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The Carrara Marble: geology, geomechanics and quarrying

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Abstract. The industrial exploitation of the Carrara Marble dates back to I century B.C. with the Romans. After a black out in the Early Mediaeval age due to barbarian invasions, since XIII century the Carrara Marble has becoming more and more used for ornamental purposes and appreciated and requested worldwide. Geologically the Carrara Marble derives from a Tertiary polyphasic tectono-metamorphic deformation of an Early Jurassic epicontinental carbonate platform. That got rise to the diverse merceological types of the Carrara Marble, this and two neo-tectonic sub-vertical fracture systems, NNE-SSW and NW-SE trending respectively and grouped into bands irregularly spaced, control the geo-mining setting of the Carrara Marble. For centuries the Carrara Marble has been excavated only following the feeling the quarrymen had with the rock-mass, but the new cultivation technologies with diamond-wire cutting machines and saw-cutting chains, with big frontal-loaders and excavators, have greatly increased the production and require for a robust design based on reliable geomechanical data. Underground quarrying is increasing because technical and environmental concerns and asks for robust design and in situ stress determinations.

1. Carrara Marble exploitation

The excavation of the worldwide famous Carrara Marble (Tuscany, Italy) began with the Etruscan [1]; in I century B.C. it become an "industrial" activity with the Romans, thanks to Caesar who wanted its own quarries for counterbalance Lucullo who had quarries in Eubea Island and Pompeo who had quarries in Frigia [2]. The quarrying activity progressively underwent the supervision of the Emperor's staff, leaded by a *Praefector marmorii*, and executed directly by this staff, or by the colonies, or by private contractors. In the Luni quarries (Luni being the ancient Roman town marketing the Marble before the settlement of Carrara in Medieval age) 30,000 slaves were employed in the quarry works, plus free workers, security and administrative staff, the exploitation was under the directions of a *Probator* (geologist?) [2, 3, 4, 5].

The marble exploitation practically stopped with the fall of the Roma Empire, but then started again in the XIII century and increased during the Renaissance [6], when the Carrara Marble was used for most masterpieces, especially by Michelangelo Buonarroti who spent many times in Carrara for selecting the best graded marble for his sculptures. In these time quarriers were exploited by small family enterprises with a few workers. Carrara Marble exploitation gradually 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 amount of marble and to organize the exploitation itself.

In the whole Apuan Alps 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 Mining District.

Despite this drop in the number of active quarries, the production of raw blocks has been increasing; this trend implies fewer but much larger and industrialized quarries [2, 7, 8].

In this paper we explore the relationship that exploitation strategies and geostructural setting has have during centuries according to available technologies and man-power.

2. Geostructural and Geomechanical 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 terrains throughout the Northern Apennines orogenic belt [2, 9, 10].

The Carrara Marble is part of the Apuan Alps Metamorphic Core Complex; its protolith was an Early Liassic (Hettangian, 210÷200Ma) massive limestone of carbonate platform origin, with its own facies' organization from external ramp to internal lagoon, tidal flat, shore and tidal channels and emerged and karst areas, as today in the Persian Gulf [2].

During Tertiary (27 to 12Ma), it underwent to the deformation of the Northern Apennine orogenic belt; that resulted into polyphasic tectono-metamorphic deformation events (28 Ma to 12 Ma), which gave rise to a complex tectonic assemblage of the carbonate platform lithofacies, now transformed into marble types: white, statuary, veined, grey [2, 10].

The main elements of the mesoscopic tectonic fabric recognizable in the field in the Carrara Marble body (figure 1) are:

- the main tectono-metamorphic schistosity called *verso* by quarriers.
- two sets of sub-vertical anastomosing fractures, due to Neogenic uplifting and tectonic unloading, trending NNE-SSW and NW-SE and respectively called by quarriers *secondo* and *contro*. Fractures can be grouped into bands from a few meters to a few tens' meters wide, called *finimento* by quarrymen; these fracture bands are from a few tens of meters to one hundred of meters apart.

