KARST AND THERMAL WATER IN AN UNDERGROUND MINE DURING AND AFTER EXPLOITATION

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ABSTRACT

The various evolutionary phases of the hydrology that occurred during the development of the Gavorrano underground pyrite mine, in which surface and thermal waters meet, are analysed. The effects produced underground by these waters during the productive phase are evidenced, describing risk situations as well as advantageous situations, much less frequent than the former, in which the water played a determining role. Lastly, the consequences of mine abandonment and hence of pump stoppage, inferred by considering the situation existing at the surface before the mine was dug, are summarized. Methods and operations to be implemented during flooding so as to avoid damage at the surface are outlined.

INTRODUCTION

Gavorrano pyrite mine, active with varying results since 1898 and now being closed, was dug in a zone of southern Tuscany (Italy) in which hot and cold springs were present. As shallow and deep water inflows were intercepted by the mining, the spring died out.

Without taking into account that if the mine were closed the springs would reappear, a town was gradually built above and around the point where the largest spring was located.

Given the circumstances the reciprocal influence between the mining activity and the land is evident. Initially, it was the particular situation of the land that caused trouble for the mining activity owing to the presence of aquifers that flowed into the mine when intercepted. Now, it could be the cessation of mining to disturb the new balance that the land has reached in the meantime, unless appropriate action is taken.

Although the case outlined here may appear infrequent with regard to the simultaneous flow into the workings of waters of different origin and the problems relating to the mine closure phase, it must be considered a common one with regard to the situations that water in the mine can cause. Most times such situations are risky, especially in cases - anything but rare - in which clay, possibly mixed with rocks of another kind, is present.

GEOLOGICAL SITUATION

The zone where Gavorrano mine is located is uplifted and faulted due to a Plio-Pleistocene granitic intrusion which caused the breakup and raising of the sedimentary formation, composed mainly of Lias and Trias limestones and Neogene sediments (Figure 1).

Along one of these faults, called the Gavorrano fault, pyrite mines have been dug for over a century (Arisi Rota and Kighi, 1972). Gradually connected galleries, these mines now make up a single network which extends horizontally for over 4 km and is about 500m deep. Figure 1 shows the development of the galleries of the whole mine network, dug to extract masses of pyrite mostly contained between Mesozoic limestones at the top and Quartz Monzonite at the bottom. In the north part (Rigoloccio workings) the bed formation and the pyrite itself were often loose, whereas the roof limestone was impregnated with and at times entirely supplanted by clay. In the south part (Ravi and Valmaggiore working) the pyrite was often present between limestones and phyllites. The phyllites were encountered at the bottom of the mineralisation masses when they did not taper off towards the bottom and disappear where bed and roof came into contact (Ministero Zudustria). The high conductivity of the system was due to the fractures and faults in the bed and roof, in the ore and

