Guide Book

September 21st - Carrara Marble quarries

September 22nd - Etruscan and last century mines

Prof. Geol. Massimo Coli and Prof. Geol. Carlo Alberto Garzonio

Firenze, Italy, 2009 September
- PRESENTATION

The 1st Annual ISRM Technical and Cultural Field Trip, September 2009 Florence - Italy, is devoted to the Carrara Marble quarries and the historical quarrying and mining activities which have taken place in Tuscany since Etruscan times (about 700 B.C.).

The excursion starts from Florence.

- September 21st
  Carrara Marble quarries, the quarries from which Michelangelo took the marble for his masterpieces; the visit concerns both a large open pit and underground quarries.

In the evening, a technical around-the-table-talk is planned.

Overnight will be spent in Versilia, close northward of Viareggio.

- September 22nd
  The XXth century disused mine of Gavorrano, and the Etruscan and medieval mine of the San Silvestro site of the Metalliferous Hills National Park, northeastward of Piombino.

Back in Florence for dinner.

Organisation is by the University of Florence through: Prof. Geol. Massimo Coli, Dept. Earth Sciences, and Prof. Geol. Carlo Alberto Garzonio, Dept. of Restoration and Conservation of Architectural Heritage.
- GEOLOGY OF THE NORTHERN APENNINES

In order to allow participants to the Field-Trip to better follow the geological concerns of the two areas visited during the excursion a short summary of the geology of the Northern Apennines is here outlined.

The Northern Apennines is a NE verging chain built-up by ocean-derived tectonic units (Ligurian Units), over-thrust onto the Adria passive margin foreland, whose deformed units constitute the Tuscan and Umbrian-Marchean units. These latter consist of a thick Triassic basal evaporite layer, overlying by ~2km-thick Mesozoic carbonate succession and a 2-3km-thick Upper Oligocene-Miocene siliciclastic foredeep sandstones.

The Northern Apennines orogenesis presents two main stages: a Late Cretaceous-Early Eocene oceanic subduction phase during which the Ligurian Units were off-scraped, tectonically stacked and accreted, and a Late Eocene to Early (-Middle?) Miocene stage of E-NE verging collision between the Corsica-Sardinia block and Adria Plate involving crustal thrusting with development of crustal-scale shear zones, that gave rise to the metamorphism and polyphased folding of the inner Tuscan Units (Apuan Alps and Southern Tuscany metamorphic units) (Boccaletti et al., 1971; Doglioni et al., 1998; Marroni et al., 2002; Molli & Tribuzio, 2004). During this continental tectonic stage, the Tuscan and Umbrian-Marchean Units were progressively tectonically overlain by the Ligurian Units. Satellite basins developed on top of the advancing Ligurian Units, and were filled by thick sequences of coarse sediments referred to as Epi-Ligurian Succession (Epi-Ligurian sequence; Ricci Lucchi, 1986). The collisional processes gave also rise to an eastward migrating frontal foredeep basin that was progressively involved in the thrusting and accreted to the chain (Ricci Lucchi, 1986).

Subsequent, crustal extension affected the internal chain since Middle-Late Miocene, generating the Tyrrenian Basin and dissecting the pre-existing nappe pile (Boccaletti et al., 1985; Sartori, 1990). It resulted into a series of inner sedimentary basin (Martini & Sagri, 1993) filled by paralic and clastic continental deposits. This process also promoted crustal melting and the emplacement of several subalkaline magmatic bodies and volcanic rocks of the Tuscan Magmatic Province (Coli et al., 1991; Serri et al., 1993, 2001) and correlated ore deposits.

Schematic cross section of the Northern Apennines in Northern Tuscany, from the Apuan Alps to the Ferrara fold-belt buried below the Po Plain (modified from Bonini et al., 2008).
Geological sketch map and general cross-section of the Northern Apennines, outlined the areas interested by the field trip (modified from Boccaletti et. al., 1991)
Schematic cross section of the Northern Apennines in Southern Tuscany, from the Larderello geothermal field to the Adriatic fold-belt buried below the Adriatic Sea (modified from Cerina Ferroni et al., 2004).

Neogene sedimentary basins of the Northern Apennines. Key: 1) main thrust front; 2) master-faults; 3) main transverse lineaments (transfer-faults?); 4) passive margin (modified from Bartolini et al., 1983); outlined the areas interested by the field trip.
CARRARA MARBLE QUARRIES

1. - INTRODUCTION

The excavation of the world famous Carrara Marble (Tuscany, Italy) (Fig.1) began with the Romans. The quarrying activity was directly supervised and planned by the Emperor’s staff under the supervision of a “Praefector marmorii” and employed 30,000 slaves to work in the Luni quarries (Luni being the ancient Roman town marketing the Marble before the settlement of Carrara) (Dolci, 1980; Coli, 1991).

The marble exploitation decreased in the Middle Age, but then increased again during the Renaissance. The exploitation gradually, but slowly, increased up to the end of XX century when both the technology and the increment of international assets brought to the necessity to evaluate the marble amount and to organize the exploitation itself.

![Figure 1 – The Carrara Marble mining area in the frame of Tuscany and Italy.](image)

Since the Roman time the Carrara Marble excavation activity has increased from about 12kt/y up to 1.5Mt/y today (these estimates refer to the commercial blocks, which are on average only 30% of the actual quarried material, the remainder being discumbled and constitutes the typical large debris covering about 60% of the Carrara Marble outcrops (Fig.2 - Coli, 1991; Coli & Grandini, 1994).

In that time span there were only three instances of Marble exploitation planning: in Roman times when the Marble quarries were under the direct administration of the Emperor. In the XVIII Century with the edit of Maria Teresa d’Este Duke of Modena. In the XX Century with the mine-law (R.D. 1443/1927) of the Italian state received by the Carrara Municipality only in 1994 by means of an accompanying regulation, revised in 2001.
In the Carrara Marble District more than 730 quarries were opened in the course of time, but currently only about 160 quarries are active, 81 of which in the Carrara district. Despite this drop in the number of active quarries, the production of raw blocks has been increasing to about 1.5 Mt/y; this trend implies fewer but much larger and industrialised quarries (Fig. 3).

Figure 2 – Carrara Marble district: quarry debris (dashed areas); Marble outcrops (light blue); no marble (pinkly) (from Coli et al., 2000a).
In the last twenty years environmental concerns and mining optimisation induced many quarries to move underground in order to lower the environment impact and increase dimensional stone percentage production. At the beginning many of these underground quarries, due both to cultural heritage and the lack of specific laws, were worked without any geomechanical study, any design, or any bolts or reinforcements, guided only by the instinct and experience of the quarrymen.

Present day intense Carrara Marble exploitation, which includes the widening of the underground quarries, up to very large sized caverns (Fig.4), new concerns for safety and new specific laws have forced quarriers to apply to designers for up-to-date exploitation projects.

In turn designers were forced to develop geomechanical studies oriented to understand the geostuctural setting, geomechanical properties and stability behaviour of the Carrara Marble in order to correctly design safe large caverns (up to 120m wide, 50m long and up to 80m high) for mining the best grade Marble of the Carrara district (Coli & Modugno, 1999).
2. - GEOSTRUCTURAL SETTING

The Carrara Marble is one of the lithostratigraphic formations of the Apuan Alps Metamorphic Core Complex, which constitutes the main outcropping body of metamorphic terranes throughout the Northern Apennines orogenic belt (Boccaletti et al., 1982).

The protolith of the Carrara Marble is an Early Liassic (Hettangian, 210÷200Ma) massive limestone of carbonate platform origin (Coli, 1989a). The platform contained several sedimentary environments that resulted in a complex 3D network of carbonate facies (Fig.5) (Coli & Fazzuoli, 1992a; 1992b).

