ORNAMENTAL STONES NETWORK

EUROPEAN COMMISSION
Competitive and Sustainable Growth Programme

QUARRYING SECTOR

OPTIMISING QUARRYING TECHNIQUES AND PRACTICES

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Forward

Quarrying is one of the most important stages in the production of ornamental and dimension stones as many critical parameters concerning the cost and the quality of the final stone product and defined at this stage. Moreover, due to the huge quantities extracted material and the big amounts of the waste material produced it is necessary to exploit the store reserves in a reasonable way in order to avoid the various environmental problems that may be encountered. On the other hand quarrying is a very difficult task including a lot of uncertain factors and in this respect stability and thus safe operation of the quarries is of at most importance.

This is the second volume of Quarrying Sector editions focusing on the optimisation of quarrying techniques and practices.

I am sure that with this contribution the readers will attain a complete view on all the important issues concerning both current practise and the most contemporary use of quarrying technologies.

Prof. I. Paspaliaris

OSNET Coordinator

Preface

The European Region, although poor in metalliferous and energy resources which could be economically exploited, is on the contrary rich in natural stone resources. Since many years ago, stone has represented in Europe a very important resource and, indeed, it has been part of Europe historic-artistic heritage, as its use as a construction material still characterises and adorns most of the buildings and public places throughout European cities. It is important to stress that many natural stones have today a "cultural" value: they may be considered as "classics", as they have been exploited since antiquity and they are an element of architectural heritage in many countries.

Dimension stone[1] quarrying is a very significant economical activity in Europe, as a source of wealth and employment. The production enterprises show great variations in size, level of industrialisation and technological application but mainly the sector is represented by very small enterprises: production units down to 500 m^3 of stone per year can still be viable. Stone products of excellent quality are obtained using both simple traditional tools and manpower or highly sophisticated machines. However, dimension stones generally have an international market, with a worldwide outlet, getting high unit prices, which can balance the high production costs typically faced by quarrying enterprises.

Despite its very long tradition, stone sector is a very dynamic industrial activity: it has been progressively modernised in order to meet more advanced extractive and processing technologies, thus contributing to higher levels of production and quality, and increasing competitiveness in stone markets. Furthermore, ornamental stones sector is important not only for the primary production of stone materials but also for the industries of stone processing, construction, and equipment manufacturing.

Worldwide stone production and usage are steadily rising, marking a 7% average growth during the last twenty years and reaching a total raw production of about 77 Mt in the 2002[2]. Europe still covers the 45% of the world stone production and shares the 35% of the stone consumption[3], keeping a leading role in this sector. Nevertheless, European stone quarrying industry has to face two important challenges: the increasingly higher competition from low labour cost countries such as China, India, Iran, and Brazil and on the other hand, rigid environmental regulations and restrictions.

Social concern to environmental aspects, steadily increasing in European Countries, has been leading to stricter regulations for many productive activities: among them, mining and quarrying sectors have been often criticised for their potential or realised impacts on land and environment. Actually, it can not be overlooked that an intensive quarrying activity is land "invasive" and causes a concentrated environmental pressure. Referring to dimension stone exploitation, quarries are often grouped in extractive basins, where

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[1] The terms ornamental stone, natural stone and dimensional stone are here used as synonymous.
[2] Napoli S. "Stone Sector 2002". Internazionale Marmi e Macchine, Carrara (MS - Italia), 2003.
[3] Montani C. "Stone 2002". Gruppo Editoriale Faenza Editrice, Faenza (RA - Italia), 2002.

the resource is localised with suitable quality and quantity: this fact has sometimes raised critical environmental situations. Although, very restrictive environmental protection policies have led to severe limitations of quarrying activity, the results do not seem to be completely positive in terms of sustainability: on one hand, closing-down stone quarrying activities imposes a shrinkage in local social and economical development; on the other, quarrying activity is moving to developing countries, environmentally un-protected, simply to put off the problem for the near future.

