The post-closure mine hydrogeological problems of Gavorrano (Italy)

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ABSTRACT

The paper describes the hydrogeological problems linked to the rehabilitation and re-utilisation of the water resources of the mining area of Gavorrano (Tuscan, Italy). The results of the studies and the recent situations concerning circulation, quality and discharge of the mine water are reported, with particular reference to the effects of the controlled water rebound and the complex measures necessary for the dewatering stoppage. Different uses and possible actions are proposed, taking into account thermal, chemical and discharge characteristics as well as local planning objectives. The Gavorrano mine was one of the largest pyrite mines in Europe throughout the last century. The company is trying to give up its mining concession by adopting the safety measures required by the Bureau of Mines for the decommissioning. A major aspect of the rehabilitation involves the evaluation of the underground openings. In particular, the present study described the results of a new geognostic campaign and the setting up of monitoring system of the water level and water chemistry changes, both during and after an important phase of mining operations.

Introduction

Over the last few decades mining activity has decreased progressively in Italy as in other countries. The decommissioning of a mine triggers off a series of problems regarding social safety, health and the economy. So the closure of a mine is regarded as an environmental threat and an economic problem. Mine water drainage is a problem during mining but also after mining activities has completely ceased. Water level recovery after exploitation causes different problems for the stability of underground openings, but in particular for the environment and the reconstitution of groundwater resources. Acid mine drainage is one of the most common consequences associated with mining operations and with the oxidation of sulphide minerals (e.g. pyrite) during exposure to air and water (Banks et al. 1996; Bell and Bullock, 1996; Crosta and Garzonio, 1998). This exposure can occur both in a mine or in spoil or mineral stockpiles. If no acid drainage is produced, the presence of toxic elements, metal or salts could exclude the uncontrolled discharge of these waters and their use for different purposes. At the same time, the recovery and re-utilisation of mine drainage waters show some very interesting aspects, especially where increased water resources are required because of increasing demand. The Gavorrano mine was one of the largest pyrite mines in Europe throughout the last century. Production ceased in 1981 and since then the mine has been under maintenance. The company is trying to give up its mining concession by adopting the safety measures required by the Bureau of Mines for the decommissioning. In particular the dewatering operations are described, and the recent effects of the water level rebound and the evaluation of the groundwater volume storable within the mine in safe conditions. The water drainage problem was analyzed starting from the hydrogeological scheme of the area, through historical data concerning both water springs and water level recovery, and moving on to hydrochemical data.

Fig 1: Valsecchi shaft

Geological and Hydrogeological outlines

Gavorrano is located in south-western Tuscany, in the Metalliferous Hills (Colline Metallifere), 150 kilometres south of Florence and a few kilometres from the sea. The area is characterized by rapid topographic changes passing from a very flat plain (Follonica gulf, Pecora river valley) up to rocky hills with a maximum elevation of

about 500 m.a.s.l. (Mt. Calvo). The area is characterized by NNW-SSE elongated post-orogenic basins developed over an antecedent extensional horst and Graben structure consequent to the Tyrrhenian sea opening. Intrusive bodies, with decreasing age from west (7-8 My) to east (4 My), are typical of this tectonic province, and their emplacement was followed by their greater extension. The activity of the province is attested by important geothermal fields (Larderello, Amiata) located within a major mining district (Campiglia, Elba island, Amiata). The hydrogeological system in the Gavorrano area is complicated by the presence of three sub-systems: a superficial alluvial system, a karstic system and a deep hydrothermal system.
The first system consisted of a small multifalda aquifer in the area around the sub-inclined plane of the alluvial and debris plane of the large village of Bagno di Gavorrano. Waters from the last two systems have been forcefully mixed by the mining activity. In fact, 500 m of production levels were excavated in over a century of mining. The pre-existing groundwater circulation, with springs placed at a maximum height of 180 m a.s.l., was depressed up to -250 m b.s.l., when old thermal springs (Bagno di Gavorrano, Terre Rosse) were drained through the underground drifts system. The permeability classes were attributed by considering: the lithology, the degree of fracturing, the degree of weathering and alteration, the presence of karstic structures, as observable both at the surface and within mine drifts.

