Hypogea 2015

Proceedings of International Congress of Speleology in Artificial Cavities
Italy, Rome, March 11/17 - 2015

EDITORS

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SOCIETA' SPELEOLOGICA ITALIANA
ROMA SOTTERRANEA

PERTICARA MINE (EMILIA-ROMAGNA, ITALY): FIRST RE-EXPLORATION, DOCUMENTATION AND PROBLEMS

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Abstract
The Emilia-Romagna Regional Speleological Federation recently launched a complex research project: "Eastern Romagna Gypsum and Sulphur", aimed at surveying and studying the artificial and natural cavities in Eastern Romagna (Northern Italy). Many important artificial cavities exist in the area, which hold impressive industrial archaeology, historical and social values. Among these, the mines that quarried sulphur from the Gessoso-solfifera Formation. Undoubtedly the most interesting one is the Perticara Mine (Novafeltria), that was, in its heyday, the most important sulphur mine in Europe.
Keywords: Perticara Mine, gypsum, sulphur, artificial cavities, breathing apparatus, gas detector.

Riassunto
La Federazione Speleologica Regionale dell'Emilia-Romagna, per il periodo 2014-2015, ha varato un complesso progetto di ricerca dal titolo "Gessi e Solfi della Romagna orientale", che si prefigge di rilevare, documentare e studiare le cavità naturali e artificiali della Romagna orientale. Il territorio interessato si estende dalla valle del Savio (provincia di Forlì-Cesena) fino al nuovo confine regionale con le Marche, dopo l'annessione dei sette comuni dell'alta Valmarecchia nella provincia di Rimini, includendo inoltre anche il territorio della Repubblica di S. Marino. La zona in esame ha, dal punto di vista delle cavità artificiali, un importante valore archeologico industriale, storico e sociale per la presenza di numerosissime zone minerarie di estrazione dello zolfo, appartenente alla Formazione Gessoso-solfifera. Il progetto si prefigge di studiare e documentare tale patrimonio in stretta collaborazione con gli enti del territorio: parteciperanno infatti la Regione Emilia-Romagna, le Università di Bologna, Modena e Reggio Emilia, la Società di Ricerca e Studio della Romagna Mineraria, il Museo Sulphur e l'Ente di Gestione per i Parchi e la Biodiversità – Romagna. Le numerose miniere di zolfo di questa zona, che hanno lavorato con certezza almeno fin dal periodo rinascimentale, hanno rappresentato una realtà economica importante per la zona, quindi saranno investigate dal punto di vista socio-economico le implicazioni dell'estrazione dello zolfo sul tessuto sociale, sulle condizioni di vita e di salute dei lavoratori. Il programma di ricerca si prefigge anche il recupero di mappe minerarie e cartografia storica della zona, con digitalizzazione e georeferenziazione del materiale reperito. Il progetto infine prevede la "ri-esplorazione" delle miniere ancora percorribili e la loro documentazione fotografica. L'emergenza storicamente più interessante è sicuramente quella di Perticara (Novafeltria), che fu la miniera di zolfo, durante il suo massimo splendore, più importante d'Europa. Nel presente lavoro si presentano i risultati delle prime ri-esplorazioni della miniera, la documentazione delle gallerie e le prime osservazioni effettuate sullo stato dell'aria delle gallerie.
Parole chiave: *Miniera di Perticara, gessi, zolfo, cavità artificiali, autorespiratori, misuratori di gas.*

Introduction

The Emilia-Romagna Regional Speleological Federation (FSRER) has recently launched a complex research project: "Eastern Romagna Gypsum and Sulphur", aimed at surveying and studying the artificial and natural cavities in Eastern Romagna (Northern Italy). The area of analysis stretches from the Savio Valley (in the province of Forlì-Cesena) to the new administrative border with the Marche Region, and also includes the Republic of San Marino. Many important artificial cavities exist in the area, which hold impressive industrial archaeology, historical and social values. The mines quarried sulphur from the Gessoso-solfifera Formation. The project will be developed in cooperation with the following organizations: the Authority of the Emilia-Romagna Region, the University of Bologna, the University of Modena and Reggio-Emilia, the Romagna Mining Research Society, the Sulphur Museum and the Authority for the Management of Parks and Biodiversity - Romagna. The numerous mines, that have undoubtedly existed since the Renaissance, were an important economic sector in the area. In the following sections of this projet they will be studied both from an economic and a social standpoint, concerning the sulphur extraction's repercussions on social structures and on the workers' health. Moreover, the research programme is determined to recover historical cartography and old mining maps, that will be digitized and geographically positioned. The project aims also at carrying out the possible mines re-exploration and their photographic documentation. The most interesting mine is surely the Perticara Mine (Novafeltria), that was, in its heyday, the most important sulphur mine in Europe.
This paper presents the first results of the tunnels re-exploration and observations about the air composition.