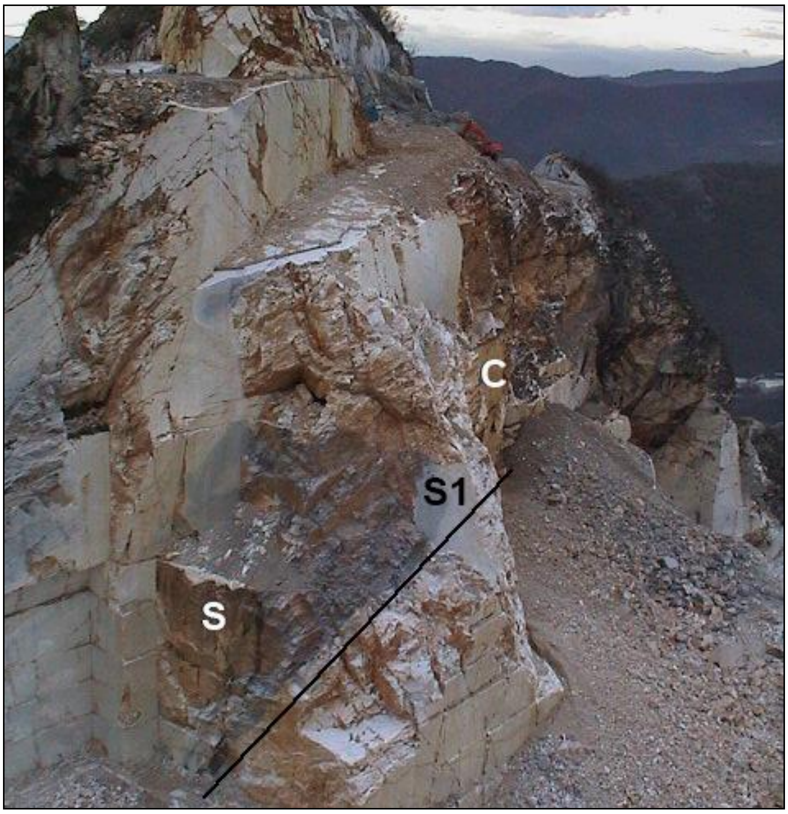

Figure 1. Reciprocal relationship among the *Verso* (S1) main schistosity and the two fracture systems: *Secondo* (S) and *Contro* (C).

Both the setting of the marble types and these structural features deeply affected the marble body and its excavability, merceological grade and blocks dimensioning.

3. Quarrying strategies

Quarrying strategies have been changed through the times according to the availability of man-power and of the instruments/machinery in use and consequently how it was possible to address the excavation to the marble rock-mass according to its fracturing state for exploiting the best grade marble types.

3.1 Roman Age

The Romans had a large availability of man-power, the excavation tools were the classic ones: pick, chisel, hammer, pole [11-15]; transport occurred by sledges and charts to the Luni harbour.

We have registered at least 23 Roman quarries in the Carrara District (figure 2); field survey allowed us to outline the excavation strategy in respect to the geostructural and geomechanics settings.

