 0.8 m.

The Colombacci and Argille Azzurre Formations are marginally present in the NE area of study, close to Crivellari village.

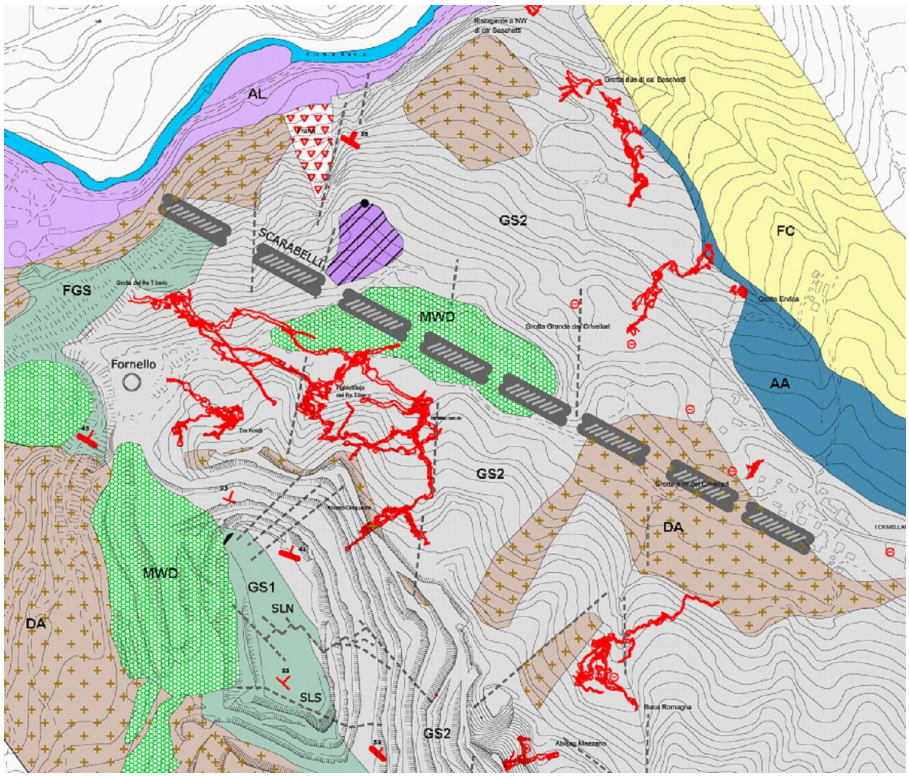

Fig. 2: Geological map of Monte Tondo area. GS1 = Gessoso-Solfifera Fm. lower layers; GS2 = Gessoso-Solfifera Fm. upper layers; FGS = fractureted zone of Gessoso-Solfifera Fm.; FC = Colombacci Fm.; AA = Argille Azzurre Fm.; AL = stream sediments; DA = anthropogenic detritus deposits; MWD = mining waste dumping zones; SLN,SLS = Sasso Letroso north and south faults; karst elements in red color (circles = dolines, reticules = cavities development).

3 Investigation and analytical methods

Data collection and interpretation include field and laboratory works. New aerial photo acquisition in DFR system and remote sensing analysis have been carried out to support geological, structural, karst-morphology and hydrogeological field survey.

An initial environment impact assessment, according to UNI EN ISO 14001/2004 procedure, was made to analyse the Monte Tondo mining process and work environments, identifying the major anthrophic hazards and potential pollution zones to be monitored. Electrical methods in geophysical prospecting have been used to find cover subsidence sinkholes and dolines. Direct geological investigation, consisting in n. 5 drill cored boreholes, was done inside and outside the quarry area to implement geological data know-how. In all boreholes were installed piezometers (in addition to the 2 existing ones); water table and chemical-physical

basic parameters (pH, temperature, electrical conductivity and redox) have been monitored on a monthly base for one year. Karst systems and quarry galleries, as a natural window on the underground, were used for hypogeal geological survey, as valid tool to rebuild the structural setting, integrating new data with existing surface information. A detailed structural, hydrodynamic and geomorphological mapping has been developed in the Re Tiberio caves and in the four rooms and pillar mining levels. Groundwater hydraulic data were obtained through slug tests in wells and galleries karsts inrush and/or galleries drainage flow capacity measurements.

Water chemistry characterisation was done sampling 32 spots, including surface and groundwater, during four field campaigns distributed during wet and dry seasons, over two years. A special well-sampler was used to sample piezometer groundwater at different depths. Characteristic water level to be sampled was decided after a preliminary physical parameters logging probe of the well water column; this approach was useful to identify different water groups. All water samples were analysed in laboratory for major cations and anions; in some cases, isotopic determination and hydrocarbon contents (mineral oil) were investigated as well.

Field data and analytical results were correlated and represented in a whole elements map and a new hydrology conceptual model (Figure 4) was proposed to support environment issues and mining engineering developments.