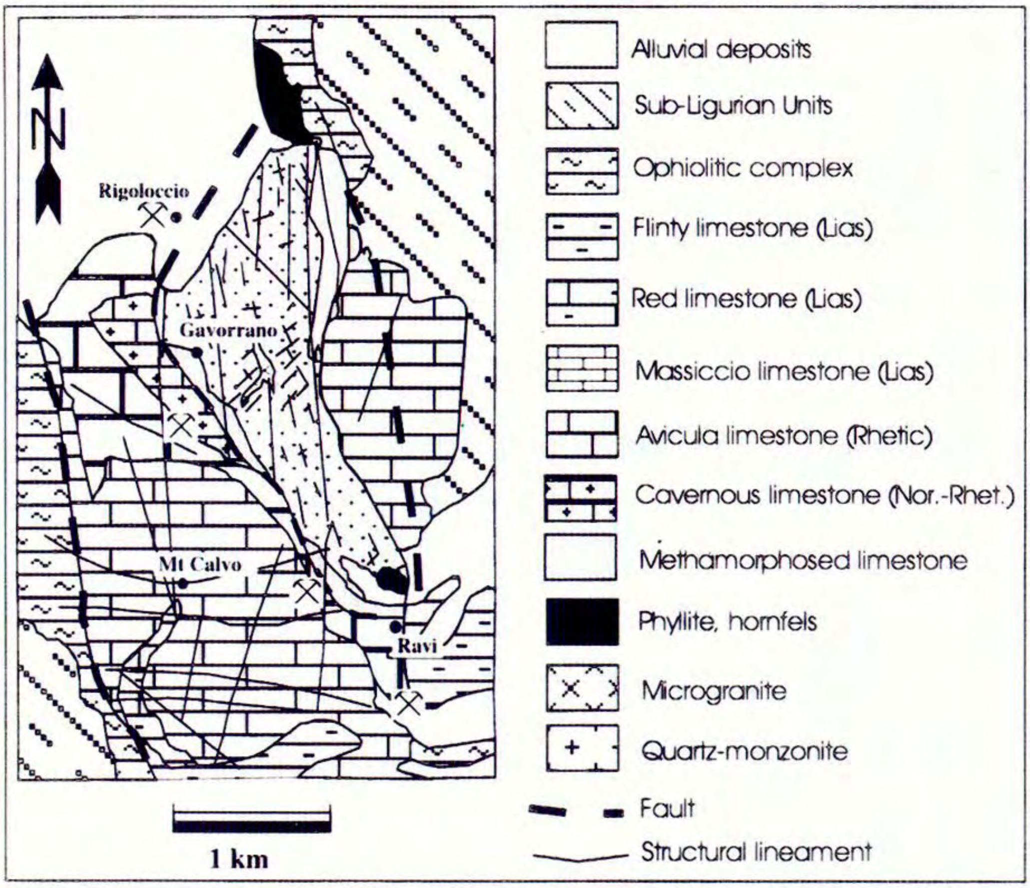

Fig 2: Geological map

Karstic features and degree of fracturing were determining factors in distinguishing carbonate rocks. A groundwater balance was performed by attributing different coefficients of potential infiltration to the different lithotypes and by computing the contributing areas for each lithotype. In particular, the potential infiltration coefficient for the carbonate rocks was estimated within the range of 8.7 to 10.1 km²/s, as a function of the increase in fracturing and karst conduits. However it must be stressed that rock mass properties, in particular hydraulic conductivity, have been strongly and permanently influenced by mining and subsequent induced processes (e.g.: tunnel presence, the increase in the fracturing degree and the enlargement of existing fractures by acid water circulation and water level lowering which increased karst solution in places). In fact, tunnels and drifts form a drainage network characterised both by voids and refilled spaces.