Historical framework

In the Romagna and Marche regions, sulphur mining probably dates from Etruscan or Roman times.
The most antique document, that provides information about Perticara sulphur mining, is the papal grant to

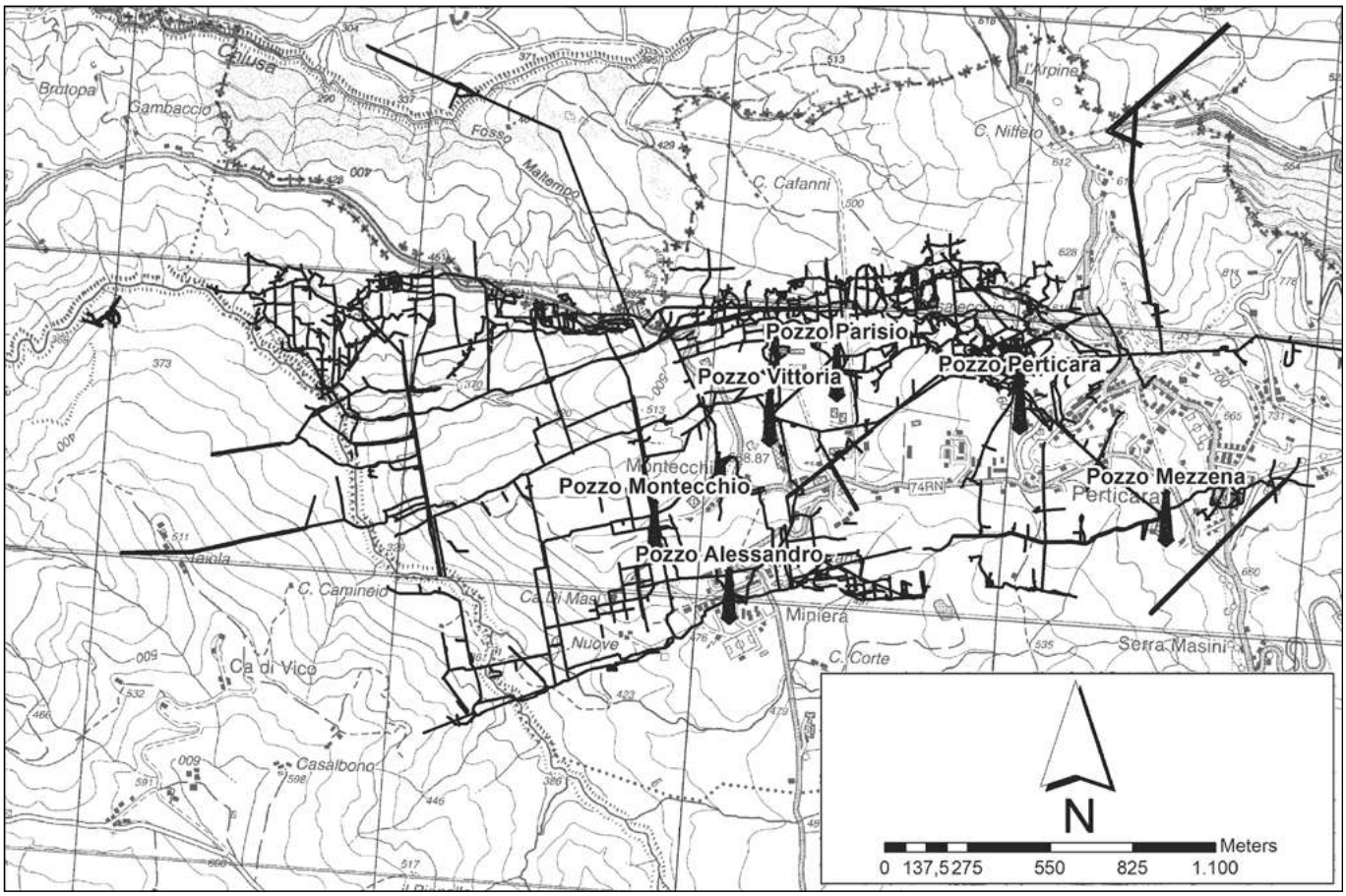

Fig.1: tunnel plan, positioned in the Technical Regional Map, scale 1:25.000.
Fig. 1: schema delle gallerie, georiferite su Carta Tecnica Regionale 1:25.000.