Stone sector demand for a sustainable balance between social-economical productive needs and environmental protection points out the problem of the sustainable development: *"reconciling the need for more secure and less polluting extractive activities while maintaining the competitiveness of the industry"*[4]. The target is quite complex but, of course, challenging for the development of new solutions, which should incorporate effective legal frameworks, suitable technologies and careful planning.

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[4] Communication from the Commission. "Promoting sustainable development in the EU non-energy extractive industry". COM (2000) 265.

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1

Quarrying methods and cutting techniques

MARILENA CARDU, ENRICO LOVERA

The morphological and geological variability of stone deposits and the natural differentiation of the materials physical characteristics, from one site to another, is the reason for the huge spectrum of quarry types that can be found, even within the same geographical area. As a result, there is an extremely wide range of technical solutions developed and adopted for stone quarrying, which often reflect traditions and experiences matured in specific situations. In the last years, evolution and adaptation of new quarrying technologies has been considerable, even if today, still some "underdeveloped" situations exist next to fully mechanised quarries, where the lack of technical development not only does affect productivity, but it has severe impacts on the environment and creates insufficient safety conditions.

Quick technological evolution and constantly changing market orientations (in other words fashion) create a "dynamic" aspect of the stone deposit concept: in fact, the combination of the market demand for a given material with the technical possibility of economically extracting it, is able in a short time, to "transform" a simple stone deposit to a valuable reserve. It is important however, to point out some general issues of dimension stones exploitation, which have to be considered when such an activity is planned. These are given in the following points, focusing on those aspects strictly connected to the object of exploitation and to the area in which the activity is carried out:

- variability of lithotypes of potential extractive interest is very wide and mostly connected to the inconstant demands of markets;

- materials are often chosen for the intrinsic “ornamental” value, with sale prices typically about hundreds of €/m^3, in relationship to the real quality of the stone;
- productions are relatively limited, generally at the order of magnitude of thousands of m^3/year of “marketable” material per quarry;
- the ratio between “marketable” material obtained and total material extracted is low, which means that considerable quantities of waste are produced during the exploitation process;
- the position of stone deposits is usually characterised by great difficulties of connection with the transportation network;
- geo-morphological conditions of the quarry are usually “irregular” – as far as geometry, structure, position, etc. are concerned – therefore with different and case specific operational difficulties;
- quarry types are very different concerning production levels, availability of accesses, natural exposure and elevation; therefore, some quarries are operational only on specific seasons of the year and present different opportunities of environmental rehabilitation;
- business sizes are rather inhomogeneous, with a lot of quarries being almost family business, while other quarrying units are more complex and industrially organised, which process the raw material (blocks) exclusively to their own modern processing plants.

The factors that have a direct influence on the management of stone quarries are manifold and interdependent, affecting at the same time the choice of type, method and technology for the exploitation (Table 1).

Table 1. Primary factors which influence management choices for stone quarries.

Factor	Influenced choice
Geography and local morphology	Accessibility, layout of roads, location of the dumps, water control, etc…
Geometry of the rock body (predominantly horizontal or vertical development)	Height of the faces, internal viability, hauling systems, etc…
Uniformity of the rock body	Selectivity of the method, dimension of primary detachment etc…
Structural anisotropy (visible or hidden)	Orientation of cuts
Hardness and abrasiveness of the material	Quarrying technology (mechanical cutting or explosive)

Firstly, the geographical position of the deposit and the local morphology affect the logistics of the quarrying activity, as, for example, the connections to the processing centres or to the principal accesses of transportation. Furthermore, the geometric properties of the deposit, in relationship to the morphology of the land, may condition the type of quarrying and partially the permissible methods of exploitation, sometimes determining some technical problems and additional costs, such as, for instance, the accessibility of the stopes, the location of the dumps, the water management, etc.

On the contrary, the structural characteristics of the deposit and the physical-mechanics properties of the rock have a great importance in the choice of methods and technologies for cutting. Schistosity or stratification, according to the genesis of the rock, may condition the method of exploitation, while the fractures (together with the hardness and abrasiveness of the rock) affect the selection of technologies and the orientation and dimension of cutting.

