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Sustainable development for underground mining of strategic industrial minerals: the geological and geotechnical modelling as a key factor. The case of the "Marmorino" mineral deposit (Sacile - NE Italy)

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Abstract. The growing industrial minerals demand, in the perspective of a sustainable development of mining activities, implies a strong orientation to underground operations in the near future. In complex geological areas, for the definition of a reliable 3D ore body model a methodological approach, aimed to improve geological and geotechnical model reliability allows a confident mineral deposit evaluation and a reliable mine design, or, in other terms, costs reduction, safety increase and mining project sustainability. The described method finds its maximum application in complex geological and structural contexts, such as the Valmadonna-Pedemonte "Marmorino" quarry.

1. Introduction

Industrial minerals are part of everyday life but even if we take our industrial minerals for granted, there is increasing pressure against extraction, largely on environmental grounds. According to Manning (1995) [22], an industrial mineral can be simply defined as a geological material (mainly rock or mineral) obtained by mining and which represents a non-metallic, non-fuel, raw material of commercial value.

The present study concerns a calcium carbonate deposit whose rare chemical properties allow classifying it as "strategic ore". Despite a growing industrial minerals demand several factors can negatively affect the investments for exploration and resources/reserves evaluation, namely: i) small volumes extraction; ii) environmental, landscape and visual impact of open pit mining; iii) important stripping ratios; iv) intrinsic monetary value of the commodity; vi) costs for mineral processing and to transport to market.

In this framework, especially in complex geological areas, the geological and geotechnical modelling become a key tool to define a reliable 3D ore body model and mine design, as a synthesis of a multidisciplinary approach by skilled geologists and mining engineers. In addition, the increasing trend to develop new operations by underground mining requires more accuracy in defining the geotechnical model for the rock mass interested by the opening of underground cavities like adits, ramps, declines, shafts and production drifts.

Only an integrated approach can lead to sustainable mining projects, although small sized operations if compared to metallic ore bodies, combining safety, environmental and economic issues. The Valmadonna-Pedemonte "Marmorino" quarry represents an example where the geological and geotechnical modelling have been a key factor for the evaluation of future underground operations.

2. Underground mining in industrial minerals exploitation

Sustainability of mining industry is today an imperative issue to be achieved by developing and integrating economic, environmental, and social components. Sustainable practices involve resource efficiency, environment, community, economics and safety. In this frame underground mining, as an alternative to open pit exploitation, is expected to experiment a strong impulse in the near future.

Compared to open pit mining, the development of underground operations represents usually a costs increase; nevertheless this choice allows to: i) minimize the environmental impact of exploitation (by reducing deforestation, dust dispersion, noise, etc.); ii) improve mine safety and health; iii) optimize the extraction of the mineral resource by reducing the stripping ratio and consequently the production of waste materials and related stockpiles volume; iv) improve the quality of extracted mineral; v) increase the use of advanced technologies facing the challenges of automation, remote control, digitalization, energy saving, etc.; vi) developing local qualified skills.

3. Geological and geotechnical modelling for mining project sustainability

Underground mine projects involve first of all the evaluation of mineral deposit (in terms of quality, extension, volume, etc.) in order to report on mineral resources and ore reserves (according to international standards). Different solutions in terms of mining method and excavation techniques must then be identified and compared in the frame of the productivity, stability, quality, safety, environmental and legal requirements. Especially in complex geological contests the above descripted steps are addressed by the results of the geological and geotechnical ore body characterization. Reliable geological and geotechnical models allow a confident mineral deposit evaluation and a reliable mine design, or, in other terms, detailed economic analyses on proven reserves and mine-planning, costs reduction, safety increase and hence mining project sustainability.

3.1. Improving geological model reliability

The starting point of every underground mining project is the definition of a reliable reference geological model. Most subsequent steps (including hydrogeological model, geotechnical model, mine design) are strictly dependent on it. Geological model reliability is conditioned by three key factors (Perello, 2011 [25]): i) quality and accuracy of the investigation methods adopted to explore the rock volume to be exploited; ii) adequacy of the interpretation criteria applied to fit the data to a model; iii) geological complexity of the rock volume. Data collected during investigations represent "potential" information becoming "effective" information thanks to interpretation. In other words, geological model is a "picture" in which the various observed elements are connected one to each other.