Malatesta to manufacture saltpetre and sulphurous powder in Perticaja o Perticaglia area (Bartolini, 1974). Countless owners come in succession in following century; in 1816 the mine is owned by the count Giovanni Cisterni, who spurred the works to dig the Alessandro and Paolo pits. He was followed by the Society Anonima Miniere Zolfuree di Romagna and the Trezza Albani Society. In 1917 the Montecatini Society took the mine from Trezza Albani Society with a bankruptcy price: the sulphur quantity in the places was worth more than the price that they had paid (Scicli, 1972).
The Montecatini Society managed the mine, improved and rationalized the digging methods and the production until the end of the Second World War. The society dug new pits, regimented the waters and dugs three big levels, labeled as, respectively, 0, 1 and 2. In depth they dug new levels, using, wherever possible, the previous works.
Perticara mine closed definitively in 1964 (Rinaldi, 1987).

The deposit

The Perticara deposit is inside the messinian Gessoso-solfifera Formation, that is locally about 120 meters thick. It consists of 13 gypsum layers alternated between marl and bituminous marl, locally named "ghioli". The last five gypsum layers contain sulphur; the biggest is named "Strato Maestro" (literally, "Master Bed") and it is about 22 meters thick: it

Fig. 2: speleologists with breathing apparatus and gas detector.
Fig. 2: speleologi con gli autorespiratori ed il misuratore multigas.