Figure 5 - Carrara Marble paleogeographic and palinspastic reconstruction (redrawn from Coli & Fazzuoli, 1992b). Key: 1= ramp; 2= high energy; 3= inner lagoon; 4= emerged and karts; 5= external slope with megabreccias; 6= pelagic; A= Grezzoni platform (Norian-Rhaetian); B= Nero di Colonnata and Breccia di Seravezza (Late Rhaetian); C= Marble platform (Late Hettangian); D= transition to pelagic (Sinemurian).
Shallow water carbonate platform sedimentation began in the Apuane Alps zone in the Late Triassic time and had persisted until the Late Hettangian. In the lithostratigraphic succession two superimposed shallow water carbonate bodies can be recognized: the lower dolomitic "Grezzoni" and the upper "Carrara Marble".

Sedimentation of the Alpine cycle started during Upper Carnian on a peneplained hercynian basement: fluvial quartzose sandstones and transitional quartz-dolostones (Verrucano and Vinca Fmt.) were deposited. During Norian the "Grezzoni" hyper-hyaline carbonate platform developed. During Rhaetian a period of tectonic instability occurred: in the northern Apuan Alps a calcareous marly unit (Nero di Colonnata “Black of Colonnata”, AUCTT.) deposited in a ramp environment, below fair-weather wave base, indicating a phase of deepening. In the southern Apuan Alps residual and karts breccias (Brecce di Seravezza or “Brecce Medicea”) are present. They record a tectonic uplift that resulted in emerged and karts areas. A transgressive phase at the Rhaetian/Hettangian boundary led to the development of the "Marmi” carbonate platform, which corresponds to a inner platform upper-inter-tidal flat (Dolomitic marble) grading upward to a marginal wide barrier island complex and inner lagoons (Carrara Marble). Pelagic and then turbidite sequence followed up until Early Oligocene.

In spite of the tectono-metamorphic deformation, several lithologies, corresponding to different sedimentary facies, have been recognized within the Carrara Marble. Facies of inter-tidal environment are most frequent; other facies can be referred to marginal oolitic, restricted lagoon and ramp environments (Fig.6).

![Figure 6 - Correlation among the Carrara Marble types and the carbonate platform environments.](image)

The lateral as well as vertical distribution of the lithologies at the marbles evidence the complex morphology and evolution of the carbonate platform. Around the Late Hettangian the platform was dissected and different blocks drowned in different way. This tectonic phase is marked by the occurrence of neptunium dykes, karts features and fault scarp breccias on top of Carrara Marbles. The sinking of the platform blocks seems to be diachronous and younger from south-east to north-west; on top pelagic sediments were
deposited. The several carbonate platform lithofacies, combined with the tertiary tectono-
metamorphic deformation get rise to the different commercial types of Carrara Marble; their
tectono-geometric layout displays in the field the trend of the first-grade commercial
Marble. In the Tertiary (27 to 12Ma) the marble platform, as a part of the Apuan Alps
Metamorphic Core Complex (Coli, 1989b) underwent the tectogenes of the Northern
Apennine orogenic belt.

The tectono-metamorphic deformation resulted into three superimposed deformation
events (D1, D2, D3) (Boccaletti et al., 1983). The tectono-metamorphic deformation lasted
about 15My and gave rise to a complex tectonic assemblage of the marble lithofacies
(Carmignani et al., 1987): they resulted involved into a series of first-order ductile (NE-E
verging) nappe-folds (Carmignani et al., 1987; Coli, 1989b; Coli & Pandeli, 1992) (Fig.7).

Figure7a – Tectonic sketch map of the Apuan Alps metamorphic core complex and sections (from Carmignani
et al., 2000). Color key: MU= Massa Unit; P= Paleozoic units; G= Grezzoni; DM= Dolomitic Marble; CM=
Carrara Marble; M= Mesozoic-Tertiary pelagic units; 1= Vinca Anticline; 2= Orto di Donna Syncline; 3=
Tambura Anticline; 4= Arnetola Syncline; 5= crest of the late Tertiary uplift; TN= Tuscan Nappe; 1-6 traces
of the geological cross sections of Fig.7b.
Sediments were involved in tectono-metamorphic deformation at a low-grade metamorphic condition (350 to 400 °C and 3 to 4 kbar) which resulted into a green-schist facies (phengite mica+quartz+ albite+bio-ite+chlorite+epidote+chloritoid) for pelites. Those conditions correspond to a depth of about 10 km (Kligfield et al., 1986; Coli, 1989b; Coli & Pandeli, 1992).

Deformation rates ranged from 0.8 to 2.5 mm/yr (2.5 to 7.9 \times 10^{-15} \text{cm/s}) (Kligfield et al., 1981; 1986; Coli, 1989b), with finite strain ratios varying from 4.0 to 12.5:1 with average values of 7.0:1 (Kligfield et al., 1981).

Deformation occurred with no evidence of exotic fluids flowing through the marble body (Früh-Green et al., 1991); extrapolations of existing flow laws suggest that the marble may have deformed by grain-size-sensitive super-plastic deformation mechanisms (Olgaard, 1990; Paterson, 1990).

During post-8 Ma brittle uplifting and exhumation, the whole body of the Apuan Alps metamorphic terrains was cut by sub-vertical fractures (D4).

During the first deformation phase, strong transposition events occurred in the axial-plane high-strain zone. These resulted into the formation of sheets of “fault-rock” which layering especially marks the synform-syncline axial-plane. In the Carrara Marble these sheets are “tectonic-origin marble” (Fig. 8) with the main synclines marked by the “Nuvolato”, which is rich of quartz due to the transposition in the marble of the overlying cherty limestone.

At the transmission optical microscope (TOM) the Carrara Marble shows a homeoblastic grano-xenoblastic texture, grain size ranges from 0.2 to 0.8 mm, sutured and indented grain boundaries, relics of twins and glide surfaces and sub-grain partitioning in the larger grains (>0.6 mm). New crystals free of strain have linear, sharp boundaries and polygonal shapes (Coli, 1989a).

The main elements of the mesoscopic tectonic fabric recognizable in the field (Coli, 1995; 2001a; 2001b) in the Carrara Marble body are:

- The main tectono-metamorphic schistosity (S1) called versus by quarriers. The versus has the morphology of a continuous cleavage type 1, marked by different scales of grey. In the West side of the Apuan Alps chain versus dips towards SW at medium values, whereas in the East side it dips towards NE always of medium values. This because the main schistosity (S1) was uplifted and dome-shaped folded by the D3 deformation event.
- Two sets of sub-vertical anastomosing fractures, due to Neogenic uplifting and tectonic unloading, trending W-E and N-S (Fig.9) and respectively called by quarriers secondo and contro. Fractures are grouped into bands from a few meters to a few tens of meters wide. Fracture bands, called finimento, are spaced from a few tens of meters to one hundred of meters apart. The secondo and contro are related to the last brittle uplift (D4) of the Apuan Alps Core Complex as a tectonic horst bounded by the Versilia and Serchio Valley normal faults. These two step-of-faults display a vertical-slip of about 10km (Versilia) and 5km (Serchio), respectively. The contro is a typical unloading structure in massive rock.
2. – GEOMINING SETTING

The Carrara Marble commercial types setting derives from both the tectonic folding and refolding of the protoliths (marble of sedimentary origin) as well as by transposition processes (marble of tectonic origin).