Finally, the quality state of the deposit – i.e. the spatial distribution of the textural and chromatic characteristics, besides the possible "defects" and alterations of the rock – imposes the adoption of methods and techniques that will allow good selectivity, limiting the production of waste.

It is evident that the characteristics of the deposit affect the choice of the exploitation methods and technologies; the rational organisation of production and, as a consequence, the mining recovery, the block yield and finally the general "performance" of the quarrying activity, depend on these factors. In the current technical use, the term "recovery" often refers to rather different concepts; therefore, it could be useful to specify that the term "mining recovery" indicates the ratio between the volume of extracted stone and the volume of material available in the exploited deposit.

On the contrary, the term "block yield" or "quarrying yield" indicates the ratio between the marketable volumes obtained and the total volume of the bench originally extracted. The product of the ratios can be consequently considered as "performance" of the quarrying.

$$\begin{array}{ccccc} \dfrac{\text{volume of extracted rock}}{\text{volume of available rock}} & \cdot & \dfrac{\text{volume of marketable rock}}{\text{volume of extracted rock}} & = & \dfrac{\text{volume of marketable rock}}{\text{volume of available rock}} \\ \uparrow & & \uparrow & & \uparrow \\ \textit{Mining recovery} < 1 & & \textit{Block yield} < 1 & \rightarrow & \textit{performance} \ll 1 \end{array}$$

Further and not negligible losses of material are then attributed to the different phases of the following processing (e.g. sawing in slabs of various thicknesses, clipping in modular or custom elements, etc). A reduced mining recovery is usually due to the necessity of leaving on the spot some material potentially usable but that can't be extracted, because its needed to assure the geotechnical stability, global and local, of the pits, either open-cast or underground (e.g. pillars to support voids); especially in the underground case, the necessity of rock structures that guarantee the self stability of the stopes may limit recovery to 60%. The size of these structures is in relation to the geomechanical strength of the materials and to the entities of the acting lithostatic loads.

Bench yield – besides the geo-structural conditions of rock – depends on the production process used for the primary extraction, the volume management and the squaring cuts for the production of commercial elements. In any case, operative possibilities are manifold, with different productivities both in quantitative and qualitative terms. Hence, a correct technical/economical analysis of the quarrying activity can not avoid considering all the aspects of the production problem; indeed, it is always necessary to consider operational safety, in order to limit the worker's exposure to potentially risky situations, pursue the "certainty of effect" for the workings and, sometimes, choose quarrying methods which involve higher costs but higher safety conditions.

Nevertheless, from the point of view of profitability, it has to be said that not always the business optimum, specifically in the stone sector, corresponds to the technically possible highest production. Furthermore, during both planning and management phases of a quarrying project which aims to an integral exploitation of the stone resources compatible with the environment, it is more and more realistic to seek for those conditions that will make a large part of the extracted material, previously characterised as unusable for ornamental purposes, suitable for promotion to other productive sectors, as “secondary” raw material.

The most important factors to be considered for rational planning and management of a quarrying activity for dimension stones are presented in Figure 1, underlining the interconnections among the different phases. Nevertheless, geo-mining exploration, exploitation and rehabilitation, processing and commercial use of the dimension stones should be viewed as one and not as several different aspects, as demonstrated in some of the most important productive activities in Europe.