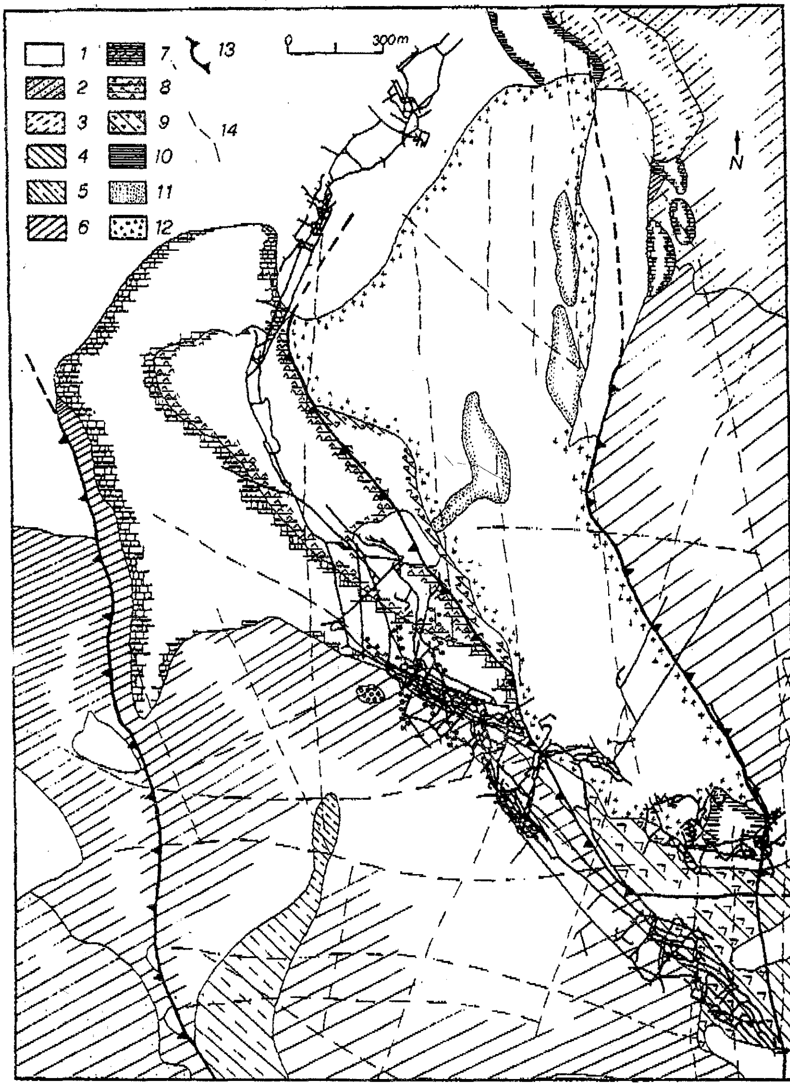

Figure 1. The Gavorrano Underground Pyrite Mine, Tuscany, Italy: Outcrps, faults, fractures and mine network.

1. Alluvium 2. Neo-Autochthnous Sediments 3. Allochthonous Flysh 4. Stratified Flinty Limestones (Lias) 5. Stratified Limestones (Lias) 6. Limestone (Low Lias) 7. Stratified Limestones (Upper Trias) 8. Cavernous Limestone (Upper Trias) 9. Metamorphosed Cavernous Limestone 10. Phillites (Upper Trias) 11. Microgranitic Lode 12. Quartz Monzonite 13. Faults 14. Fractures

in the bottom formation, to the breccias and deep alterations along the contacts, as well as to the extensive karst phenomena in the roof formations.

MINING AND HYDROGEOLOGICAL EVOLUTION

At the start, nearly a century ago, the mineralisations were mined at over 100m above sea level. Later the mines were deepened and extended until in 1981, the year in which the extractive activity ceased, they reached the depth of 240m below sea level and the horizontal extension indicated in Figure 1 through the main gallery network.

Only in an initial period were caving methods used for the exploitation. Owing to damage at the surface to buildings due to mining subsidence. The waste filling, according to the chronological order in which it was used, was composed of: washery wastes; washery wastes mixed with clay grout to avoid high temperatures in the workings and fires due to the oxidation of the pyrite inevitably contained in the washery wastes; limestone rubble mixed with clay grout; cemented waste filling. This last was introduced between 1966 and 1969 in the workings below 73m, 152m and 99m below sea level, respectively in the north, central and south parts of the mine (Corps delle Miniere, 1898-1981).

On the basis of the overall volume of the raw material extracted from the beginning to the end of the activity, the volume of the hollows derived from digging galleries, shafts, audits and ramps and the volume occupied by the waste filling, a theoretical overall volume of 3 620 000 m^3 was obtained for the residual hollows produced during the whole mining period. This activity had deep repercussions on the hydrodynamics of the land, which before the mining was manifested by the hot and cold springs, respectively indicated both black and white circles in Figure 2.