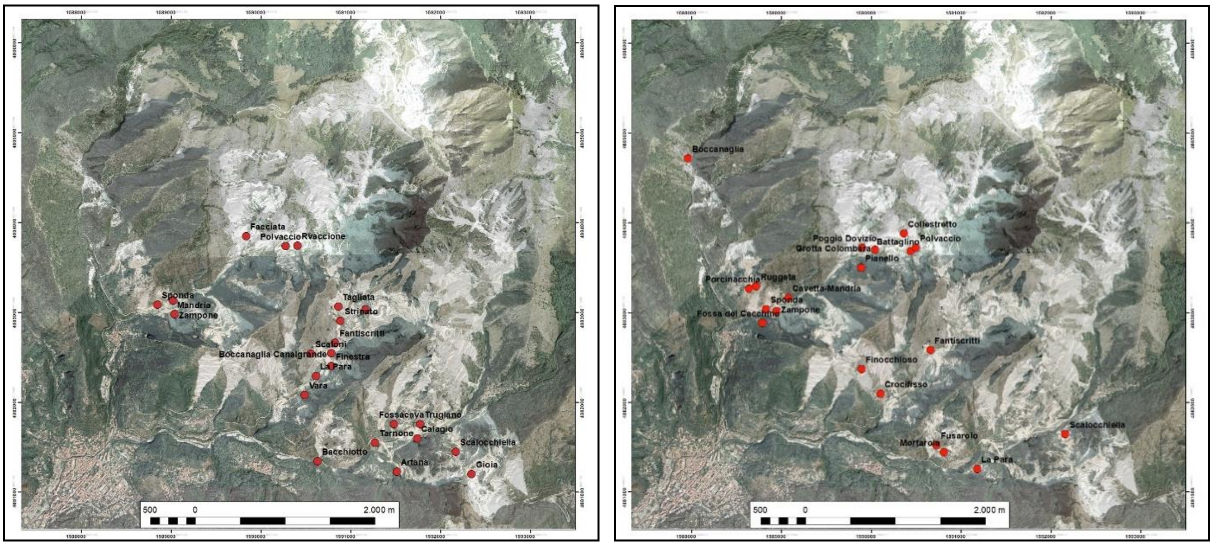

Figure 2. Location of the Roman (left) and Renaissance (right) quarries in the Carrara Marble District.

Thanks to the large number of workers the Romans can dismantling large slabs of marble where fractures were 1-2 m spaced by cutting the blocks from in between the fractures (figure 3), or directly cutting the intact marble where fractures were largely spaced in order to extract dimensional block up to 20-30 tons (figure 4). Romans were used to take blocks oriented laterally on the *secondo*, back on the *contro* by detaching along the *verso*, which is a plane of weakness (figures 3, 4).

After extraction blocks were squared, usually with the *verso* running straight in the blocks; in late Empire and in Byzantine age the *verso* was preferred running at 45° on the *secondo* cuts.

3.2 Renaissance Age to XIX century

The Carrara Marble cultivation started to grow up again in the XIII century, and in the Renaissance, at the time of Michelangelo Buonarroti in the XVI century, at least 20 quarries resulted active [16] (figure 2). Quarrying was a well-established activity in the hands of a few outstanding families and performed by teams of few skilled workers.

This aspect resulted into the need of using at the best the slabs that can be obtained by exploiting the zone with fractures meter-spaced in order to optimise the work/yield ratio. This procedure lasted until the late XIX century and is well-documented by the Salvioni's drawings [17] of 1810 (figure 5).

This modus operandi implied blocks were preferentially taken with the *verso* running at 45° on the *secondo* side of the block.

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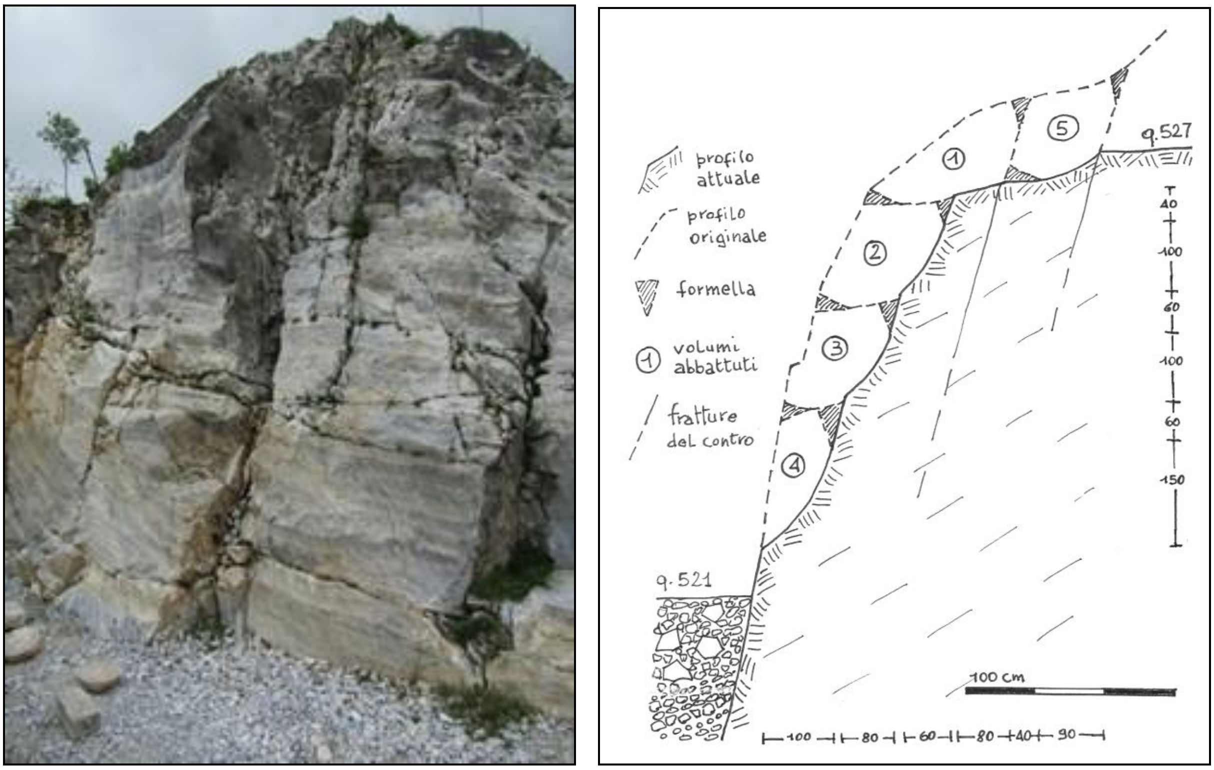