In the context of mining projects, interpretation can be done using a geostatistical criterion or a genetic one. In the first case geological model is the result of the statistical treatment of a more-or-less extended data set, where the geological discontinuities are traced as an extension of punctual observations. The genetic criterion involves a more complex logical path, where some fundamental stratigraphy and/or structural geology rules, in the frame of a "conceptual model" from literature, must be considered thus establishing mutual relationships among data.

In complex geological contests (from the point of view of lithostratigraphy, ductile and brittle tectonics), simple geological reconstructions based on geostatistical approaches are often not applicable and the only practicable way is that of the genetic interpretation.

In this frame the effort to follow a rigorous and transparent process for the definition of the reference geological model to improve reliability could be summarized in these steps: i) analysis of the literature and identification of the main uncertainties; ii) rigorous presentation of the results of the investigations carried out in the frame of the project; iii) definition of the reference geological model by genetic criteria;

iv) use of geological maps, geological vertical and horizontal cross sections and three-dimensional geological model to check the congruence between the model and the available data.

Implementing this process, the experience of a multidisciplinary team of experts (stratigrapher, sedimentologist, petrologist, geomorphologist, structural geologist, hydrogeologist, engineering geologist) is essential.

3.2. Improving geotechnical model reliability

Based on the geological model, the geotechnical model defines homogeneous zones in the rock mass and describes them with a set of parameters in order to represent their mechanical behavior at the scale of the volume interested by the underground mine project.

Reliability of the reference geotechnical model is related to: i) the reliability of the geological model; ii) the quality, statistical representativeness and quantity of the investigations carried out to describe intact rock and discontinuities; iii) the methods to integrate the scale effect reducing intact rock parameters to the rock mass scale; iv) the adequacy of the models used to represent the mechanical behavior of rock mass (continuous model, discontinuous model, …) and the adequacy of the chosen failure criterion; v) the presence of complexity elements involving difficulties in sampling and site investigations, difficulty in geomechanical classification under usual systems, and undesirable physical and mechanical behaviors.

A work methodology conceived to increase geotechnical model reliability includes firstly the existence of a reliable geological model, then ([1], [3], [4], [5], [19], [20], [21], [24]):

- A rigorous characterization of the intact rock by facies analysis, thin section lithological analysis and laboratory tests to measure physical and mechanical properties.
- The understanding of the structural asset in the frame of an essential hierarchization (basically based on continuity and associated geotechnical properties) of the structures in the way they influence the rock mass behavior; discontinuities sets description using recognized standards.
- The description of the rock mass quality through well documented observation of outcrops (using rock mass quality classifications when applicable), seismic prospection (cross-hole, down hole, seismic tomography, etc.), geological log of drill cores.
- The use, the comparison and the synthesis between alternative methods to manage the scale effect (use of rock mass classification, correlations between seismic velocity and rock mass deformability, in situ tests, back analysis of monitoring data if available, stability evaluation of existing excavations).

4. Case history: the Valmadonna "Marmorino" quarry (Sacile – NE Italy)

4.1. The strategic mineral resource "Marmorino"

The company Mineraria Sacilese S.p.A. extracts calcium carbonate of extreme purity (>99,6 % of calcium carbonate) from the ore body, locally known as "Marmorino" deposit, located at the base of the Cansiglio massif in the town of Caneva (PN) in the Regione Autonoma Friuli - Venezia Giulia (North-Eastern Italy). The ore body represents a unicum in Italy, with very few alternatives worldwide: only another European site reaches comparable qualitative levels (the deposit of Bouches-du-Rhône in France). Thanks to the low content in heavy metals and magnesium, the "Marmorino" is considered as indispensable raw matter, thus "strategic", for its application in chemical, pharmaceutical and food industry.

The ore body is exploited today in an open pit quarry, the "Valmadonna-Pedemonte" quarry, where the required production is achieved by drill & blast method. Until the '80s many underground extracting sites were active (managed by different small companies), exploited mainly in an artisanal way. The mine configuration was that of the room and pillar method, developed on few and irregular exploitation levels.