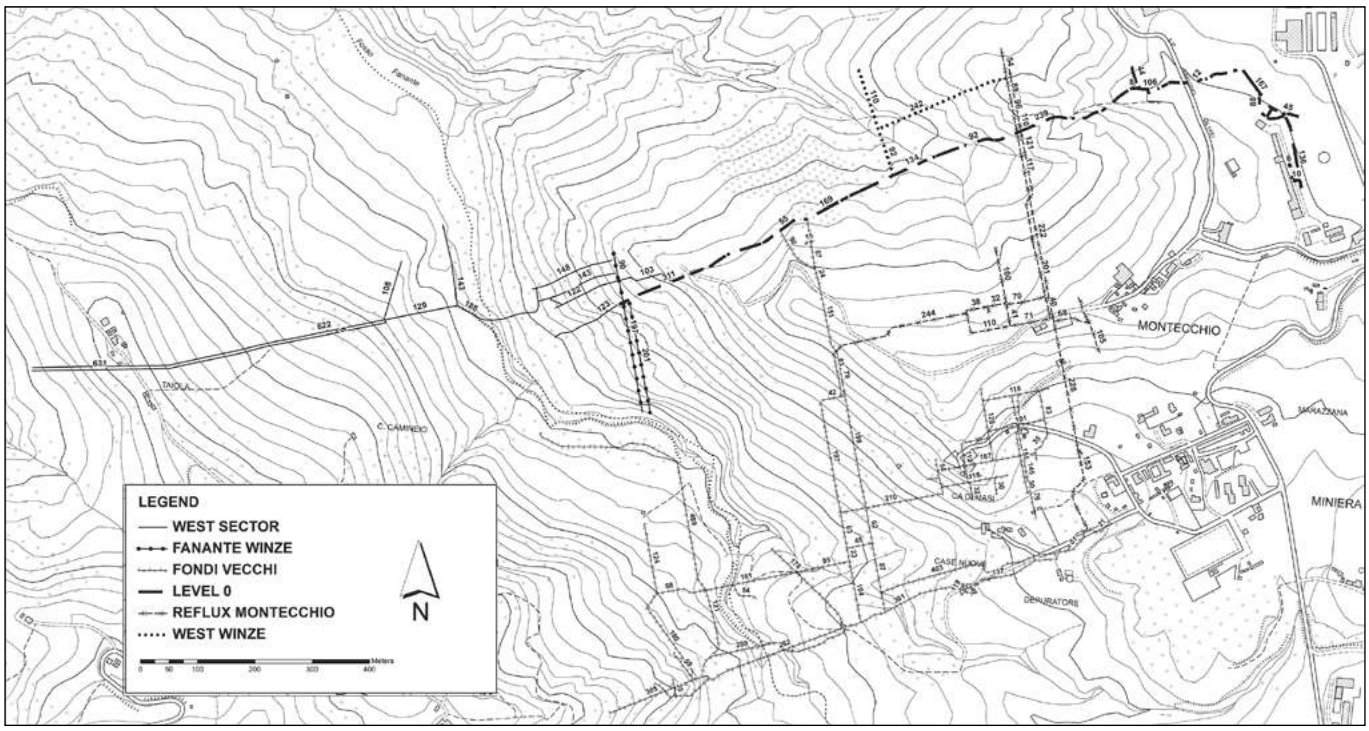

Fig. 3: potentially explorable tunnels.
Fig. 3: gallerie esplorabili.

contains about 38% sulphur.
The Perticara basin tunnels reached as far as 450 hectares. The total development of tunnels is 50 kilometres with seven pits and four winzes (Fig. 1).
The mine was functional for some 2,5 centuries; during this time the total production of raw sulphur was of 1,500,000 metric tonnes (Scicli, 1972).

The re-exploration problems
The tunnel habitat of Perticara mine is characterized by an acute lack of breathable air (in Italian, *Carenza di Aria Respirabile*, from where the acronym ACAR comes). In 1964 the Montecatini society closed all entrances (winzes and air pits). In this way, the force ventilation was interrupted. Also the dewatering stopped and the deep tunnels, below the haulage, were flooded.
The tunnels are mainly in limestone, gypsum and bituminous marl; they present a large lack of oxygen for of a series of reasons: the marls kerogene oxidation; the flooded copious wood oxidation; the sulfates and hydrogen sulphide oxidation-reduction.
The stable situation of contacts between air and water with colloidal sulphur film makes the diffusion of dissolved gases very slow. The speleologists presence disturbs by the simple vibration close the aquifer; it produces a sudden degassing and put into the air circulation poisonous or blasting gases, such as H_2S, SO_x, methane, etc.
The entrance is very dangerous and caution is needed. To walk through the mine with relative security, it is necessary to use breathing apparatus for confined spaces and breathable air lack (ACAR) and gas detectors.
The FSRER bought four breathing apparatus Dräger PSS 3000 (Fig. 2) with steel tanks. They have a capacity of 6 liters, while the use pressure is 300 bar, total air 1,800 liters.
The breathing apparatus are compatible with the full face masks and pressurized nozzle, because the tunnels are overfilled with gases. These gases must not come in contact with the explorers' respiratory system and eyes.
The PSS 3000 is a very sophisticated equipment designed for firemen or emergency in confined spaces and mines (Draegerwerk, 2013). The equipment requires an appropriate training in order to be used; the FSRER speleologists audit a specific course in Bologna.
To integrate the equipment, the FSRER also bought two MSA gas detectors: multigas and Altair-4x Pro single-gas. The Altair-4x tests the presence of hydrogen sulphide (H_2S), carbon monoxide (CO), explosive gases (Comb/EX) and oxygen in the atmosphere (MSA AUER GMBH, 2012). The single-gas detector tests only the oxygen percentage (MSA AUER GMBH, 2006).
The tunnels practicability in breathable air varies in relation to environmental external and internal influence: the air flow inside of the artificial or natural cave is different during summer and winter. In summer, the high entrances suck air and the low entrances exhale air; in winter the air circulation is the opposite. The Montectini Society closed all the entrances, but the mine continues to act in this way. The Fanante Winze opens at namesake river level and acts like a low entrance; during the summer it gives way to an outgoing flow. The air moves from distant places and the quality worsens considerably. Barometer variations equally activate air movements from inside and viceversa.

Fig. 4: Fanante winze.
Fig. 4: discenderia Fanante.

The presence of cavers, who walk in static zones, produces barely quantifiable effects: the very low O_2 percentage air (0 - 1%) pollutes the breathable air.
It is necessary of assiduous control of gas detectors to air tanks save. The tanks (1,800 litres of air) have an endurance of about 30 minutes.
These breathing equipments are capital, because air deprivation is not perceivable, and does not show any symptoms; it is an easy and very dangerous mistake to think that oxygen deprivation can be felt. The O_2 percentages can change quickly in steep tunnels.