This complex sedimentary-tectonic history implies strict constrains in the exploitation and excavation of the Carrara Marble both from economic and safety points of view: the verso, as tectono-metamorphic features, controls the distribution of the Carrara Marble merceological types in the rock-mass. The secondo and contro mutual intersections subdivide the marble body into blocks whose sizes and shapes constrains the exploitation and excavation of the Carrara Marble both from economic and safe point of view.

In the last years the Carrara Municipality committed a joint research project with the Universities of Firenze and Siena and the Polytechnic of Torino in order to obtain detailed geological data for the planning and management of the exploitation of the Carrara Marble in the next decades (AAVV, 2002; Coli et al., 2003a; 2003b).

In the frame of the project a new geological map was developed at the scale 1:5.000, with cross-sections, of the Carrara Marble types (Figg.10, 11), secondo and contro fracture bands distribution (Fig.12), and of the large debris cover (ravaneti) (Fig.10).
Figure 10 – Mining maps of the Carrara district (from Livi, 2005)
Figure 11 – Geological sections of the Carrara Marble in the Carrara district (from Carmignani et al., 2000).

Figure 12 - Sketch-map of the main secondo and contro fracture bands (finimenti) distribution in the Carrara Marble outcropping in the Carrara district (from Livi, 2005).
3. - GEOMECHANICAL DATA

The Carrara Marble has been characterized for a long time in terms of composition (Tab.1) and mechanical properties of the intact rock (Hoek & Brown, 1980a, 1980b; ERTAG, 1980; Morandini-Frisa, 1988, Primavori, 1997 – Tab.2).

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CaCO₃</strong></td>
<td>&gt;98</td>
</tr>
<tr>
<td><strong>Dolomite</strong></td>
<td>1.76</td>
</tr>
<tr>
<td><strong>MgO % mol.</strong></td>
<td>1.32</td>
</tr>
<tr>
<td><strong>SiO₂ %</strong></td>
<td>0.71</td>
</tr>
<tr>
<td><strong>Sr ppm</strong></td>
<td>114±160</td>
</tr>
<tr>
<td><strong>Residual %</strong></td>
<td>1.37</td>
</tr>
<tr>
<td><strong>Grain size µm</strong></td>
<td>200÷800</td>
</tr>
</tbody>
</table>

Table 1. Carrara Marble average composition

Some authors (Blasi et al., 1990; Alber & Hauptfleisch, 1999) introduced also for the Carrara Marble the concept of “residual” strength ($σ_c'$), i.e. the ultimate strength under long time loading, which results to be about 2/3 of the usual $σ_c$.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density kN/m³</td>
<td>27.05±0.05</td>
</tr>
<tr>
<td>Imbibition coefficient °/°°</td>
<td>0.6±0.6</td>
</tr>
<tr>
<td>Uniaxial comp. strength (σ_c)</td>
<td>131±3 MPa</td>
</tr>
<tr>
<td>“Residual” un. comp. strength (σ_c')</td>
<td>80 MPa</td>
</tr>
<tr>
<td>Un. comp. strength (iced cycled)</td>
<td>126±6 MPa</td>
</tr>
<tr>
<td>Tangent elastic modulus MPa</td>
<td>75,000±700</td>
</tr>
<tr>
<td>Secant elastic modulus MPa</td>
<td>83,550±250</td>
</tr>
<tr>
<td>Bending strength MPa</td>
<td>16.9±0.4</td>
</tr>
<tr>
<td>Wear thickness loss mm</td>
<td>5.6±1.7</td>
</tr>
<tr>
<td>Impact collapse height cm</td>
<td>53±5</td>
</tr>
<tr>
<td>Linear thermal expansion coeff. $10^{-6}$°C</td>
<td>6.3±0.5</td>
</tr>
<tr>
<td>Knoop index MPa</td>
<td>1.463</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.274</td>
</tr>
<tr>
<td>Rigidity MPa</td>
<td>21,700</td>
</tr>
<tr>
<td>“Los Angeles” test %</td>
<td>-30</td>
</tr>
</tbody>
</table>

Table 2 - Carrara Marble mechanical properties

Many field data were collected in order to rightly characterize the Carrara Marble geomechanical features and subsequently to rightly compute its rock-mass physical-mechanical properties; the surveyed features were:
- rock-mass distribution that resulted from the presence, spacing and persistence of the *secondo* and *contro* discontinuities;
- morphologies and features of discontinuities, according to ISRM recommendation and finalized both to the GSI classification (Hoek, 1994; Hoek et al., 1995; Hoek & Brown, 1997; Hoek et al., 1998; Marinos & Hoek, 2000), Bieniawsky (1989) RMR rock-mass classification and Barton (1976), Barton & Choubey (1977) and Barton & Bandis (1990) JRC and JSC parameters. Further observations were widespread carried out, out of quarries, on marble outcrops throughout the Apuan Alps.

Because discontinuities are mainly distributed into bands up to a few tens of meters wide, it was possible to categorise the Carrara Marble rock-mass into four rock-mass typologies: intact, scattered fractured (*bancata*), systematically fractured (*finimento*), intensely fractured (*secondo- and contro-finimento* cross) (Coli 2001a, 2001b; Coli & Livi, 2002).

Intact and scattered-fractured marble correspond to the main body of the Carrara Marble, out of the fracture bands where the mining exploitation is best. Systematically and intensely
fractured marble occur within and in the intersections of the fractured bands, they also represent areas of lower mining profit and of major safety hazard.

Each one of these four rock-mass typologies is characterised by specific features of discontinuity morphology and spacing (Tab.3).

<table>
<thead>
<tr>
<th>INTACT ROCK-MASS</th>
<th>SCATTERED FRACTURED</th>
<th>SISTEMATICALLY FRACTURED</th>
<th>INTENSELY FRACTURED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniaxial compressive strength</td>
<td>131 MPa</td>
<td>131 MPa</td>
<td>131 MPa</td>
</tr>
<tr>
<td>Density</td>
<td>27 kN/m$^3$</td>
<td>27 kN/m$^3$</td>
<td>27 kN/m$^3$</td>
</tr>
<tr>
<td>Hoek &amp; Brown index m$_i$ (Hoek, 2000)</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>R.Q.D.</td>
<td>100%</td>
<td>100-90%</td>
<td>75-50%</td>
</tr>
<tr>
<td>Discontinuities spacing</td>
<td>=</td>
<td>&gt;2 m</td>
<td>60-20 cm</td>
</tr>
<tr>
<td>Discontinuities aperture</td>
<td>=</td>
<td>0.1-0.5 mm</td>
<td>0.5-2.5 mm</td>
</tr>
<tr>
<td>Discontinuities persistency</td>
<td>=</td>
<td>10-20 m</td>
<td>10-20 m</td>
</tr>
<tr>
<td>Discontinuities roughness</td>
<td>=</td>
<td>rough</td>
<td>rough</td>
</tr>
<tr>
<td>Discontinuities morphology</td>
<td>=</td>
<td>planar</td>
<td>planar</td>
</tr>
<tr>
<td>Discontinuities infilling</td>
<td>=</td>
<td>none</td>
<td>soft</td>
</tr>
<tr>
<td>Wall rock weathering</td>
<td>=</td>
<td>none</td>
<td>moderately</td>
</tr>
<tr>
<td>JRC (Barton, 1995)</td>
<td>=</td>
<td>12-16</td>
<td>12-16</td>
</tr>
<tr>
<td>Discontinuities hydraulic condition</td>
<td>=</td>
<td>dry</td>
<td>dry</td>
</tr>
<tr>
<td>Excavation category (Barton, 1995)</td>
<td>C (ESR=1.6)</td>
<td>C (ESR=1.6)</td>
<td>C (ESR=1.6)</td>
</tr>
<tr>
<td>Excavation method (Barton, 1995)</td>
<td>undisturbed</td>
<td>undisturbed</td>
<td>undisturbed</td>
</tr>
<tr>
<td>RMR / GSI</td>
<td>= / 100</td>
<td>90 / 85</td>
<td>60 / 55</td>
</tr>
</tbody>
</table>

Table 3 – Carrara Marble geomechanical input data.