The valorization of the strategic non-renewable resource and a sustainable development of the extractive activity require the transition to a new and modern underground mine exploitation based on mechanical excavation.

4.2. The geological and structural model of the Valmadonna site

4.2.1. Existing studies and open issues. The study area is located in the Carnic Alps and, from a geological point of view, in the Southern Alpine Domain south vergent fold-and-thrust belt (Agard and Lemoine 2005 [2]).

Despite the relevance of the "Valmadonna-Pedemonte" deposit, few studies approach the geological and structural aspects of the area, the existing ones being mainly directed to geotechnical considerations. In 1978 Fontanive ([16]) defines a scheme based on a continuous stratigraphic succession, dislocated by a deep-seated gravitational slope deformation (also in Devoti et al. 2015 [13]). More recently, in 2007, Regione Autonoma Friuli - Venezia Giulia and the University of Trieste, realized a wide-ranging study ([11]), based on surface geological mapping of a 20km^2 area on the entire mining district, defining the large-scale limits of the "Marmorino" deposit. In the same study the facies "Marmorino" was described as a mylonite related to units overthrust with important recrystallization of the original rock mass.

Starting from these references, a detailed geological study has been conducted in order to answer a series of questions concerning the local geological and stratigraphic model, the geological significance of the "Marmorino" and the limits (hanging wall and footwall) of the "Valmadonna-Pedemonte" ore body.

4.2.2. Geological and stratigraphic asset. Geological investigations, coming from open issues, involved the realization of a geological and structural detailed map (of each the surface quarry and neighboring areas and underground stopes), the definition of the boreholes number and position, the mapping of the existing underground levels, the sampling for microscopic analysis and core-logging. The characterization of the deposit was based on: i) the facies and micro-facies analysis and ii) the study of the structural elements affecting the rock mass. Observations were conducted by direct facies analysis on surface outcrops and underground excavation faces and detailed analysis of drill cores. The main lineaments of the area were observed on aerial photos and then checked by field observations.

In the study area, the Cenozoic evolution of the Southern Alpine Domain is expressed as a wide SE vergent anticline fold involving Jurassic and Cretaceous units (**Figure 1**). The fold is an asymmetric drag fold with a partially reversed flank, resting on a series of medium-low angle thrusts ramp and flat surfaces. The local stratigraphic framework is dominated by Jurassic and Cretaceous limestones, the mainly formations being: i) the Cellina Limestone consisting in a wide succession (more than 100 m thick) of stromatolitic and bioclastic limestones locally rich in foraminifera and bivalves and ii) the Monte Cavallo Limestones consisting in white, massive, bioclastic limestones very rich in rudist fragments.

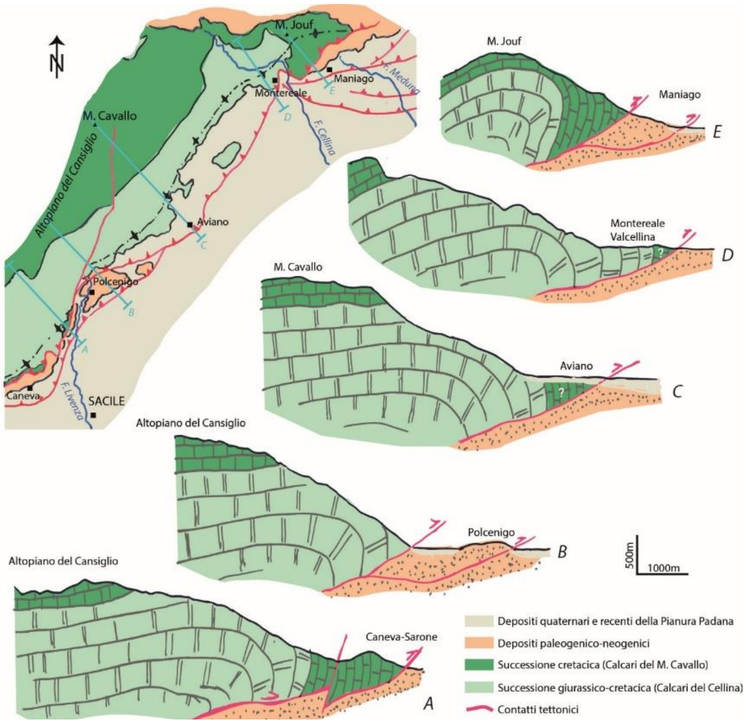

Figure 1. Geological sketch and geological profiles between Caneva and Maniago (adapted from Swinburne & Noacco 1993 [27], Carulli 2006 [9], sheet 100.000 of the Geological Map of Italy).