The re-exploration
The map in figure 3 shows the tunnels that may be explorable with the available equipments at present. These tunnels have a great historical importance for their function or age.
All the following unreachable tunnels have been removed from the map:
- all overflowing levels;
- the too far away zones.

To re-explore, the speleologists self-adjust with behaviour methods, that try to make safer the ACAR way: a member of the team reads the gas detector and checks the time, whilst another member checks the companion pressure gauge to supervise the air consumption (EIGA, 2009).
The re-exploration activities regarded so far the tunnels: Fanante Winze, Level 0, West Winze, Fondi Vecchi.

Fanante Winze
The Fanante Winze (Dash-dot line in Fig. 3) is today the mine only entrance; the winze is made up of 3 tunnels: the haulage for mineral extraction, the worker gallery and a service tunnel (Fig. 4). The winze connected the 0 Level with the external yard (Montecatini, 1960). When it was explored in April – June 2014, O2 level was around 18%; in August – September the O2 level dropped to 16.5 % very close to the entrance.

Level 0
The Level 0 (Dashed line in Fig. 3) is the mine main haulage and the only explorable tunnel, because the other haulages are overflowing. The level connects several winzes and some pits in the mine. It is a very large horizontal level (Figs. 5 and 9); there are up to three rails and the mechanic's workshop for the electric locomotive. In the way there are few doors to interrupt the air current or the fire front. At the intersection with internal winzes, there are the winches' rooms; the room for the West Winze was named "Giro Cavalli" (Fig. 6; Montecatini, 1960). The explorers walked through the tunnel almost always up to the Giro Cavalli, and found inside breathable air; only in one occasion the O2 levels were lower, at 17%. The Level 0 continues beyond the crossing with the West Winze to Reflux Montecchio and Vittoria Pit. Till now it has covered only 150 meters; the tunnel is rather damaged; there are, collapses easily overcome. The oxygen level

Fig. 5: level 0.
Fig. 5: livello 0.

Fig. 6: the winch room Giro Cavalli.
Fig. 6: Giro Cavalli.

varied between 14% and 4.9% (Table 1).

Log MSA Altair 4x					
Date	Hour	CombEX %	O_2 %	CO %	H_2S ppm
11/5/14	11.36	0	19.7	0	0
11/5/14	11.41	0	***14.0***	0	0
11/5/14	11.44	0	***9.7***	0	0
11/5/14	11,53	0	19.2	0	0
11/5/14	11.55	0	***11.8***	0	0
11/5/14	11.59	0	***4.9***	0	**1**
11/5/14	12.03	0	19.3	0	0

Tab 1: log gas detector beyond Giro Cavalli (italic font the dangerous levels).
Tab 1: log Misuratore di gas oltre il Giro Cavalli (corsivo i livelli pericolosi).

Log MSA Altair 4x					
Date	Hour	CombEX %	O_2 %	CO %	H_2S ppm
26/4/14	11,56	0	19.9	0	0
26/4/14	12.02	0	***16.7***	0	0
26/4/14	12.05	0	***0.1***	0	***9***
26/4/14	12.08	0	***-0.1***	0	***20***
26/4/14	12.11	0	***0***	0	0
26/4/14	12.14	0	19.3	0	0
2/6/14	10.25	0	19.7	0	***1***
2/6/14	10.28	***7***	***9.1***	0	***1***
2/6/14	10.31	***13***	***1.2***	0	***1***
2/6/14	10.34	***13***	***1.4***	0	***1***
2/6/14	10.37	***7***	***7,8***	0	***1***
2/6/14	10.40	0	19.2	0	***1***

Tab. 2: log gas detector West Winze (italic font the dangerous levels).
Tab. 2: log Misuratore di gas Discenderia Ovest corsivo i livelli pericolosi).

West Winze

The West Winze (dot line in Fig. 3) begins in the Giro Cavalli winch room and connects the Level 0 with all the mine deeper levels, now overflowing. It is a very steep tunnel with rails and fills on both sides. In the crossing with Giro Cavalli there is a wall with a door (Fig. 6). This door obstructs the air change, therefore the winze atmosphere is always in ACAR: Oxygen 0%, H2S 20 ppm and CombEx 13% Lower Explosive Limit (IUPAC, 1997; Table 2).
At 200 linear meters the tunnel is overflowing, because it reaches the phreatic aquifer level; the water is black with a colloidal sulphur film (Fig. 7).