According to the Hoek-Brown failure criterion (Hock et alii, 2002) and the empirical estimation of rock mass modulus (Hoek & Diederichs, 2006), the correspondent rock-mass physical-mechanical properties were computed for each Carrara Marble rock-mass type (Tab.4 - Coli, 1995; Coli, 2001a, 2001b; Coli et al., 2006) and now re-evaluated by using RocLab software (©ROCSCIENCE INC).

<table>
<thead>
<tr>
<th>INTACT ROCK-MASS</th>
<th>SCATTERED FRACTURED</th>
<th>SISTEMATICALLY FRACTURED</th>
<th>INTENSELY FRACTURED</th>
</tr>
</thead>
<tbody>
<tr>
<td>RMR / GSI</td>
<td>= / 100</td>
<td>90 / 85</td>
<td>60 / 55</td>
</tr>
<tr>
<td>Modulus ratio (MR)</td>
<td>850</td>
<td>850</td>
<td>850</td>
</tr>
<tr>
<td>Intact modulus: E$_i$ (MPa)</td>
<td>11350</td>
<td>11350</td>
<td>11350</td>
</tr>
<tr>
<td>Hoek &amp; Brown index: m$_b$</td>
<td>9</td>
<td>5,267</td>
<td>1,804</td>
</tr>
<tr>
<td>Hoek &amp; Brown index: s</td>
<td>1</td>
<td>0,1899</td>
<td>0,0067</td>
</tr>
<tr>
<td>Hoek &amp; Brown index: a</td>
<td>0,5</td>
<td>0,5</td>
<td>0,504</td>
</tr>
<tr>
<td>Rock mass cohesion (MPa)</td>
<td>27,1</td>
<td>13,9</td>
<td>6,8</td>
</tr>
<tr>
<td>Rock mass friction angle</td>
<td>41°</td>
<td>39°</td>
<td>31°</td>
</tr>
<tr>
<td>Rock mass uniaxial comp. strength (MPa)</td>
<td>131</td>
<td>56,9</td>
<td>10,5</td>
</tr>
<tr>
<td>Rock mass global strength (MPa)</td>
<td>121</td>
<td>58,9</td>
<td>24,3</td>
</tr>
<tr>
<td>Rock mass tensile strength (MPa)</td>
<td>-14,5</td>
<td>-4,7</td>
<td>-0,489</td>
</tr>
<tr>
<td>Deformation modulus (GPa)</td>
<td>110.718</td>
<td>103.176,13</td>
<td>45.462</td>
</tr>
</tbody>
</table>

Table 4 – Carrara Marble rock-mass physical-mechanical property values.
3.1. – YELD STRESS
In order to develop a correct stability analysis suitable to ensure safety at workers it is fundamental to know the in situ stress, but no determination of the in situ stress is available for the Apuan Alps area. A few sporadic determinations were occasionally made in some quarries, but data are not shared and in any case they are not validated.

If we refer to a structural level below the equipotential surface represented by the geoid, in the range up to about -1,000m below its surface, the incremental vertical \( \sigma_v \) matches the plate tectonic stress (Hoek et al., 1995) and the stress-field can be related to the formula: \( \sigma_1 = 12.2 \text{MPa} + 0.0403z \), being z the depth (Christiansson & Martin, 2001). But, in our opinion, the Carrara Marble quarries are all located above the geoid, therefore we can assume for computation a pure lithostatic stress with the K-ratio between \( \sigma_v \) and \( \sigma_h \) given by the Terzaghi & Richart (1952) formula: \( k = \nu/(1-\nu) \), being \( \nu \) the Poisson’s ratio.

4. – STABILITY AND SAFETY CONCERNS
In the last decades many researches were developed on the stability concerns related to the high vertical cuts that resulted from the cultivation in the marble quarries (Coli & Modugno, 2000; Coli 2001a; 2001b; Coli & Livi, 2002; 2009; Coli et al., 2000; 2006; Livi, 2005). The main results achieved are:
1. According to the Limit Equilibrium Method, the stability Safety Factor of a sub-vertical pit slope cut along a fracture was verified taking into account the variation of fracture dip and cut high following the Mohr-Columb, Patton and Barton criteria. The Mohr-Columb criterion appears to best fit the situation of the Carrara Marble; the worst situations in terms of safety appear to be related to pit slope higher than 40m and dipping between 45° and 70°.
2. By using RocPlane (©Rocscience Inc.) a parametric limit equilibrium analysis was performed in order to investigate the stability of the very high quarry cut. It resulted that in the Mohr-Coulomb criterion the cut high and the fracture cohesion are the main parameters influencing stability, in the Barton-Bandis they are JRC, cut dip and friction angle. The Mohr-Columb criterion appears best applying to the Carrara Marble quarrying setting; the worst situations in terms of safety appear to be related to pit slope higher than 60m and dipping between 50° and 60°.
3. The stability of marble rock-mass related to the high and steep pit slope of the Carrara Marble quarries was analysed by means of the Mohr-Columb and Hoek&Brown criterions. At the stress-state reached in the Carrara Marble quarries there are no appreciable difference between the Hoek&Brown and Mohr-Coulomb criterions. The Mohr-Coulomb criterion seems to fit best the safety analysis of the marble pit slope; the most critical stability conditions appear to be related to pit slope higher than 100m cut in a fractured band.
4. Current underground quarrying by diamond techniques proceeds with the opening of a top horizontal shaft (about 3m in high) followed by downward excavation cuts (6m or 9m in high). Different sequences of the downward block-cut was simulated by means of a FEM code (namely PHASE2 (© Rocscience Inc.) in order to verify the stress-state induced and to evaluate the related Safety Factor. It resulted to be preferred the CDEAB sequence (Fig.13).
5. By means of a FEM code (namely PHASE2 (© Rocscience Inc.) it was verified the influence of the different marble rock-masses in safety concerns during the advancing of the underground excavation. The presence of *finimenti* decrease the rock-mass behaviour and the safety regarding rock-mass stability. Approaching the less rated rock-mass type the residual “pillar” of best rated rock-mass type can underwent to rock-burst (Fig.14).
5. – THE “RAVANETI” QUESTION
In the Carrara district it is estimated that debris (ravaneti) amount up to 80Mm$^3$ and cover about the 60% of the exploitable marble outcrops. In order to achieve both an environmental restoration in the area and the possibility to exploit presently covered marble bodies such as to correct plan a commercial use of the ravaneti, they were mapped in respect to: location; typology (white; grey); activity (active; no-active; old; historical); clast-size (block; boulder; cobble; fine); presence of infrastructure over; withdrawal in act or not (Fig.15).
REFERENCES


Ricci Lucchi, F. (1986) *The Oligocene to Recent foreland basins of the Northern Apennines*. Special Publications International Association Sedimentologists, 8, 105-139.


THE MINES IN TUSCANY
THE METALLIFEROUS HILLS NATIONAL MINE PARK
AND THE CASES OF GAVORRANO AND SAN SILVESTRO

1. - INTRODUCTION
The mining history in the Tuscany (Central Italy), is representative of the major part of the exploiting activities in Italy, also considering the stone sector. Today, all the mines are closed either because of seam exhaustion or because, and above all, of unfavourable economic and environmental conditions (with the exception of the numerous quarries, underground quarries of Carrara marble, sandstones, etc. and the particular situation of the rock salt mines of Volterra). Tin, copper, lead, zinc and iron are deposits present in central and southern-western Tuscany in the Metalliferous Hills and in Elba island (Fig.1).