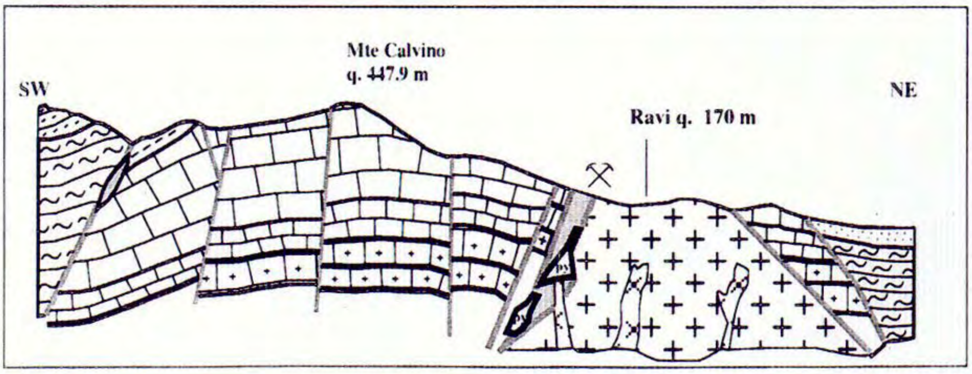

Fig 3: Geological section

Geomorphological outlines

The three basic elements that characterized the geomorphological set-up of the area are: karstification, subsidence and mining activity. In the summit area of Calvo mount we can see Karrens and Dolines. The last ones are bowl shaped with a diameter of 20-30 m.

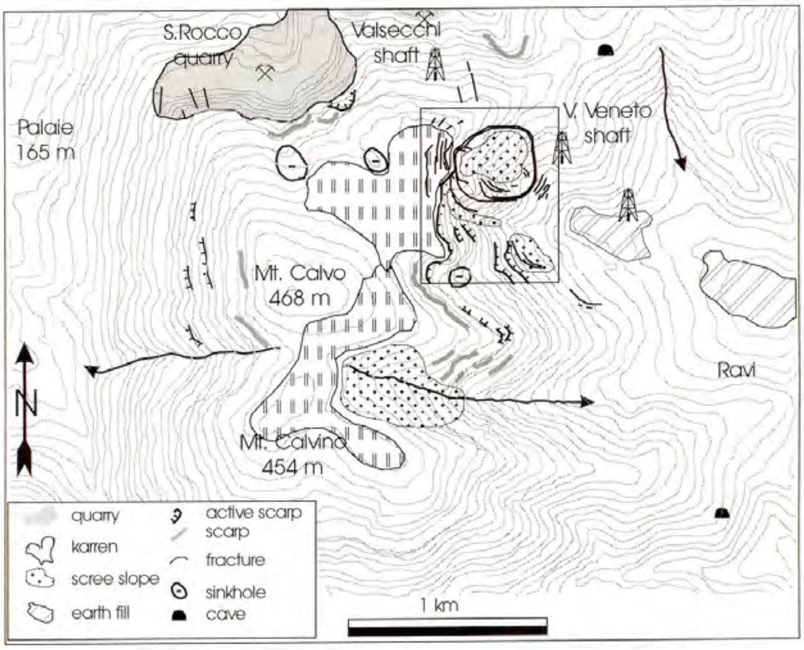

Fig 4: Geomorphological map

Subsidence contributes more to morphology, especially in the east side of the Calvo mount characterized by a wide circular area reduced by the presence of several sub-vertical slopes where we can see, at the base, collapse phenomena. When limestones are not covered by detritic blankets we can find fissures and fractures.

Water discharge

Groundwater level recovery is typical of the closure of mines. It is a common process that can give important information for understanding the effects, starting from the data recorded during the water level lowering and some occasional or accidental water risings. The control of groundwater rebound, in progress at the Gavorrano mine since August 1995, is regulated by a submersible pumping systems. These systems consist of two pumping points immerged in the Rigoloccio Shaft and the Roma shaft respectively. They are adopted to avoid too fast a rising in the groundwater level, which could induce turbulent flow and internal erosion of the back-filling; excessive hydraulic gradients and groundwater re-emergence at the surface within inhabited areas (Bagno di Gavorrano).