4 Discussion and results

The Monte Tondo quarry represents an important national site from a social-economic point of view, in terms of annual volumes exploited, it is considered as one of main European gypsum mining areas; the local Vena del Gesso landscape alteration due to quarrying activity, since 1958 to present, can be quantified in 9.3 million cubic meters of rocky mass exploited, of which 1.3 million correspond to underground mine.

The five old mining levels, developed from 220 m to 100 m, have irreversibly modified the karts auriferous and groundwater hydrodynamic of the SW Monte Tondo's original hydrogeology basin. The SW morphology basin has increased up to 119% surface, with respect to the original hydrology equilibrium, reducing the NE basin to 81%. The interaction between anthropic galleries and natural caves has deactivated saturate karsts sections or activated the water flow in relict karsts systems, modifying and complicating the hydrodynamic and the hydrochemistry of the investigated area. Two main water drainage were detected in the underground galleries; the 1^{st} groundwater drainage-high conductive system (3-4.52 mS/cm), developed from 220 m gallery to the Serio river level (at 100 m), collects principally the rain water drained inside the open pit quarry, with a minimal amount of water from secondary permeability, as faults, fractures and pelitic layers intersecting the tunnels at different levels. The 2^{nd} groundwater drainage-low conductive system (2.32-2.80 mS/cm) is dominant karts aquifer collected from Abisso Mezzano, Abisso 50 and Re Tiberio caves, intersected by the gallery at 140 m depth and channelled though the bottom gallery at 100 m. Field data show the 2^{nd} drainage system as continuous flowing during all year with flows capacity ranging from 1.5 to 3 l/sec. Flow increases are directly related to intensive and medium continuous rain events. In general, gypsum karsts aquifers, due to their high flow rates and lack of any possibility of self purification and due to the fact that they are potential storage traps of pollutions [3], are highly vulnerable by all kinds of pollutants, as civil waste, quarry and chemical fertilizers. In this case study, Re Tiberio caves complex, even if locally structurally damaged by the mining operations, is well preserved from waste and contamination. However, due to the mining process and work environments, and due to the interaction of karts auriferous in tunnels, the quarry activity needs to define specific programs to prevent water pollution hazards.

The field and hypogeal structural survey has been useful to understand the tectonic hydraulic natural barriers and ground water flow in the preserved gypsum deposit of the NE hydrological basin; in particular, five fracturation systems and the evaporitic layers immersion (NNE/23°-55°), represent the preferential way to the infiltration rain water in depth. The three major fault systems, immerging SW and SSW, represent

a sort of natural barrier, responsible for confined or semi-confined aquifers. Structural data summary is published in Table 1.

Table 1: Monte Tondo structural systems surveyed in quarry tunnels and Re Tiberio caves.

System	Immersion	Inclination
A - Fault	SW	82°-90°
B - Fault	SSW	85°-88°
C - Fault	SSW	70°-78°
D - Fracture	SW	50°-90°
E - Fracture	ESE	69°
F - Fracture	NNE	54°
G - Fracture	NE	16°
H - Fracture	NNW	70°

Structural survey underground has been a valid tool for identifying plan faults and cinematic indicators, that usually on evaporitic outcrops are not possible to identify, because the rapid dissolution effect and alteration of the gypsum. Besides, the Re Tiberio caves characterization has contributed to update the karts mapping and morphologies know-how, as chemical deposits (concretions and secondary minerals), uncommon in gypsum cavities.

The water samples analysis, plotted in Piper diagram (Figure 3), shows different water groups in the study area. Water chemistry in quarry environment derives totally from the gypsum dissolution process and can be classified as sulphate-calcium composition. The groundwater sampled in the well in tunnel 200 m (borehole, S2/PZ2) is instead characterized by a sodic-chlorurate composition with high salinity and hydrocarbon association. This particular case is probably related to a confined salt relict aquifer, trapped by tectonic elements. Surface waters are chemical composed by both groups described above; during the dry season the chlorinate waters influence chemistry composition. Molecular water isotopic analysis confirms different aquifer origins and groundwater circulations.

The quarry activity seams not to effect negatively on the groundwater quality; hydrocarbon results are lower then 1 mg/l, with variable content during the different seasons. Some spring waters, sampled outside the quarry, have shown very high hydrocarbon content due to natural origins. Nitrates contents are seasonal variable and always under the environment legal comply limits; their presence can be related to blasting material usage and/or to bats excrements in old tunnels.

As represented in the geohydrological conceptual model (Figure 4), differently as proposed by previous studies, the groundwater can't be considered as a homogenous and sutured aquifer in gypsum deposits; new data can sustain that groundwater's of Monte Tondo is a multi-aquifer system, where selenitic layer (easily karsificable) play a rule of semi permeable levels and the faults or horst and graben depth structure, are able to confine or semi-confine groundwater at different levels.