Many sites were exploited since at least 1 millenium B.C. up to 1970’s-1980’s. There is a lot of evidence which attest exploiting activity during the etruscan, medieval and modern period (see in particular the historical literature by Vannoccio Biringuccio, 1480-1538). Some historical mines are placed in Northern-western Tuscany (Apuan Alps), characterized by mineralogic variety, but scarce quantity (however, the presence of Barite and Ag was interesting).

The mining industrial period, since the end of 1800 up to 80’s was based on pyrite, iron, barite cinnabar and lignite deposits (Tanelli, 1983). The cinnabar mines were situated around Mt. Amiata. In this ancient volcanic area the geothermal resource are very important as well as in the northern area of Metalliferous hills (Larderello village, named from the Count F.G. Larderel, which carried out a first industry producing boric acid from geothermal fluids). The lignite was exploited from the large open mine in Saint Barbara, closed some years ago (Upper Valdarno, near Florence), and from Ribolla underground mines, near Grosseto, closed down straight after a serious accident which provoked 45 victims (4 may, 1954). The pirite was used mainly in the chemical industry, and subordinately as iron, together with Elba mines (limonite and ematite). The pyrite mines are concentrated in a restricted area in the northern Grosseto district. The main ones are Gavorrano, Fenice Capanne, Niccioleta and Campiano. Gavorrano mine is famous because representative of historical evolution of mining techniques in many small drifts. It was one of the largest pyrite mines in Europe. Campiano is representative of modern mining based on wide rooms.
The history of the Metalliferous Hills from Etruscan times to the present day has been profoundly marked by human activities linked to the extraction and processing of minerals. This centuries-old activity, especially during the twentieth century, has left a huge number of signs (quarries, slag heaps, decanting reservoirs) and structures (tunnels, shafts, headframes, installations – Fig.2) and a large depository of documentary and oral sources regarding the organisation of work, production techniques, geological and mineralogical features and social and political history.

Over the last few decades mining activity has decreased progressively in Italy as in other countries. The idea of a Metalliferous Hills National Parks was tabled as far back as 1993 when the mining industry was already in a state of total crisis. All the mines had closed, only the very modern plant of Campiano (Montieri) was still open, albeit with its closure only a year away.

Thus, looking at the situation in terms of the economic redevelopment of the region, and the conservation of the socio-economic, technological and historical values the went with the mines system, a series of interventions was envisaged at the level of Tuscan local and regional institutions. The most important of these being the realisation of a Mines Park. Since ancient times, even pre-Etruscan, the region which includes the Metalliferous Hills and Elba, the main island of the archipelago, has been involved in exploitation of mineral resources including their subsequent transformation into metals.

This in turn fed a growing manufacturing industry and encouraged the intense trading activities which made the local population rich and powerful – we have only to think of the history of Etruscan Populonia. Such activity ceased during the Roman and medieval eras,
only to start up again in force in the eighteenth century, when the rich deposits of argentiferous galena (lead and silver) and chalcopyrite (a copper ore) began to be exploited.

From the end of the 14th century, epidemics, famine and war led to a period of crisis which had repercussions on the mining industry. Activities started up with high intensity in the 19th century when, thanks also to the involvement of many foreign companies, mineral prospecting increased and the many new deposits discovered led to an era of intense production. As well as the minerals exploited since ancient times, now also lignite was “mined”, boron (isolated from endogenous gases) and, from the end of the century, pyrites, considered of no interest in the past, but now, thanks to the chemical industry, an important raw material for the manufacture of sulphuric acid.

The history of the 20th century, is in fact the history of the pyrites mines and a period of intense mining activity, in which our mines were the most productive in Europe – there were even new villages established to accommodate the influx of an immigrant work-force for the mining industry. This was followed by years of crisis which led inevitably to the definitive closure of the mines of the Metalliferous Hills.

The decommissioning of a mine triggers a series of problems regarding social safety, health and the economy. Therefore 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. When a mine is abandoned and de-watering by pumping is discontinued, the water level rebound and groundwater reoccupies geological formations in an attempt to re-establish an old water circulation system. Nevertheless, mining acts as a drainage and percolation system, so that the water can rarely return to its original conditions and circulation path.

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 & Bullock 1996; Crosta & Garzonio 1998a). This exposure can occur 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 (Fig.3).
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.

A multi-purpose study was set up in 1995 to evaluate the possibilities of creating The Nature Reserve and Mines Park, now partially realised, by recovering the mining area and all its historical mining structures. The environmental rehabilitation of the area includes quarries (with trekking and rock climbing tracks and the construction of an open-air theatre), tailing ponds, the reforesting and stabilisation of spoil dump areas and the restoration of significant old mining structures. A major aspect of the rehabilitation involves the evaluation of the stability of slopes and underground openings as well as that of the pollution deriving from acid mine drainage resulting from the mining activity and the recovery of water resources. In particular, the de-watering operations, and the recent effects of the water level rebound and the evaluation of the groundwater volume storable within the mine in safe conditions.

1.2. - MINE WATER MANAGEMENT AND PROBLEMS.
At present time, except to lapidous extraction, the only working mines regard the particular activity of rock salt exploitation (near Volterra, by Solvay S.P.A.). Great and excessive quantities of fresh water from the Cecina river and from wells are utilized (10^6 m^3/year) to extract, by dissolution, about 2.10^6 ton/year of salts, for soda and chlorine producing. This activity induces hydrologic and hydrogeologic problems, in particular ground water pollution and subsidence.

Although all mines were closed, some of these since more than 30 years, we can observe wide and different situation characterized by water pollution phenomena and acid waters around small dumps. It is due to the fact there was a deficiencary or an incorrect approach adopted in environmental protection. The most serious problems are linked to the presence of wide tailings ponds (Gavorrano, Campiano, Fenice Capanne) and above all, the dewatering interruption, the water rebounds and flooding in the pyrite mines.

Table I shows some characteristics to point out the main aspects correlated to some large Tuscan mines involved by underground water problems. In particular in the Campiano mine, which closed down in 1995, the flooding fed a spring with a discharge of about 16 liter/sec of typical acid mine waters (these ones are the result of mixed fresh and thermal waters). The polluted waters, characterized by pH 4, sulphates and metals (iron, copper, zinc and arsenic), produce serious environmental effects in the Merse river in an area of particular natural and tourist interest.

<table>
<thead>
<tr>
<th>Mine</th>
<th>Minerals extracted</th>
<th>Mining method</th>
<th>Volume mined (m^3 10^6)</th>
<th>Filling (m^3 10^6)</th>
<th>Theoretical voids (m^3 10^6)</th>
<th>Mine waters</th>
<th>Water discharge (l/s)</th>
<th>Acid water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gavorrano</td>
<td>Pyrite</td>
<td>Horizontal cut and fill</td>
<td>10.12</td>
<td>6.5</td>
<td>3.62</td>
<td>Pumped</td>
<td>60-120*</td>
<td>No (some episodes, now NO)</td>
</tr>
<tr>
<td>Niccioleta</td>
<td>Pyrite</td>
<td>Sub-Level</td>
<td>5.06</td>
<td>0</td>
<td>5.06</td>
<td>Flooded</td>
<td>230</td>
<td>Yes/No</td>
</tr>
<tr>
<td>Campiano</td>
<td>Pyrite</td>
<td>Filled sub-level</td>
<td>1.5</td>
<td>0.64</td>
<td>0.86</td>
<td>Flooded</td>
<td>16*</td>
<td>Yes</td>
</tr>
<tr>
<td>Abbadia San Salvatore</td>
<td>Cinnabar</td>
<td>Horizontal cut and fill</td>
<td>6</td>
<td>3.18</td>
<td>2.82</td>
<td>Flooded</td>
<td>-</td>
<td>No</td>
</tr>
</tbody>
</table>

* Presence of thermal waters
The decommissioned Gavorrano mine (Fig.4) is involved by an important and delicate underground storage project. The Gavorrano mine is affected by failure phenomena (subsidence, sinkholes,) due to mining voids or the collapse of drifts and shafts (Crosta & Garzonio, 1998). But the major problems are due to the future effects of water rebound and of re-birth of hot springs (interrupted in 1957) in the Bagno di Gavorrano Village, where around the ancient thermal springs site now there is a wide urbanized area. At present days significant acid waters are not surveyed.