Furthermore, the controlling of the rebound allows us to evaluate the volume of water storable within the mine voids system, as well as the changes in the chemical composition of drainage waters. The passage of the Second World War front between 1944 and 1945 caused a forced water level rising and, together with data collected since 1995, these are the only ones available for the mine. Data for the 1944-45 forced rising are available for the main mining centers of that time (Rigoloccio, Boccheggiano-Gavorrano and Valmaggiore from N to S).

Fig 5: Water in the mine (-110m b.s.l.)

These data suggest a power law trend for the groundwater level rise with decreasing rate and with the general form:

$$\Delta H = -(Ht+Ho)*exp(-a * \Delta t) +(Ht+Ho) \quad (1)$$

where Ht and Ho are the initial and final groundwater level elevations, and Δt is the elapsed time. In fact, the rising rates at Boccheggiano-Gavorrano and Valmaggiore are quite similar while at the Rigoloccio the rate was lower (Crosta & Garzonio, 2000). The recent records were compared with the old ones by putting each of the 10 rising steps (from -197 m b.s.l. to -143 m b.s.l.) in sequence, without considering the steady level intervals. It must be stressed that the mines were separated from each other during the 1944-1945 period, and have only been linked since 1969. Since 1995 the pump discharge has remained almost constant at 65 l/sec, with the exception of three periods of heavy rainfall with discharge until 110 l/sec. This allowed the storage of about 300*103 m3 of water, excluding the initial uncontrolled water level rising between -236 m b.s.l. and -197 m b.s.l. Using the data recorded during the two phases (1997, 1998) of increased discharge, it was possible to perform a recession analysis which gives us a good insight into the aquifer structure. Starting from these data and the recession analysis, confirmation of the previous results concerning the groundwater balance was obtained. In fact, according to the recession analysis, the average water resources that are renewed yearly amount to 2.2 M cubic meters or 66 l/sec. These values are quite comparable with the average yearly pump discharge (65 l/sec or 2.08 M cubic meters). Finally, by comparing these data with the ones obtained by the effective infiltration analysis (1.1 Mm3) it emerges that almost 1 Mm3 of hot water flows regularly from the deep circulation system into the mine every year. 50.

The second important operation started in May 2005. The two submersible pumping systems were stopped for the second time (Rigoloccio and Roma shaft) to overflowing the mine until -110m b.s.l. (only for 30m). The water level rising is being realized in three steps of 10m. Before the first step of 10 metres, from -140 m b.s.l. to -130m b.s.l., the water discharge was 73,4 l/sec. After 12 days (May 2005 14th) of dewatering stoppage the water level arrived at -130m. After 4 days the water discharge was at 65 l/sec. We had calculated the water volume in this first interval like 7000 cubic meters. Considering the fact that the meteoric waters in the last years were approximately the same quantity, we can suppose the aquifer system is wider than before, because the water has found new ways in the fractured rockmass. At this point we waited 1 month to re-begin the second step. The stop started in June 2005 the 13th and it finished in June 2005 the 21st . Now the water elevation is at -120m b.s.l. and we are waiting for the third step. After these three periods of the water level risung, a new research program will be carried on to analyse new sample and to compare these with previous ones. By the analysis (stratigraphy, water level, etc..) of the 4 control wells, we suppose there was an important water flow at the contact between superficial layer (clay, sand and palustrine debris) and the cavernous limestone layer. It is due to the presence of high permeable zone constituted of limestone with many voids derived by the erosion of the thermal waters with the same composition of the mine waters. These results make possible to developed numerical simulations of the water flow to establish the water circuit and to plan the control of water rebound and/or pumped discharge.

Geognostic campaign

With the aim of the survey in particular of the inhabited area of Bagno di Gavorrano, a new geognostic campaign to monitoring water levels during the controlled flooding of the mine has been carried out. Five boreholes, named PZ1, PZ2, PZ3, PZ4 and PZ5 (at present not finished) in fig 8, have been drilled in the site in order to control aquifer, chemistry and temperature data. These results have been compared with the old ones (Filippi, 1988). The new boreholes have pointed out a new and interesting stratigraphy of the site and the exact location, the characteristics of the cavernous limestone. In this unit there is the deep thermal circuit and it is linked to the the mine reservoir. In all wells will putting automatic equipment to provide, with temperature and water level data, pH and electric conductivity values.