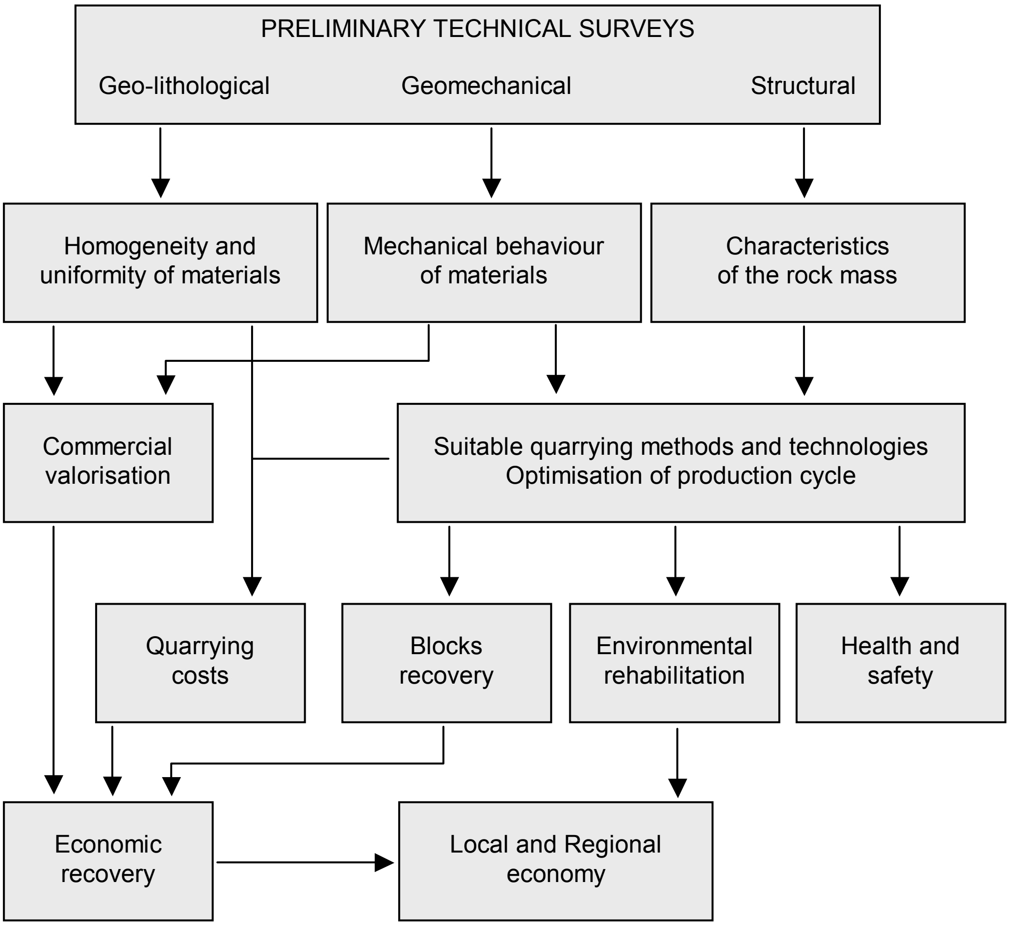


Figure 1. The most important factors to be considered for rational management and planning of a quarrying activity for dimension stones.

1.1. Quarrying methods

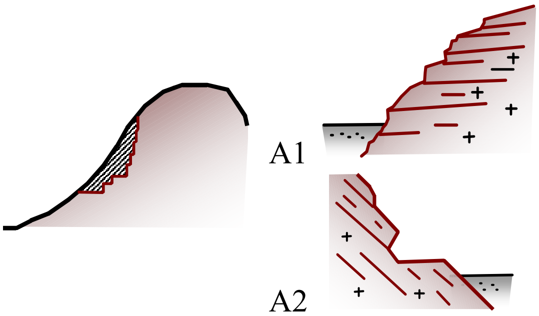
Dimension stone quarry layouts differentiate according to the geological and morphological conditions of the site and the particular production demands. However, it is useful to set the specific characteristics of every single quarrying case in a wider classification, in order to develop more general considerations on the problem of the stone quarrying optimisation (Table 2).

The first classification category refers to the fact that dimension stones can be exploited opencast (surface mining) or underground. Where stone deposits are near the surface with little or unaltered overburden, the development of opencast activity is evidently the simplest and the most immediate method of exploitation. The option for underground exploitation, imposed in the past by the technical-economical difficulties of removing thick overburdens, is nowadays a choice that may be introduced and sustained by different operational situations.