The ore body ("Marmorino") consists in white bioclastic limestones referred to the Monte Cavallo Formation (Upper Cretaceous, Figure 2 and Figure 3), almost completely composed by rudist fragments and, secondary by echinoderms, gastropods and bivalves fragments, with spathic calcite (Figure 4). The matrix is absent. From the paleoenvironmental point of view, the ore body represents wave reworked deposits, deposited near the base level of the tidal waves and/or storm waves, where the high energy of water caused the complete removal of the micritic fraction from the deposit.

Figure 2. White limestones "Marmorino" in the "Valmadonna-Pedemonte" quarry.

Figure 3. Core drill in the white limestones "Marmorino" in the "Valmadonna-Pedemonte" quarry.

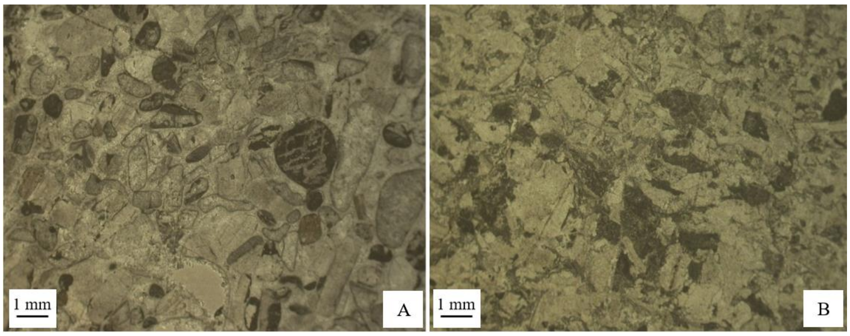

Figure 4. White limestones “Marmorino”. A) microfacies consisting in Grainstone formed by intraclasts; B) microfacies consisting in Grainstones formed by rudist fossils.

4.2.3. Structural asset. From the structural point of view the sector is characterized by an articulated convergence of tectonic structures developed in regimes of compression and/or transpression. The most relevant structures conditioning the ore body structuring are (Figure 5): i) The Caneva- Maniago thrust, a N45E-N50E striking surface that overlaps the Cretaceous limestones with the tertiary succession (). Evidence of this structure was observed in the field, being represented by low angle surfaces and by high angle faults forming “deformation channels” where the rock mass is highly fractured; ii) The Caorle-Montaner Lines/ Caneva Lines with an average N310/N320E strike. High angle faults sets were detected during site mapping. They represent the decoupling structures of the Southern alpine thrusts; iii) The Cansiglio line, a high angle strike-slip structure, with medium N15E/N20E strike.