PZ1

The first borehole localized in the “S. Francesco farm” is 200 meters deep and 2,5” inches large, is named PZ1. Inside it was situated an automatic surveyor that control water level, temperature and pH via PC. Geophysical data are obtain by seismic down-hole campaign made after few days (fig.6-7).

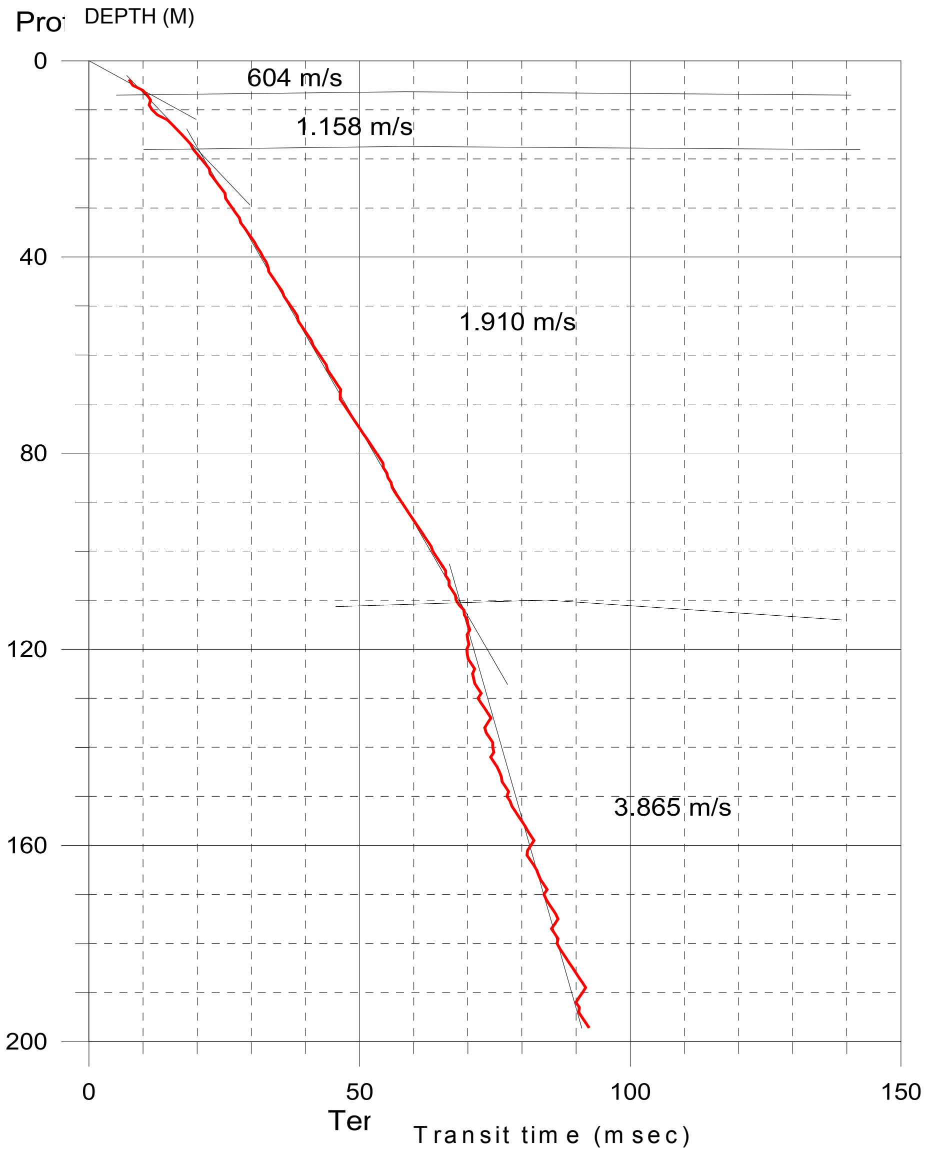

Fig 6: Transit Time diagram and velocities for the PZ1

We are obtained a stratigraphic column consisting of “Renone debris”, for the first 82.5 m from the surface and then “Cavernous limestone” until the end of the borehole (200 m from the surface). The elevation of well is 61.2 meters a.s.l. so it reaches -140 meters under sea level: the same elevation of the water level in the mine before the present phase of overflowing.