Figure 3. Roman cuts: left) vertical cut normal to main fractures; right) cuts sequences for obtaining blocks, named “froda” cultivation. Lines: dashed *verso*, subvertical *contro*, figure plane *secondo.*

Figure 4. Roman cuts: left – festooned cut (*caesura*) along the *contro* in large fracture spaced rock-mass; right – base tiled-cut in fractured rock along the *verso*.

3.3 Large deficient blasting

Since the late XVIII century to the first half of the XX century, it was also in use blasting for breaking down large amount of slope, from which debris obtain a few blocks to be sized at the right dimensions (figure 6). This method become in use because the increasing of the marked request and the scarcity of skilled workers.

Of course, this type of cultivation did not take into account the rock-mass setting, the important target was to obtain a large volume of debris from which collecting dimensional blocks.

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Figure 5. Renaissance cuts: quarrymen used meter-spaced fractures for obtaining slabs (left) or blocks (right).

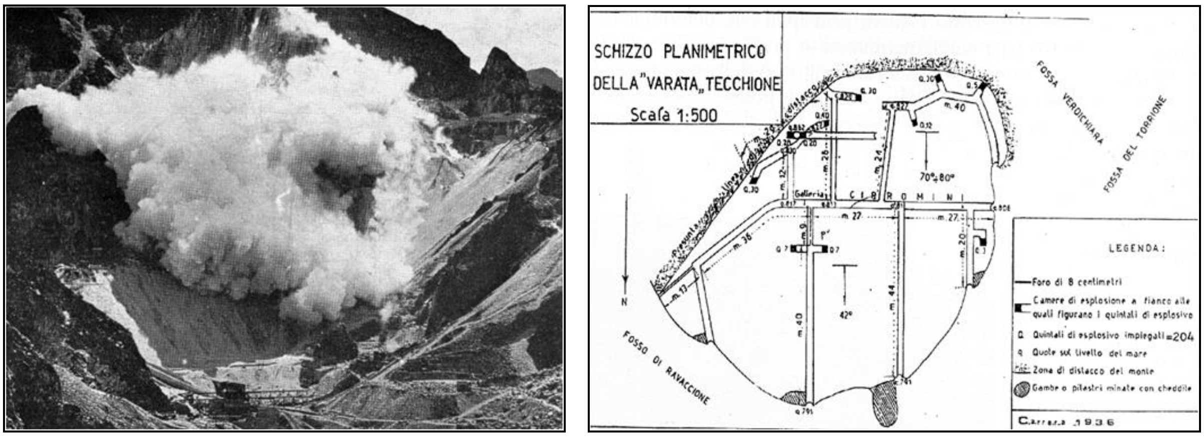

Figure 6. Year 1936 - left) large deficient blasting with black powder of a large portion of a slope; right) project of that blasting.

3.4 Late XIX century – XX century

In the late XIX century it was introduced in the marble cultivation the helicoidal wire, which consists of a strand of three iron wires wound in a helicoidal braid. The helicoidal wire was pressed against the marble and made to slide by a pulley, quartz sand was introduced into the cut and conveyed by the wire cut the marble, and water to remove sand and marble powder and cool (figure 7).