Figure 4 - Gavorrano mine area with location of main historical sites

2. – GEOLOGICAL AND HYDROGEOLOGICAL FEATURES

Gavorrano is in south-western Tuscany, in the Metalliferous Hills (Colline Metallifere), 150km south of Florence and a few kilometers 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 500m a.s.l. (Mt. Calvo). The Mt. Calvo ridge is just above the Village of Gavorrano and it is linked to the lower relief of the Finoria hill.

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) within a major mining district (Campiglia, Elba island, Amiata).

The sedimentary sequence and a Pliocene (4.9±0.15 Ma) quartz monzonitic intrusion are shown in the geological map (Fig.5). The intrusion, with successive micro-granitic dikes prevalently oriented N-S, NE-SW and NW-SE, is weathered at the surface and it is frequently bounded by a thick zone of loose soil-like-material (“Renone”).

This weathering and alteration disappear along the mining drifts but the “Renone” has often been found along the tectonic contact. The intrusive body is limited by two normal faults (Fig.6) to the eastern (45° dip) and western sides (60° dip). Minor faults are to the north of the intrusion (Rigoloccio), and to the W of Mt. Calvo, putting the stratigraphic series in contact.
The geomechanical characterization of the area was based mainly on a series of geomechanical field surveys (Crosta & Garzonio 1998a). These field surveys were carried out within the main geological formations, at the surface and in underground excavations (mine of Gavorrano).

The aim was to characterize the rock masses for a general evaluation of their mechanical properties; to assess slope stability and the distribution and persistence of joint planes; and to assess hydraulic conductivity. The field work highlighted the persistence and the frequency of two sub-vertical extensional discontinuity systems.

The dominant sets were parallel and normal to the axis of the intrusive body and of its main flow structures (lineations). Secondary sub-vertical faults with the same trend were observed at different sites with the same trend, sub-parallel to the faults limiting the intrusive body. A NNW-SSE and ENE-WSW discontinuity direction characterizes the rock mass. The former set is predominant, with the exception of the central part of the intrusive body, where normal or cross joints are more frequent. These discontinuities, often accompanied by dike intrusions with pyrite mineralization, are characterized by changes in the dip angle due to their normal trend with respect to the flow lineations.

This situation of highly jointed rock mass, together with the superficial condition of crushed-poorly interlocked materials (RMR 20-30), leads to the intensive and deep
weathering processes, particularly in correspondence with the faults, where the de-cohesion phenomena of the quartz-monzonite due to the fluid circulation reach a thickness of 50 m along the dip plane in the depth.

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 multilayered aquifer in the area around the sub-inclined plane of the alluvial and debris plane of the large village of Bagni di Gavorrano (Fig. 7).

Figures 7 - Hydrogeological map of the Gavorrano complex.

Waters from the last two systems have been forcefully mixed by the mining activity. In fact, 500m of production levels were excavated in over a century of mining. The pre-existing groundwater circulation, with springs placed at a maximum height of 180m a.s.l., was depressed up to -250m b.s.l., when old thermal springs (Bagni di Gavorrano, Terre Rosse) were drained through the underground drifts system.

Hot water springs (up to 47°C) were found during mining, both at particular sites and diffused in specific ore bodies (Rigoloccio). The permeability classes (Fig.7) were attributed by considering: the lithology, the degree of fracturing, the degree of weathering and alteration, and the presence of karstic structures, as observable at the surface and within mine drifts. Alluvial deposits have been separated from the other materials, because of their characteristics and their natural northward groundwater flow direction. Karstic features and degree of fracturing were determining factors in distinguishing carbonate rocks.

Because of their very low permeability, flysch and shales act as a permeability threshold which controls the location of the main springs around the carbonate massif. Intrusive rocks are characterized by a relatively low permeability because of superficial weathering and the low fracture density.

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 10.1s⁻¹km², as a function of the increase in fracturing and karst conduits. Varying values of the coefficient can be attributed to the quartz-monzonite...
changing with the degree of fracturing and weathering. Some in situ tests were recently carried out to evaluate the real infiltration in the carbonate outcrops (Massiccio limestone), in different attitude, and in the intrusive body. With regards to this aspect some data can also be inferred from the water level rebound analysis which up to now has only been carried out on the granite mine.

Average annual rainfall in the area ranges between 750mm/y and 800mm/y, with an average evapo-transpiration of 430mm/y and a rainy season lasting from October to February, with the maximum average monthly rainfall in November (120mm) and very low precipitation in summer (20mm in July). From these data, the calculated evapo-transpiration and a series of infiltration coefficients, it emerges that 1.2Mm$^3$ of water forms the annual groundwater recharge.

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 characterized by voids and refilled spaces.

Finally, as far as water discharge and the hydrogeological modeling related to resource re-utilization are concerned, some exceptional climatic events were of particular interest. In August 1997 and January 1997 and 2001 (with precipitation of 180, 210, 260mm, respectively) and in the last winter (2008-2009), with the most rainy January of the last 150 years (with water discharge of more 150 l/sec.) (Fig.8).

Figure 8 - 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 rising. 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 Impero Shaft and the Roma shaft, respectively (Fig.3-9).

Subsequently a new pumping point (Rigoloccio shaft 3) was realized (in 2000). 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 (Bagni di Gavorrano). Furthermore, the controlling of the rebound allows the evaluation of the volume of water storable within the mine voids system, as well as the changes in the chemical composition of drainage waters.

A deep borehole was recently drilled to increase the monitoring system of the water levels (where the piezometers are too near the surface), and to identify the lithological and mechanical characteristics of the terrains near the Bagni di Gavorrano Village. Furthermore, because of the almost constant temperature of the pumped water, it can be assumed that the hot water discharge increases with the fresh karstic water discharge during wet periods, maintaining an almost constant ratio between the two.

Geophysical and geo-mechanic soundings were carried out to identity the geometry of the aquifer above the built up area of Bagni di Gavorrano, above all to assess the hazards. The results of the mechanical soundings (S. Guglielmo borehole), for a depth of over 250 m, which went through a debris and “Renone” cover (granite alteration) for less than 30 m, then a crystalline calcareous level and finally the cavernous limestone, are in contrast with previous geo-structural analyses and the geophysical results. In other words, the cavernous limestone is less permeable than elsewhere, with few and closed fissures, few cavities, even though scarce in gypsum levels.

However, the possibility of local and important fractures or small faults is not to be excluded. More information will be collected by geoeletric or by new soundings to set up a monitoring system. For all these reasons too, before carrying out further drillings, it was...
decided to re-open a shaft near Rigoloccio to reach the tunnel (up to –200m b.s.l.), which connected the Rigoloccio mine with the Gavorrano one (Roma shaft), and then intercept the waters, analyze them and install a new pumping system. An initial analysis has shown that this operation could produce good results, not only for the control and the safety of the water rising operations, but also for the separation, albeit not total, of the hot and cold waters infiltrated in Mt. Calvo.