PZ2

The second borehole is in the “S. Giuliano farm”, 500 m from *Bagno di Gavorrano* village. The depth and the diameter are the same of the first one, but not its elevation. It reaches -150 m below sea level. The stratigraphic column is almost the same. The first drilled component from the surface is always the “Renone debris”, but towards the limestone contact, this sediment become always much fine until “clayey-slimy”. Around this borehole geophysical analysis have been carried out to survey to verify the stratigraphic and to draw a geological and structural section.

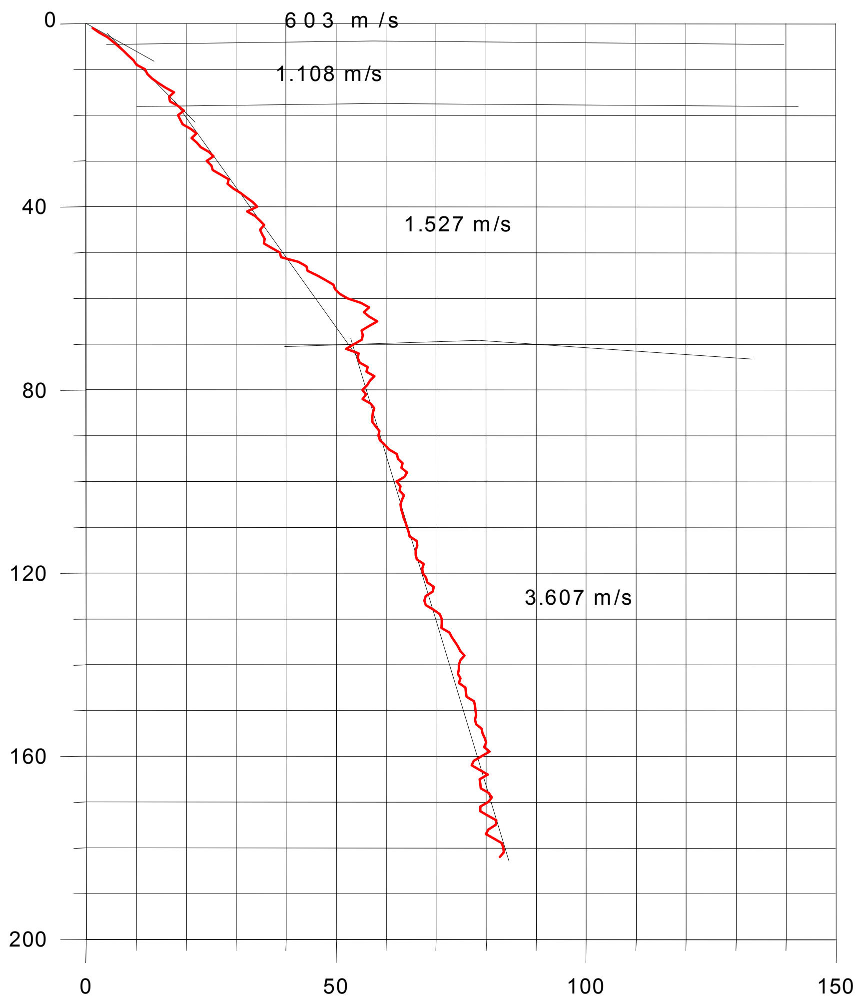

Fig 7: Transit Time diagram and Velocities for the PZ2

PZ3- PZ4

The third one is similar to the others. Its elevation is 50.9 m a.s.l. and "Renone Debris" is present until 55 meters under surface level, so "Cavernous limestone" arrives to the end of the borehole (200 m). The difference with the other ones is the presence of thermal waters (a small circuit) The fourth borehole was almost in the centre of the village and "Cavernous" limestone is situated at 37.5 meters under ground level. The elevation of this point is 42.8m a.s.l.. At the end and in centre of the borehole we have highlighted clayey and clayey-sandy layers. This stratigraphic anomaly has pointed out the presence of an important fault system, and It defines the possible geometries of the groundwater flows and the conseguent hazard effects due to water rising under the Bagno Village.