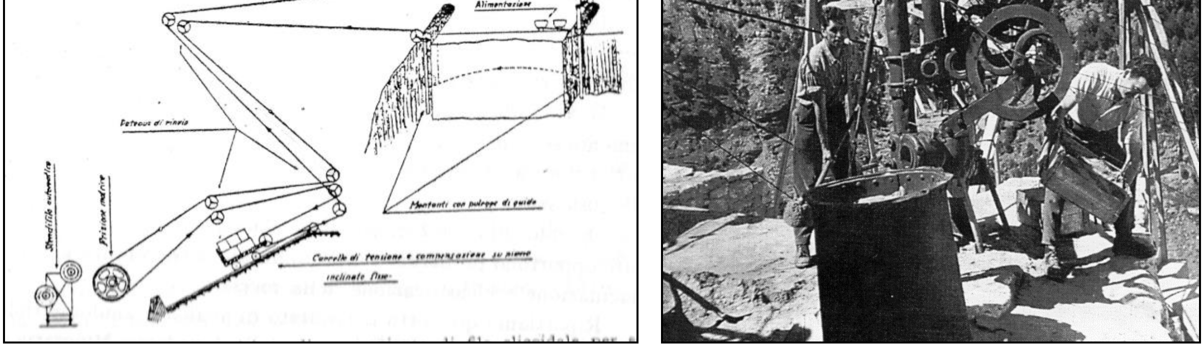

Figure 7. Helicoidal wire: left) design of a cut; right) pulleys, workers, bin of water and buckets of sand on a cut.

In order to be profitable, this type of cultivation required the execution of large cuts for removing big blocks of marble, to be subsequently cut at the right dimensions.

Therefore, the best cultivation can only occur where fractures are very largely spaced and there are large volume of intact marble rock-mass. But, in order to open corridors from where operate laterally at the back of large intact marble rock-mass, the bands of thin spaced fractures where manually dismantled.

Helicoidal wire technology asked for vertical and horizontal cuts, therefore blocks were taken with sides along the *contro*, *secondo* and horizontally, with the *verso* running at 45° on the *secondo* faces.

3.5 Late XX century – XXI century

In the 1980, the diamond-wire cutting machines and toothed chain saw were introduced in the marble cultivation; these two new cultivation technologies with big frontal-loaders and excavators, have greatly increased the quarry production up to the 1.5 Mt of the early 2000, now decreased to 1Mt.

This figure also resulted in the workers directly employed in the quarry, which decrease from about 3,500 in the 1950s to about 600 today. The active quarries decrease from about 330 in the 1950s to around 80 today (figure 8). These numbers imply a great increase of production from less but larger quarries thanks to technology and machineries improvements.