From the start of the mining there were infiltrations of surface water, especially through fractures and karstic paths pre-existing in the roof limestones. With the deepening and extending of the mine, the underground flow of these infiltrations continued to grow, because:

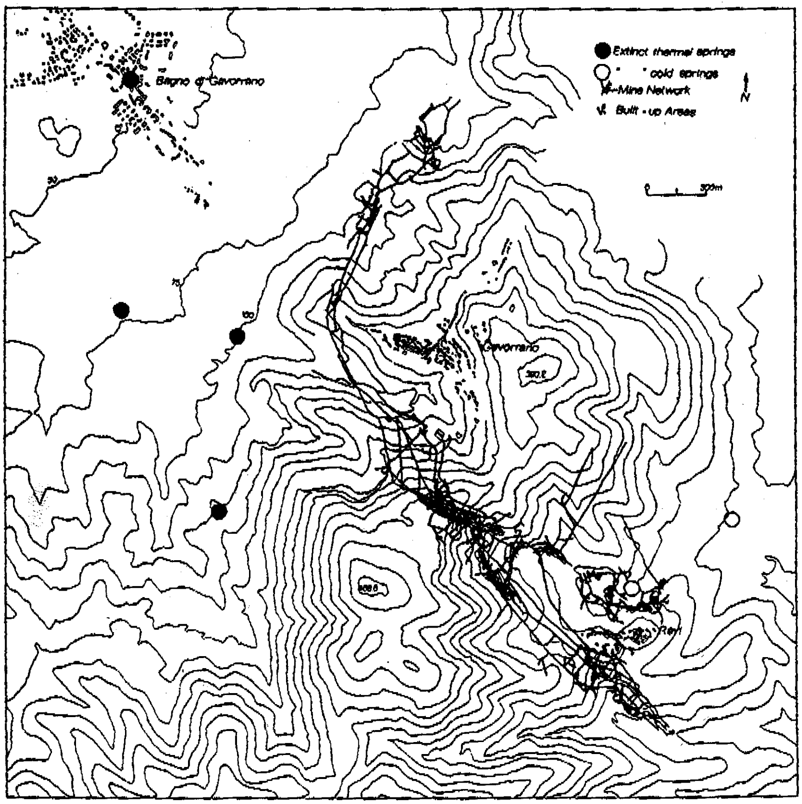

Figure 2. The Gavorrano Mine: Springs and mine network

* as new communications were created, waters of meteoric origin were drawn from larger and larger surfaces and deeper points
* the conductivity around the mine cavity increased due to the fractures induced by the work
* the percolatability above the mine cavity increased because new fractures were created by the mining, and preexisting ones accentuated.

With regard to this last effect, it was found that the percolatability through the formations overlying the central part of the mine (Massa Boccheggiano working), where the extraction was most intensive, was enhanced due both to marked steep falls, resulting from underground landslides, in correspondence to preexisting lines of discontinuity, and to leaching and erosion processes caused by the water drawn from the surface towards the stope. The small black circles in Figure 1 show the zones affected by these steep falls, along which air is also sometimes drawn into the mine and a doline representing a zone through which water is introduced into the mine.

The drawing of the cold waters towards the mine deeply disturbed their initial regimen. As a demonstration of this, it is significant that the underground diggings in the south part caused the disappearance of the two springs (Figure 2) that had fed the village of Ravi ever since the diggings reached the depth of 104m above sea level (Bini and Oti, 1993).

Thermomineral waters of deep origin were intercepted in the central and north part of the mine, mostly during crossings of contacts. When they were not completely collected and pumped out, they reappeared as the workings were gradually deepened, circulating in the waste filling. These water, which in some cases manifested themselves as intermittent inflows, were also encountered at elevations higher than 90m above sea level.