By putting in a sequence the data for each of the 11 steps used for the controlled groundwater level rising in a sequence and fitting them with the above mentioned equation, it was possible to determine the expected maximum groundwater level (+186m a.s.l.) and the time to reach it through a continuous uncontrolled rising (almost 4 years). By plotting the groundwater level recovery for the 1944-45 and the 1995-1999 periods, it was possible to observe the non-linearity of the process. In particular, the rising is slower at the beginning and faster in the final step. This can be attributed to the change in the fracturing degree of the rock mass, the opening of the main joint sets and the possible decrease in volume of the voids and of the main aquifer area.

Since 1995 the pump discharge has remained almost constant at 65 l/s, with the exception of three periods of heavy rainfall with discharge until 110 l/s. This allowed the storage of about $3\times10^5$ m$^3$ of water, excluding the initial uncontrolled water level rising between -236m b.s.l. and -197m b.s.l. Using the data recorded during the two phases (1997, 1998) of increased discharge, it was possible to perform a recession analysis (Fig.10) which gives a good insight into the aquifer structure.

![Figure 10 - Pump discharge decrease after the maximum peak as measured during the 1997 and 1998 recession events.](image)

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 2.2Mm$^3$ or 66 l/s. These values are quite comparable with the average yearly pump discharge (65 l/s or 2.08Mm$^3$). Finally, by comparing these data with the ones obtained by the effective infiltration analysis (1.1 Mm$^3$) it
emerges that almost 1 Mm$^3$ of hot water flows regularly from the deep circulation system into the mine every year.

The residual volume of the hollows produced during the whole mining activity has been estimated by Sammarco (1993) of about 3.6 Mm$^3$. Furthermore, because of the almost constant temperature of the pumped water, it can be assumed that the hot water discharge increases together with the fresh karstic water discharge during wet periods, maintaining an almost constant ratio between the two (when the discharge increases a steady value in the temperature can be observed).

2.1. - CHEMICAL ANALYSES OF THE WATERS

The mine water samples can be clearly divided into two main groups: “superficial” bicarbonate waters (from levels +240m a.s.l., +155m: Mg-Ca, +90m: Ca-Mg-HCO$_3$) and deep sulphate waters (Ca-Mg-SO$_4$, -80m b.s.l., -110m, -140m, -200m) as suggested by the Piper plot (Fig.11). 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 were made. In fact, by fitting temperature measurements, excluding samples taken at the outlet of the drainage tunnel (1.5km long), a geothermal gradient of about 75°C/km was obtained.

This geothermal gradient is in agreement with the data published by Baldi and others (1995) concerning southern Tuscany and indicates, for the marginal areas of the geothermal fields (Larderello, Amiata, Travale, Radicofani), a gradient of no lower than 70°C/km.

This is the case of Gavorrano, where all these factors acted together in generating a large and evident subsidence feature. The combined action of multiple factors accentuated the role of the gravity force in driving both the subsidence and a deep seated slope instability (Crosta & Garzonio, 1996). In fact one more aspect of the environmental rehabilitation of the area involves the difficult evaluation of underground water resources in a complex system where karstic and hydrothermal waters have been forcibly mixed by anthropic action realized through mining.

Deep mining works (almost 500m of production levels) have been realized in this area by lowering the existing water table to almost 250m b.s.l. and changing completely the old groundwater circulation drying some old thermal springs (Bagno di Gavorrano, 30m a.s.l., Terre rosse, Bagnacci, etc.). Hot water springs, up to 47°C, have been found mainly in the...
Rigoloccio area, a sector of the Gavorrano mines, and mixed with the karstic flow system of mining drifts. Karstic conduits are quite common in these limestones and may karstic features can be recognised in the field (Fig.12).

As a consequence karst played an important role on the properties of the rock mass and also on those of the in place ore bodies. Furthermore, chemical reactions causing the decrease in pH of circulating water and the consequent dissolution of iron sulphides could have been at the origin of more voids within the rock mass. This is particularly important because of the location of pyrite ore bodies right at the contact between quartz-monzonitic intrusion and carbonatic formations as well as for the presence of ore veins and impregnations within carbonatic rocks.

In fact, pyrite is a quite unstable mineral breaking down quickly under the influence of weathering. Hence, it seems important to list both the chemical reactions generating acidity (H$^+$) through the weathering of iron disulphide minerals and those inducing oxidation of pyrite to produce ferrous and ferric sulphates and sulphuric acid.

We must remember that opening of such a large mine is a way to accelerate these reaction by allowing an easier circulation both of air and water. Again, sulphates and sulphuric acid react with clay (e.g. in the renone material) and carbonate minerals to form secondary products including manganese and aluminium sulphates. Tertiary products can result from the reaction of these minerals generating calcium and magnesium sulphates. These reaction,
together to geothermal anomalies of this region, are important for the educted waters from the mine as well as their role in generating hot water springs because of their exothermic nature. Forrester & Whittaker (1976) describe the effects of mining subsidence on colliery spoil heaps overlying some mined out coal seams.

This research shows that the vertical subsidence under spoil heaps is larger, more spread and appears a little in advance than for natural flat surfaced, with the point of maximum subsidence generally coincident with the slope crest. It is evident the sub-circular pattern of cracks over the mining area with a good correspondence to the progress or the permanent boundaries of mine working. Such subsidence induced tension cracks appear throughout the entire slope and also at its foot, increasing in this way both water flow and drainage.

Main discontinuities sets have been identified through geomechanical surveying both on the surface and along mining drifts. Sub-vertical discontinuity sets with a general N-S direction and roughly parallel to the intrusion border, represent the more frequent and persistent structural feature, both as joint and faults, and frequently characterized by karstic forms.

This assemblage of fracture is at the origin of the more common types of instability (toppling, falls) along the slope. The same sets are present along the slope where the change is represented by the appearance of more subvertical E-W trending discontinuities. Again, all these discontinuities generally shows surface with rare sub-horizontal to low dipping small steps characterised by fresh rough fracture surfaces. Small evidenced of instability phenomena have been recognized near the southern slope crest and prevalently by the same mechanisms as cited above (toppling, falls) and in connection with some little vertical cliffs. These instabilities and some deeper ones are supposed to be related with the collapse of karstic depression which has been strongly influenced by the subsidence in the above described area.

Before the mine exploitation, in the Mt.Calvo area there were some thermal springs which disappeared because of dipping of mining activity. Furthermore, it is important to highlight the fact that it is not only present a problem of failure linked to deformation of backfilling, mining voids, drifts, etc., but also to the collapse of wide level characterised by physical-mechanical decay due to water corrosion of aggressive water. The characteristic of Gavorrano waters are showed in Tab.III. In particular some acid waters samples drew in mine drifts under Mt. Calvo are reported.