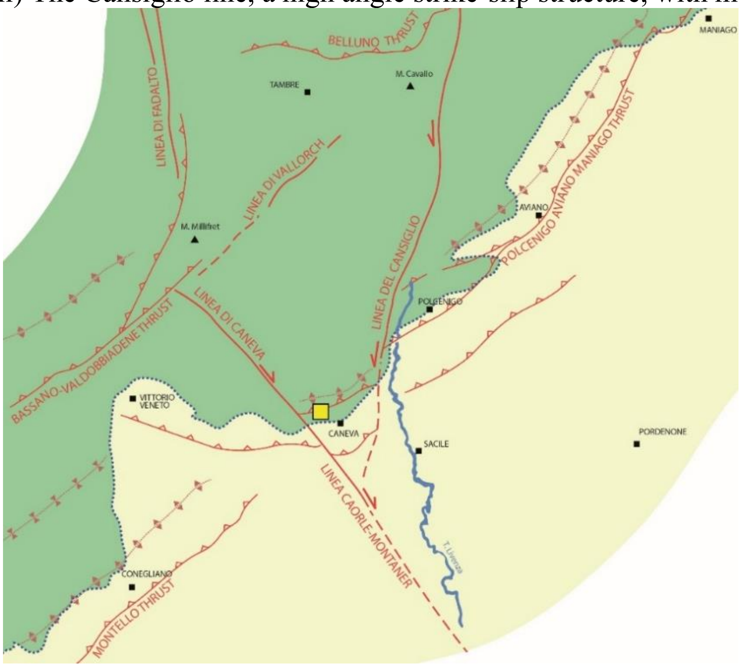

Figure 5. Structural sketch of the sector. The mountain area is shown in green, thus the hilly and plains in yellow (adapted from Burrato et al. 2008 [6], Caputo 1996 [7], Caputo et al. 2010 [8] , Carulli 2006 [9], Castellarin et al. 2006 [10], Cavallin e Martinis 1982 [12], De nardi 1965 [14], Fantoni et al. 2002 [15], Galadini et al. 2005 [17], Massari 1990 [23], Slejko et al. 1989 [26], Zanferrari et al. 1982 [29], Zanferrari et al. 2003 [30]).

4.2.4. Three-dimensional ore body model. The three-dimensional representation of the “Marmorino Valmadonna-Pedemonte” deposit has been conceived through i) the realization of a geological surface map at 1:2000 scale, geological plans of the existing underground exploitation levels at 1:1000 scale and a series of cross section defining a < 200 m spacing mesh, ii) development of a conceptual geological reference model, iii) identification of the most relevant stratigraphic and tectonic surfaces and iv) representation of these surfaces using a cad tool. The work was conducted by execution of systematic “in itinere” validation processes to check the congruence of the surfaces and volumes with the geological reference model and the information arising from the geological mapping activities and boreholes core-logging. The boundaries of the ore body were defined in the 3D model, allowing to determine the volume of the resource “Marmorino” in the “Valmadonna-Pedemonte” quarry (Figure 6).

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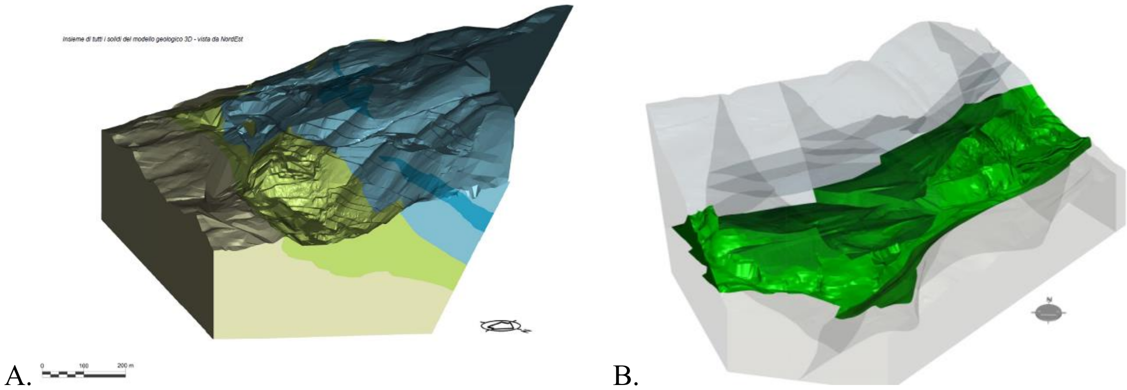

Figure 6. A) Three-dimensional geological model of the “Valmadonna-Pedemonte” deposit, B) identification of the ore volume

4.3. The geotechnical model of the quarry

Approaching the geotechnical study of “Marmorino” the main issue concerned the presence of a geomechanical unit that, for its exceptional whiteness and good excavatability, has been named by miners as the “coarse salt” facies. The structural study allowed to understand that the “coarse salt” is related to preferential “deformation channels” along high angle N45E-N50E striking fault core zones. According to the faults rock classification of Woodcock e Mort ([28]) the rock massif belts along the “deformation channels” can be described as a “crackle breccia”, composed by clasts of dimension >2mm, in percentage higher than 75%, separated by thin layers of cement or matrix, in a mosaic-like structure perfectly composed.