As their underground flow gradually increased, the flow rates of the thermal springs indicated in Figure 2 decreased until they completely died out. Mainly due to the work in the central part of the mine (Massa Boccheggiano), the intermittent thermal springs located south of the present town of Bagno disappeared. While the thermal spring formerly present where the built-up area of Bagne now stands died out as a result of the digging in the north part (Rigoloccio). This spring, whose initial flow rate was 80 l/s, disappeared, reappeared and in 1956 definitely died out; simultaneously, the rate of hot water pumped from the Rigoloccio workings increased, decreased and considerably increased again.

EFFECTS OF THE WATERS IN THE PRODUCTIVE PHASE

In the course of the mining the presence of the water usually caused, according to the circumstances, situations which were more or less serious and rarely advantageous. These situations are outlined below.

Landslides

When the water was encountered while loose terrains were being crossed, they became greatly prone to landslides and crossing then was very difficult. The dynamic of the slides varied depending on the nature of the terrains. In the case of Quartz Monzonite sand, deriving from the weathering of the Quartz Monzonite, the sandy pyrite, both frequent in the north part, the infiltrating water impaired their mechanical characteristics until, in the lack of effective supports, it caused them to give way. The yielding could be more or less violent according to the permeability of the terrain. In the case of clays, also present in these workings, the absorbed and absorbed water caused them to swell, which unlike in the first case was not to be prevented, and at times produced sudden inrushes.

In the period in which clay grout was used to cement the washery wastes and later the limestone rubble of the waste filling, the water that circulated in the filling was substantially the cause of: in cases in which the waste filling had been emplaced recently, removal of the grout and resulting slide of the water filling; in cases in which the waste filling was already consolidated, the clay plasticizing again, overloads on the timberings, already considerably overloaded (Cotza and Piga, 1962) especially due to the considerable thickness of the waste filling above the timberings, such as to cause them to break, and also sections of gallery to cave in.

The roof limestone, clearly karstic, was usually considerably fractured and with clayey intercalations that derived from the clayey filling of its fractures. These characteristics allowed it to break into blocks as soon as, after the exploitation, the support of the underlying waste filling became insufficient, and to follow the waste filling in its settling. In these circumstances the water which, also in the form of dripping, crossed the roof facilitated its breakage and kept it from breaking and becoming detached with a delay, that is, when there was a considerable yielding of the waste filling, thus stressing dynamically and hence with a high destructive capacity the waste filling itself. The landslide that occurred in 1980 in the Valmaggiore workings (Sedone and Sammarco, 1980) fortunately in the absence of personnel, was basically attributable to the absence of water. In that zone a nearly horizontal portion of roof limestone, 1m thick and 1800 m^3 in volume, which had come to be without support in 2m above the top of the underlying waste filling because the filling had settled, detached itself, crushing the waste filling and causing all the galleries below it to cave in. If water had crossed the roof along its fractures, always present even if less frequent than usual, its yielding would have been gradual and not sudden like the one that occurred.

Rock Detachments

In rock detachments, which together with the landslides produced over a third of the fatal accidents during the whole period of activity, the following factors played a decisive role: presence of fractures and stratifications and their orientation with respect to the working face; geometry of the fractures and material present in them; supply of water. The fractures in the rock could be preexisting and/or generated by the workings themselves, which also caused slackenings in the correspondence to joints of stratifications and some preexisting fractures. The detachments were very likely when fractures with interposed clay were encountered which diverge from the rock mass towards the edge of the gallery and into which water penetrated, although in such small amounts as not to manifest itself in the gallery. In this case two factors favourable to detachment cropped up:

* the wet clay tended to swell and to expel towards the gallery the wedges determined by the fracture

* the clay came to have less resistance and in particular less cohesion and hence less capacity to retain the wedges (Sammarco, 1993).