From the mining point of view, the depth ground water, can't be considered a problem, in term of inrush event. Actually the exploitation is dedicated to the upper gypsum layers, considered less permeable and conductive, compared to the selenitic lower layers. Underground activity in E and SE direction, between 190 and 200 surface levels, should be avoided due to possible karst aquifers in pressure, close to Abisso Mezzano caves.

5 Conclusions

The authorized open pit mining evolution, consisting in reducing the height of the natural Vena del Gesso belt and the hydrological limit between the NE and SW hydrology major basins, even though impacting significantly on the visual and landscape aspects, it has a tolerable modification of surface and karsts water

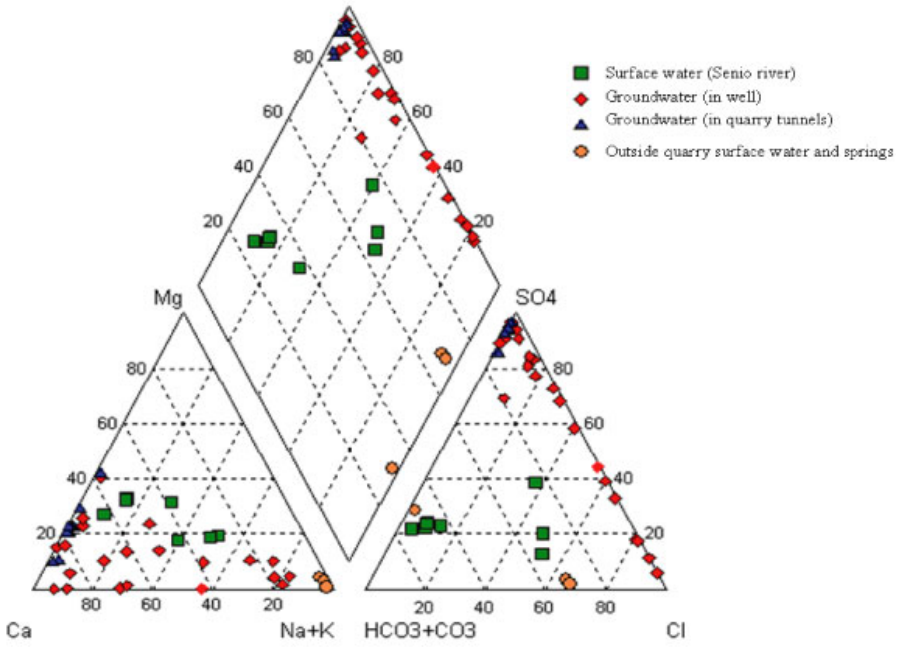

Fig. 3: Piper diagram: surface and groundwater classifications in Monte Tondo area.

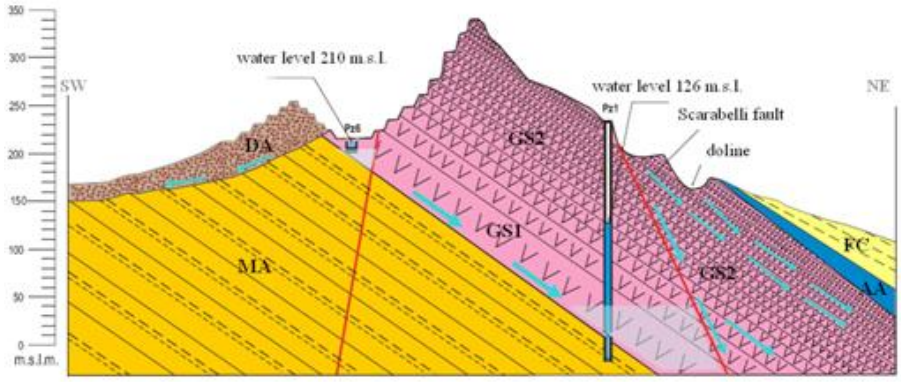

Fig. 4: Geohydrological conceptual model of Monte Tondo area**.** MA = Marnoso-Arenacea Fm., low permeability; GS1 = Gessoso-Solfifera Fm. selenitic layers, low to medium secondary permeability; GS2 = Gessoso-Solfifera Fm. microcrystalline layers, low and secondary permeability; FC = Colombacci Fm., low permeability; AA = Argille Azzurre Fm., very low permeability; DA = anthropogenic detritus deposits and mining waste, medium permeability; secondary permeability drainage directions (arrows in blue colours).

circulations. Also the quality of the water doesn't seam to be contaminated by the quarry activity effect. The Re Tiberio cavities needs to be preserved and protected from future mining due to archaeological founds, to peculiar speleothems and mineral caves discovered during the characterization, as well for the scientific interest for understanding the structural regional setting as show during the hypogeal survey.

Therefore, Monte Tondo quarry doesn't have environment impact levels classified as serious consisting in critical environment conditions, not complying with national and EU environment laws, that should request the immediate Authority emergency. However, an environment managing system is highly recommended

to control environment risks and continuous improvement of the activity, with respect of the sustainable improvement principle adopted in the major invasive industries .

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