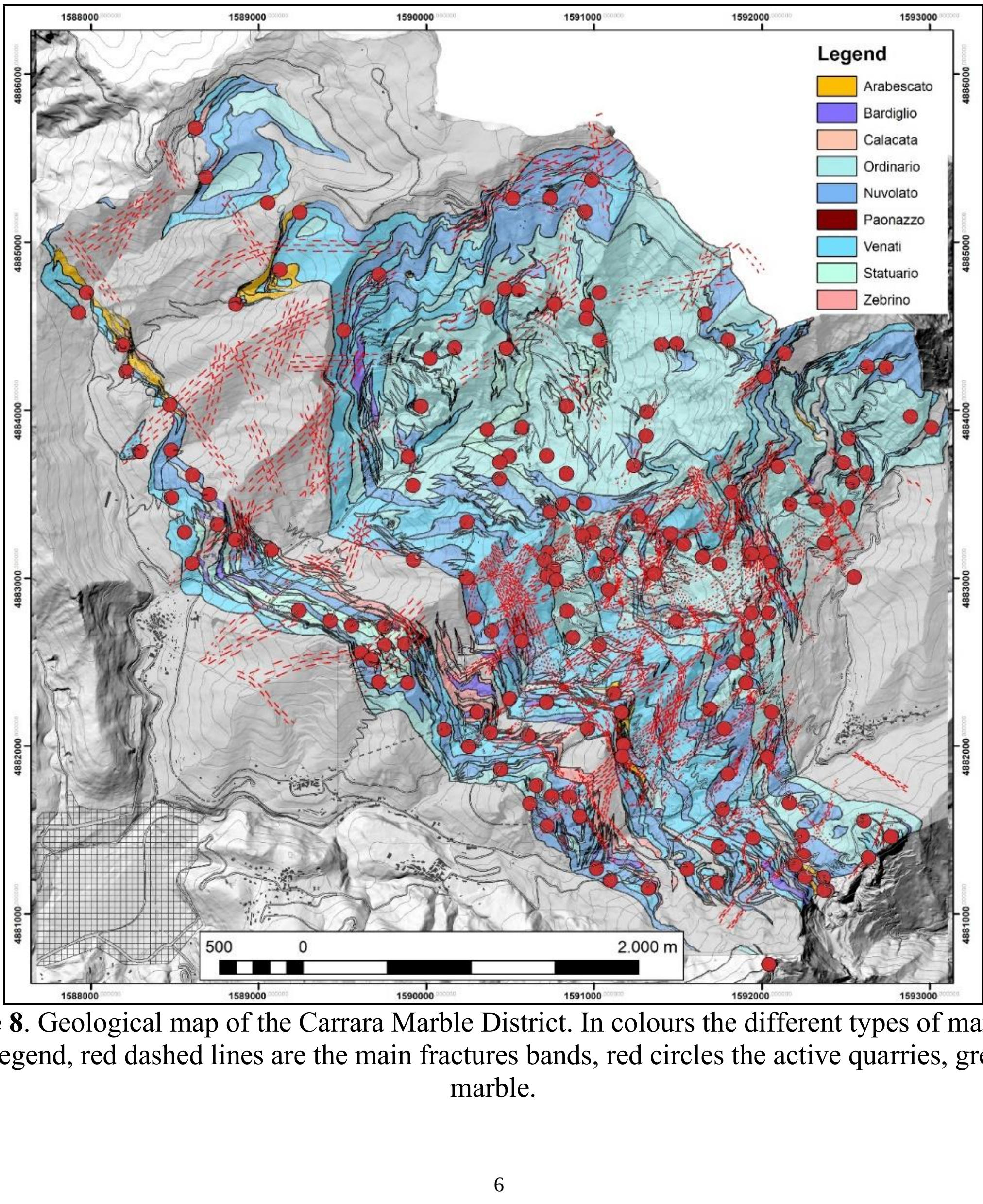

Figure 8. Geological map of the Carrara Marble District. In colours the different types of marble, as by Legend, red dashed lines are the main fractures bands, red circles the active quarries, grey no marble.

These present-day large productions overcome the feeling the quarrymen had with the marble and require for a robust design based on reliable geomechanical data; on more, underground quarrying is increasing because technical and environmental concerns and asks for robust design and in situ stress determinations. This and new concerns for safety and new specific laws have forced quarriers to apply to designers for up-to-date exploitation projects.

In turn, designers have been forced to develop geomechanical studies oriented to understand the geostructural setting, geomechanical properties and stability behaviour of the Carrara Marble. That led to correctly design safe large caverns (up to a few hundreds of a meter wide, and more than one hundred meters long and up to 80 m high) for mining the best graded Marble [2].

Therefore, geological maps of the several marbles types and of the trace of the main fractures and fracture bands are compulsory for a correct and safe quarrying design (figure 8).

Excavators can easily open corridor dismantling the bands of thin-spaced fractures so allowing diamond-wire cutting machines and toothed chain saw to cut ate the best the body of marble in between with only rare scattered fractures, so optimizing the mining yield (figure 9).

Figure 9. Left) diamond-wire cutting machine; right) battery of toothed chain saws.

These modern technologies can only profitable operating with vertical and horizontal cuts, therefore blocks are squared on the *secondo* and *contro* and horizontally, with the verso running at 45° on the secondo *sides*.

4. Final remarks

In this paper we addressed the development of the exploitation strategy for the Carrara Marble excavation that has been applying during centuries, from the Romans up today, in respect to the best exploitation in relation with manpower and available technologies and tools. Generally, we observe a best fit between the use of the technologies and the man-power in respect to the geostructural-geomechanical setting of the Carrara Marble rock-mass.

Every time schistosity attitude (*verso*), fracture bands (*secondo*, *contro*) and fracture spacing have been used at the best for optimizing the production of ornamental blocks, reducing workers fatigue.

In the last decades, when the production increasing overcome the possibility for the feeling of quarrymen to forecast the marble excavation, specified and detailed studies for the geostructural and geomechanical characterization of the Carrara Marble supply, supporting designers for safe and up-to-date designs, also avoiding rockburst occurrence (18,19).

We wish to remark the deep knowledge of the intrinsic Carrara Marble rock-mass setting that can be envisage in the exploitation strategies put on by the quarrymen through the centuries.

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