Formation of Mists

In a single sector of the mine a zone characterised by dripping of cold water and a short distance away another zone with dripping of hot water could be met, so that the air currents that passed by these zones ended up both being saturated with steam but at considerably different temperatures. In the cases in which such currents met, mist formation was registered in the zone of confluence. In reality the deepest part of the mine network was crossed by currents of ventilation air that displayed decidedly different thermohygrometric characteristics from each other, so that mists formed in points of confluence and along galleries which were colder and more humid than others. These mists appeared stationary until ventilation was modified. The mists formed accidentally following the rupture of compressed air tubes were particularly insidious because they were unexpected. Due to adiabatic expansion, in these cases there was a lowering of the temperature of the outgoing air. This air in turn cooled the ventilation air, which was usually at high temperature and humidity, causing condensation of part of the vapour contained in the ventilation current.

Fires

When washery wastes were used for the waste filling, oxidations of the pyrite still present in those wastes sometimes occurred so rapidly as to degenerate into fires. In these circumstances the water, if present, besides having an extinguishing function, took on that of blocking parasite air currents feeding the fire. When the washery waste was cemented by clay the stoppages occurred mainly due to swelling of the clay.

Dustiness

When there was circulation or stagnation of water in the rock to be extracted, dustiness was substantially excluded on priority. In the case of water inflows into the workings the dust concentration in the ventilation air was lower and the more widespread the inflows were the greater the overall flow rate of water was. In particular thermohygrometric conditions, however, the dust caused mist formation.

CONSEQUENCES OF MINE FLOODING

At present the mine is kept completely dry by continuously pumping out all the inflowing water. If the mine was abandoned by stopping the pumping and without intervening in any way, the underground water level would rise and the springs that disappeared at the surface would reappear. In reality:

* a considerable increase in transmissivity in the system that regulates the local hydrodynamics was introduced due to the mining, as it produced a total volume of cavities of $3x10^6m^3$
* the hydrostatic pressure could considerably increase on the aquifers with a lower initial pressure, flooding the mine, because the different aquifers encountered would be made communicating (Borazzuoli et al, 1991)
* notable reductions in conductivity along the paths that fed the extinct springs will undoubtedly have occurred because of the extinction of the relative watercourses (Sammarco, Sept 1990).

Therefore, once pumping is stopped, water could reappear with different flow rates and in different points from those of disappeared springs. Of the listed factors, the first two should cause increases of the flow rates of the springs with respect to the initial values, the third should cause reductions. In any case it is hard to predict the events exactly. It is certain, however, that during or after the flooding of the mine, the water will reappear at the surface. This confirmed by the resumption of an intermittent spring which appeared in the mine during the digging, disappeared as the mine was being deepened, and reappeared when, in 1994, as the wartime front passed through, the mine was deliberately flooded.

In the light of this certainty and taking into account that a town has sprung around the northernmost of the disappeared springs, it was necessary to plan interventions, most of which have already been carried out, that guarantee a disciplined flooding and in particular the possibility to raise, stop or lower the water level in the mine according to necessity so as to clearly identify the effects of the flooding and

* either limit, with appropriate pumping, piezometric levels

* or set up suitable works or interventions capable of safeguarding structures and all zones to be protected (Sammarco, May 1993).

CONCLUSIONS

During the mining activity the risks due to the presence of water were attenuated by keeping, where possible, the water tables sufficiently far below the workings. This was achieved by digging a gallery, at a level below all the workings to be protected, before activity was begun in them, and making drainholes from it to gather the inflowing water from above and allow the workings to dry. If the aquifer fractures had a larger horizontal extension than the one encountered, and that is if they were such as to allow intercepting their downward continuation, the same results could have been obtained by lowering submersible pumps into vertical boreholes from the workings.

Analogously, to avoid damage at the surface during the abandonment of the mine, it will be necessary to regulate the flooding by a submersible pump plant installed in the mine where the intercepted water inflows converge, controlling the rise of the water both in the mine cavity and in holes drilled at the surface upstream from the structures to be protected. Since the water paths that might be activated after the flooding cannot be known ahead of time, it was not possible to lower submersible pumps into them from the outside to keep the water tables sufficiently low with regard to the mentioned structures.

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