Through the five boreholes we can check water level when the two pumping systems (Rigoloccio and Roma shafts) in the mine stop. Unfortunately, the new monitoring points (PZn) haven't checked significant water level variations linked to the mine waters. It is due to the fact that the mine water level is to depth, and the water in the boreholes is fed by local flows (or by small infiltration from regional thermal waters). Now, as two dewatering systems are often interrupted, the water level is rising (for the moment to the elevation of -110m b.s.l.), and the water level and temperature measuring in the borehole could put in evidence if this waters are the same of mine waters, the presence of water flows connection, the relationship between different waters (thermal and fresh waters).

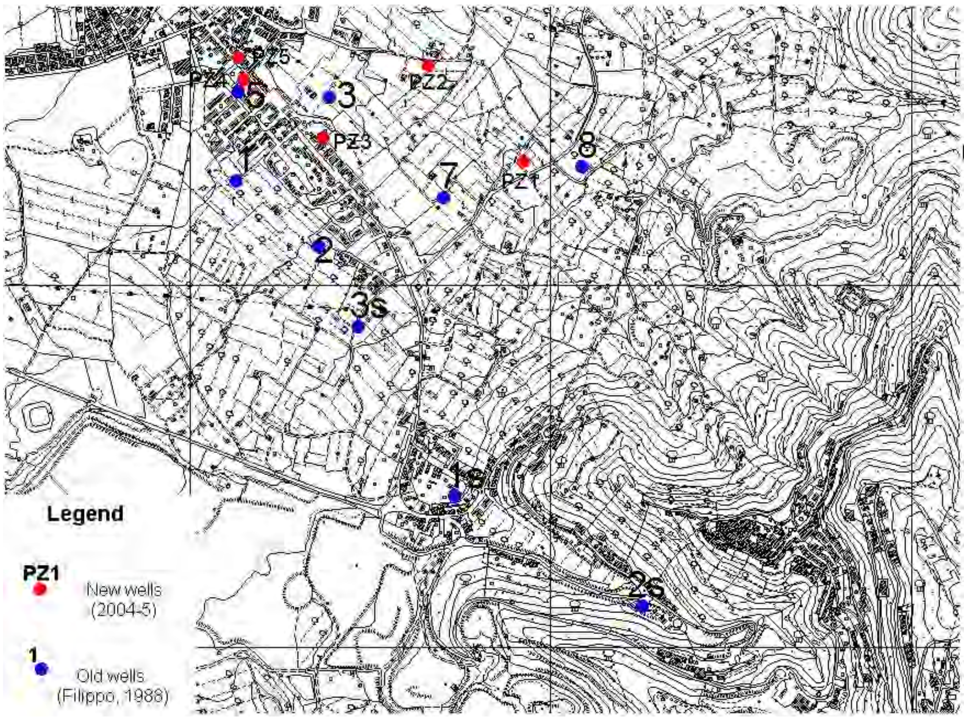

Fig 8: Localization map of the old and new boreholes

Water chemical changes

A series of samplings was performed over the last nine years to complete the data set already available. The sampling points located at the ground surface (wells and springs) and within the mine together with the ore body limits (Boccheggiano ore body) and the carbonate/intrusive rock contact. Data from superficial sampling points are given mainly for a general water classification and for a comparison between superficial thermal springs (Bagno di Gavorrano) and deep hot waters. More attention is actually given to the 30 samples taken from the mine because of their importance for our understanding of the main aquifer hydro-dynamics, the hydro-chemical composition of waters and their possible changes with the proceeding of water rising and the consequent mixing. The data must be read with care when referring to the +70 m elevation (a.s.l.) samples, because these values refer to the mine drainage waters sampled at the exit of the drainage tunnel (almost 1.5 km long and excavated in flyschoid rocks).