Fondi Vecchi

The Fondi Vecchi ("Railway" line in Fig. 3) is a tunnel and yard complex, exploited before arrival of the Montecatini Society (Rinaldi, 1987; Fig. 8). The Fondi Vecchi is connected with a long 400 meter slant, dug in the spoil. A long staircase reached this yard, and in order to improve the general movement of air, it had to be opened.
The slant's first segment (200 meter) had breathable air, whilst afterwards the following 290 meters were in ACAR with a minimum of 3.5% oxygen (Table 3).

Log MSA Altair 4x					
Date	Hour	CombEX %	O_2 %	CO %	H_2S ppm
27/4/14	10.36	0	19.7	0	0
27/4/14	10.48	0	***16.7***	0	0
27/4/14	10.53	0	***4.1***	0	0
27/4/14	10.57	0	***3.5***	0	0
27/4/14	11.05	0	***6.8***	0	0
27/4/14	11.09	0	***14.9***	0	0
27/4/14	11.13	0	19.3	0	0

Tab. 3: log gas detector Fondi Vecchi (italic font the dangerous levels).
Tab. 3: log Misuratore di gas Fondi Vecchi (corsivo i livelli pericolosi).

Fig. 7: west winze, the phreatic aquifer level.
Fig. 7: discenderia Ovest, il livello di falda.

Fig. 8: Fondi Vecchi.
Fig. 8: Fondi Vecchi.

The future re-exploration

From April 25, 2014, to the end of September cavers re-explored 1660 meters of tunnels; out of these, 700 meters were in ACAR.

The re-exploration will continue in the 2014-2015 winter, when the cold weather will create the thermal inversion. The external oxygenated air will enter from the lower Fanante Winze entrance.

The explorative targets include the West Sector – Marazzana visit (Solid line in Fig. 3), the Fondi Vecchi completion, the Reflux Montecchio reaching (Crossed line in Fig. 3), and the reaching of the internal workshop by Vittoria Pit (the dashed line eastern extremity in Fig. 3).

Documentation

During the re-exploration cavers took pictures and recorded videos, to document the mine situation and its main features.

The pictures will be used to renew the mining memories. In this territory the mine was the only productive reality for many centuries. The pictures will be used in the publications about the "Eastern Romagna Gypsum and Sulphur" project.

Cavers are also currently taking samples for the Sulphur Museum to safeguard the memories of mine work, people and technologies. The scientists involved in the project will make use of these samples, too.

The measurement of gas content in the air stimulated the interest to understand extreme environmental conditions. The research activities will continue by sampling winzes waters and by taking continuous air measurement in the West Winze.

The project equally aims to find old maps of the mine, to be displayed in the correct geographic position in the recent cartographies. These plans will be used to produce multimedia materials to Sulphur Museum, born in the 1970s to maintain the Perticara Mine historical memories.

Conclusions

The results of the observation of the gas detectors reveal that the most dangerous problem of the tunnels exploration is the lack of oxygen. The measurement of other three gases is less important: the hydrogen sulphide with 20 ppm causes eyes stinging but without any important damages, that begin with 50 ppm (USEPA, 1980); the 13% of Lower Explosive Limit (LEL) (IUPAC, 1997) of methane is a significant presence, but is quite far from explosion level (100% of LEL coincides to 4.4% of methane in the air); the carbon monoxide (CO) was never present in the air.

The gas detectors are calibrated to signal oxygen levels below 19.5%, a value higher than the hypoxia level. This level was indicated at a variable threshold between 18% and 17% (Draegerwerk, 2010).

The gas detector measures gases and does not offer an entire analysis of the air; therefore tunnels may contain unknown gases and fill the place of oxygen.

It is evident that the Perticara mine is a deadly trap. The FSRER speleologists, that are not tourists,cavers understand that there is still a lot of work to be done in terms of security: it is necessary to improve the security about the breathing apparatus, to improve the communication between the team members, and to improve the self-help procedures as well. One could say that the explorations and re-explorations described in this paper were made without all the possible safety systems.

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Fig. 9: level 0.
Fig. 9: livello 0.

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