Because of objective difficulties in sampling the “coarse salt” for laboratory tests, the preliminary geotechnical characterization of the rock mass has been obtained comparing the following different approaches aimed to parameterize the “coarse salt” unit: i) using rock mass quality index and then “scaling” the laboratory parameters determined for the non-disturbed “Marmorino”; ii) deriving deformability parameters (dynamic ones and, by means of empirical correlation, static ones) from results of in situ seismic tests (cross-hole tests) performed both in good massif zones and in fault core zones; iii) back analysis stability considerations on pillars in the four exploitation existing levels using the empirical formula of Hedley, modified according to Gonzales-Nicieza ([18]) for estimating pillar strength.

4.4. The preliminary mine design

The geological and geotechnical characterization of the ore body represented the starting point to approach the mine design for the underground development of the “Marmorino” future exploitation. Consequently, it has been possible to identify the ore sectors where it would be interesting to pursue the mining activities, according to the ore reserve volumes and then the preliminary mine-design has been performed, evaluating the dimensions of the underground openings ensuring the structural stability. This complex logical path, focused to build a sustainable underground mine-plan, has been conditioned by many input factors like production needs or the imperative necessity to avoid contamination of the ore (to fulfill the elevated quality standards of the material for its commercialization), or to merge the interferences with the open pit evolution and the existing historical underground exploitation adits or drifts.

A stope and pillars mining method, involving the creation of 6x5 m production drifts (stopes) separated by 10 m thick pillars was finally proposed. A mechanical excavation technique using roadheader equipment was considered as the best solution to ensure productivity, limiting rock contamination and rock disturbance.

5. Conclusions

The growing industrial minerals demand, in the perspective of a sustainable development of mining activities, implies a strong orientation to underground operations in the near future. In complex geological areas, like the Valmadonna-Pedemonte "Marmorino" quarry, the definition of a reliable 3D ore body model has represented a methodological approach to improve geological and geotechnical model reliability in order to obtain a confident mineral deposit evaluation and, hence, a reliable mine design. These elements are key factors for the mine project sustainability.

The first step of this project concerned the characterization of the deposit that was based on detailed field and laboratory work focusing on geology and stratigraphy (facies and micro-facies analysis) coupled with the study of the structural elements affecting the rock mass. This allowed to re-define the ore body ("Marmorino") as white bioclastic limestones almost completely composed by rudist fragments and, secondary by echinoderms, gastropods and bivalves fragments, with spathic calcite. From the structural point of view the sector is characterized by an articulated convergence of tectonic structures developed in compressive and/or transpressive regime. In the study area, the Cenozoic evolution of the Southern Alpine Domain is expressed with a wide SE vergent anticline fold involving Jurassic and Cretaceous units. The fold interesting the ore body is an asymmetric fold with a partially reversed flank, resting on a series of medium-low angle plans. The most relevant brittle structures conditioning the ore body are the Caneva- Maniago thrust, and the Caorle-Montaner Lines/Caneva Lines. High angle faults sets were detected during site mapping. The new stratigraphic and structural data, integrated by selected boreholes drilled to verify the preliminary geological model interpretations, drove to the formulation of a reliable 3D ore body model showing new areas with a strong potential for underground exploitation. But a new challenge was there: approaching the geotechnical study of "Marmorino" the main issue concerned the presence of a geomechanical unit that for its exceptional whiteness and good excavatability has been named by miners as the "coarse salt" facies. The structural study allowed to understand that the "coarse salt" is related to preferential "deformation channels" along high angle fault core zones reducing part of the deposit into a "crackle breccia" in a mosaic-like structure perfectly composed. Because of objective difficulties in sampling the "coarse salt" for laboratory tests, the preliminary geotechnical characterization of the rock mass, has been obtained comparing different approaches aimed to parameterize the "coarse salt" unit in order to estimate pillar strength.

Finally, the ore body geological and geotechnical characteristics and the production requirements preliminary merged in a room and pillars mining method, involving the opening by mechanical excavation (roadheader) of production drifts (stopes) separated by pillars.

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