At a regional scale it has been observed that sulphate waters commonly spring from the Cavernous limestone and from intrusive rocks. Calcium bicarbonate waters are mainly associated with carbonate formations and small depths and are considered the less mature water class. Seawater influence is absent, with the exception of very few points where wells probably intercepted small remnants of old entrapped seawater. Sea water intrusion is becoming problematic to the north of the area (Avio *et al*., 1995).

Mine water samples can be clearly differentiated in two main groups: "superficial" bicarbonate waters (from levels +240 m a.s.l., + 155m: Mg-Ca, +90 m: Ca-Mg-HCO3) and deep sulphate waters (Ca-Mg-SO4, -80 m b.s.l., - 110 m, -140 m, -200 m). This grouping can be done on the basis of the sulphate (from sulphide oxidation and evaporites solution), iron and silica contents and it is also suggested by the few temperature data even if more qualitative observations have been made. In fact, by fitting temperature measurements, excluding samples taken at the outlet of the drainage tunnel (1.5 km long), a geothermal gradient of about 75°C km^{-1} has been determined. This geothermal gradient is in agreement with the data published by Baldi *et al*. (1995) concerning southern Tuscany and indicating, for the marginal areas of the geothermal fields (Larderello, Amiata, Travele, Radicofani), a gradient no lower than 70°C km^{-1}.

A water type sub-group, with peculiar characteristics, is composed by four samples (13 to 16) all collected within the intrusion in a relatively localised area, and characterised by very low pH values and high TDS contents. The area was characterised by a conspicuous air flow and abundant water presence, with clear and cold waters. The pH values strongly characterise this minor group. All the other sampled waters generally presented values just a little over neutral (7-8). Mine drainage is characterized by an average temperature of 32°C, a 7 to 8 pH value, and it can be classified as a Ca-Mg-SO4 or a Ca-Mg-SO4-HCO3 water, probably as a result of temporal changes and the mixing action caused by pumping. In comparison, the water of the old spring at Bagno di Gavorrano was characterised by a constantly higher Na and Cl content, with a minor SO4 content. Recently and during the increasing of the discharge, in particular in Rigoloccio Shaft 3, we can observe higher temperature values and lower pH ones (6,3-6,6).

CONCLUSIONS

The case history of Gavorrano is associated with water recovery after the termination of pumping operations and the consequent mine water management, which would be characterized by re-using different resources. The study described includes all these aspects and highlights the great importance of continuously monitoring the water level and water chemistry changes, both during and after the completion of mining operations. It stresses the importance to realize new well points with authomatic monitoring of the water levels, to perform new geophysical tests when the water rebounds and new chemical and isothopic analyses, pumping separately and contemporaneously in the different systems. The importance of this monitoring is illustrated, for example, by the rising rates observed at different mining sites (Valmaggiore, Gavorrano, Rigoloccio) during the forced Word War II pumping arrest. The pH of the Gavorrano mine waters is almost neutral. This may be due to the content of alkaline minerals within the carbonate rocks mass, both in the upper mine levels and the tectonically lowered rock mass near the main faults of the area (thermal water flowing up at the Rigoloccio mine). The neutralisation of the naturally acid waters, which derive from iron sulphide oxidation, because of their contact with air and water after tunnel excavation, could also be the result of the material used to back-filling excavations (limestone blocks together with clay and cement). The chemical monitoring has pointed out a small trend of lowering of the pH values (6,4). The TDS content is high, but the quantities of polluting elements are very low.

The groundwater balance and the discharge rates pumped confirms the volume which could be stored, and the important presence of a thermal deep circulation coming from far away. New isotope analysis (^{2}H and ^{18}O) seem to indicate the same residence time of previous ones (Garzonio, 2000). In conclusion the new analyses and the new monitoring system have highlighted that in the present phase of the water rebound the proposals of different re-utilization project of the waters are realizable as well as the necessity of setting up of a more efficient networks and collecting new monitoring data (necessary to elaborate conceptual and numerical model of the water flows), before further change in elevation of the recovering water table.

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