<table>
<thead>
<tr>
<th></th>
<th>Poggetti Vecchi (mg/L)</th>
<th>Bagno di Gavorrano (1324) (mg/L)</th>
<th>Saturnia (mg/L)</th>
<th>Gavorrano mine -140m a.s.l. (mg/L)</th>
<th>Gavorrano mine -80m a.s.l. (mg/L)</th>
<th>Gavorrano mine (pumped waters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T(^\circ C)$</td>
<td>37</td>
<td>34,1</td>
<td>37</td>
<td>37,5</td>
<td>20,7</td>
<td>36</td>
</tr>
<tr>
<td>$pH$</td>
<td>6,65</td>
<td>6.09</td>
<td>6.09</td>
<td>2,77</td>
<td>2,91</td>
<td>6,5</td>
</tr>
<tr>
<td>$Ca^{2+}$</td>
<td>541,08</td>
<td>328,02</td>
<td>600</td>
<td>430</td>
<td>519</td>
<td>405</td>
</tr>
<tr>
<td>$Mg^{2+}$</td>
<td>116,697</td>
<td>59,89</td>
<td>130</td>
<td>174</td>
<td>254</td>
<td>97</td>
</tr>
<tr>
<td>$Na^+$</td>
<td>36,784</td>
<td>29,70</td>
<td></td>
<td>40,4</td>
<td>69</td>
<td>46</td>
</tr>
<tr>
<td>$K^+$</td>
<td>3,44</td>
<td></td>
<td></td>
<td>7,14</td>
<td>9,09</td>
<td>12</td>
</tr>
<tr>
<td>$HCO_3^-$</td>
<td>244,05</td>
<td>253,00</td>
<td>660</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$SO_4^{2-}$</td>
<td>1440,87</td>
<td>844,37</td>
<td>1450</td>
<td>1967</td>
<td>2611</td>
<td>1278</td>
</tr>
<tr>
<td>$Cl^-$</td>
<td>46,089</td>
<td>28,48</td>
<td>50</td>
<td>33,5</td>
<td>23,09</td>
<td>32</td>
</tr>
</tbody>
</table>

Table 3: Physical and chemical parameters: “Poggetti vecchi” (Bencini et all., 1977); Bagno di Gavorrano (Lotti, 1910); Gavorrano mine (Garzonio & Crosta; 1996); Saturnia (Official data).
The observation of so huge cracks developed in a sub-circular pattern (450m in diameter, cracks with apertures from few centimeters up to 6m, and 30m. deep), the evidences of downslope movements (maximum displacement of 30-40m) and the depth of mining drifts and ore bodies make us thinking of a complex kind of instability where vertical and horizontal components are anomalously distributed with respect to slope failures common to other sector of the Mt.Calvo area.

Nevertheless, a reliable study and in particular a numerical simulation need more geometrical and geomechanical data with respect to the actually available ones. Anyway, it has been tried to run a series of numerical simulations (by UDEC and 3DEC, ITASCA, 1993). In particular, carbonate formations have been considered the less resistant and more deformable ones (Fig.13). Numerical modelling techniques pointed out the disuniform displacements distribution along the entire slope with maxima at the slope crest and close to the ore bodies (Fig.14). This two maxima, well comparing with field observations, to correspond to the two sectors characterised by maximum depth movement.

3. – THE SAN SILVESTRO PARK

The Park of San Silvestro, opened officially in 1996, was founded in order to keep the memory alive and favor the grasp of a complex history which has always been tied to the mining activity. The area of the Park is indeed rich in minerals called “sulphides” formed following geological processes dating back to around 5My ago. The sulphides contain sulphur related to metals such as copper, lead, iron and zinc.

The traces of the extraction of metalliferous minerals and rocks indelibly mark the hills of the Campigliese. Even today, in mines which have been now closed for almost 30 years, the intensive use of the quarry materials persists (limestones and minerals for the ceramic industry).

The archaeological research began half-way through the Eighties, endeavouring to retrace the stages in mining work organized systematically already in Etruscan times. The cramped and tortuous shafts excavated by this ancient people, barely wide enough for the shoulders of a man, represent the first approach in mining prospecting. It was not geological or scientific knowledge which guided the ancient miners, but the experience of knowing how to recognize
and follow in-depth this dark rock (which the studious of the 1900s referred to as SKARN) rich in metalliferous sulphides. During the Etruscan times, the territory was controlled by aristocratic groups to whom can be attributed the tumulus tombs of Monto Pitti and San Dazio, and the settlement of Poggio alle Strette, located on the edge of the mining area.

The history of the Campigliese is closely linked to that of Populonia, the Etruscan city made famous for the extraction and mineral working of Elban iron lying only a few kilometres away. Remains of kilns for the treatment of minerals, dating back probably to this period have been found in Madonna di Fucinaia, just before the entrance to the Park (Fig.15).

After a long interruption in the Roman period and in the high Medieval period, the resuming of the mining activity in the Campigliese is tied to the founding and development of the fortified village of Rocca San Silvestro. Commissioned by the Counts of the Gherardesca, and inhabited by the miners and foundrymen, it represents, at a European level, one of the most significant examples of a residential village dedicated to mining and metallurgy.

Figure 15 – General view of the restored Ravi Park.

Other settlements of eminence desired by the Della Gherardesca family are those of Acquaviva and Biserno, of which there do not remain any traces, and the castle of Campiglia.

The mining technique used by the Medieval miners did not differ greatly from those of the Etruscans and the prospecting was concentrated in that period in particular in the Valley of Manienti and Lanzi, behind Rocca San Silvestro. In the park, the openings of around 200 ancient mines have been identified, belonging both to the Etruscan and the Medieval periods, some of which are indicated along the visiting routes.
After the abandoning of Rocca San Silvestro at the end of the 13th Century, only Cosimo 1st of the Medici, Grand Duke of Tuscany, resumed an interest in this territory, sending in specialized miners from Tyrol and Versilia.

The Lanzi, famous for their expertise, constructed buildings (Caprareccia and Villa Lanzi) and experimented with new methods of open-cast mining. Technical difficulties in the separation of the various metals caused them to abandon the area in 1559.

The discovery of the Enlightenment period and the early studies of naturalists and geologists at the beginning of the 1800s gave a new push to the mining prospecting. The extraction technique changed completely, thanks to the use of gunpowder followed by explosives, capable of crushing great volumes of rock.

The mines were organized into extraction levels on several layers, with long horizontal tunnels linked by vertical wells, used for shifting minerals and workers in industrial lifts. The Earle Shaft, with its castle of metal, represents the deepest of the five mining shafts excavated between 1800 and 1900 for accessing all levels of the mines. Many evident signs still remain of this more recent phase of mining extraction: the tunnel mouths, the shafts, the remains of the railways used for transporting the minerals, the mining buildings of the early 1900s, which today houses the ticket office, the Restaurant and the Hostel of the Park (Palazzo Gowett).

The project of the San Silvestro Park stems from a specific research experiment. Indeed, it dates back to 1984 when the first campaign for excavating the castle of Rocca San Silvestro, lead by the Teaching of Medieval Archaeology of Siena University in collaboration with the Municipal Administration of Campiglia Marittima and numerous European University Departments.

Beside the intensive excavation of the castle, a systematic research of the entire surface of the Campigliese territory was also started, in order to reconstruct, through the archaeology of the landscape, the systems of settlements in the various historical periods (from Protohistory to the modern day) and the approach of the communities to the resources available.

Today Rocca San Silvestro and its copper and silver mines constitute a reference point at European level for rewriting, on an archaeological basis, the history of the organization of the mining work in the Medieval period. The archaeological research, catalyzing the interest of naturalists, historians, administrators and protection bodies for this territory, thus gave the first push to the establishment of an Archaeological Mines Park.

The original pilot project dates back to 1989, when by appointment of the Municipal Administration of Campiglia Marittima, the general lines of the Archaeological Mines Park of San Silvestro were defined for the first time. The aim was not only to develop and create a museum from a single monument, but an entire historical landscape, the result of centuries of mining workings, combining the development of the local resources with the protection of the environmental and historical assets.

With the acquisition of land and real estate by the Municipality of Campiglia Marittima, a further and more definitive step forward was made towards the completion of the project. Thanks to the European Community funding, ex.reg. Cee n. 328/88 Resider I, it was finally possible to begin the definitive construction.
The Archeological and mine Park of San Silvestro

Old mine setting

Rocca San Silvestro

The Earle shaft

The Temperino-Lanzi touristic train