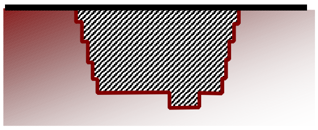
Table 2. Possible quarry layouts and methods of exploitation

Quarry types

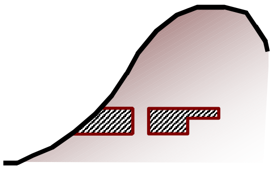
A) Surface hillside
A1) Horizontal slicing: in massive isotropic bodies or bodies with horizontal weak planes.
A2) Inclined slicing: in bodies with inclined weak planes (gravity is exploited to ease blocks removal).



B) Surface, pit
In flat land: descending horizontal slicing, below ground level.



C) Underground, room and pillars
C1) Front attack: blocks are taken from the front wall of the room.
C2) Descending slices: the stope is opened at the top and the body is then exploited by descending slices (often it's an evolution of C1)



Extraction methods

I – Cutting: blocks are separated by means of kerfs.
I1 – diamond wire
I2 – chain saw (or belt, or disc) cutters
I3 – flame jet
I4 – water jet
II – Splitting: blocks are separated by fractures, induced in pre-determined planes.
II1 – explosive (cord, black powder)
II2 – hammer and feather, wedging
III – Cautious blasting: blasting with small breakage, suitable pieces are selected from the muck.

Main products

a – Commercial block: 2 to 5 m^3, scarcely larger, to be processed in a different place.
b – Natural slabs: mainly obtained at the quarry site.
c – Shaped pieces: kerbstones, paving dices, building blocks, “opus incertum” lining, tiles and so on.

In fact, an underground exploitation often proves itself as the evolution of preceding opencast activities, motivated by different factors: unfavourable morphological conditions that will not allow further opencast quarrying operation, necessity of greater selectivity in the exploitation and consequent seeking for better production performances, possibility to reduce impacts to the landscape, etc. On the other hand, the disadvantages of underground exploitation may be related to the need for greater economic (at least in the initial phases) and technical (mostly the control of the voids stability) investments. Furthermore, strong technological (and consequently economic) limitations still exist for the underground excavation of hard and abrasive rocks.

A further distinction between quarrying methods is based on the morphological context in which the quarry is located, considering a “mountainous” area or a flat one. Hillside quarries are generally very visible, either because of their morphology or their position is on a higher altitude than the surroundings. Another characteristic of hillside quarries is the general difficulty of access, which requires the construction of haul roads and associated embankments or ramps, sometimes very difficult to construct and usually with great impact to the visual pollution of the area. Operative spaces can be very small so the disposal of stone wastes could be a problem for this kind of quarry. Among the possible configurations – piedmont, hillside, or top of the mountain – the latter is the least frequent nowadays, since several national administrations have set strong obstacles for the authorisation of this type of quarrying, which involves permanent modifications to the skyline, with notable and hardly reversible visual impacts.

Regarding flat land quarries, the principal problem is a possible disturbance of groundwater. In this case, apart potential pollution problems, water has to be continuously pumped out of the bottom of the pit. This operation is possible (with high energy costs) during the operation of the quarry, but it is not possible at the end of the exploitation. Concerning the visual impact, it is less noticeable in flat land quarries, and can often be corrected with a suitable natural screen (e.g. planted and/or seeded earth mounds).

Dimension stone quarries, despite their obvious differences depending to their location and layout, present some common elements or structures:

- high vertical stopes, often divided in benches, either for work organisation and crew protection reasons or for geomechanical stability;
- sub-horizontal floors, where materials are handled and sometimes initially processed, permanently made accessible with quarry roads and connected to the active levels through temporary ramps;
- dumps of debris, located in the quarry context or next to it and of temporary or permanent character;
- various constructions: storage areas, hovels for machinery, offices, service systems buildings (electricity, compressed air, tanks, etc.).

In opencast quarrying, a reference is frequently made to two different exploitation methods: “descending horizontal slices” or “ascending vertical slices”. The definition of the method should be adapted to the structural shape of the deposit (Figure 2). In general, “absolute” horizontality or verticality of the production levels can not be achieved when the deposit is characterised by inclined natural structures (layers, stratifications, etc.). An exploitation method by slices is presented at Figures 3 and 4.

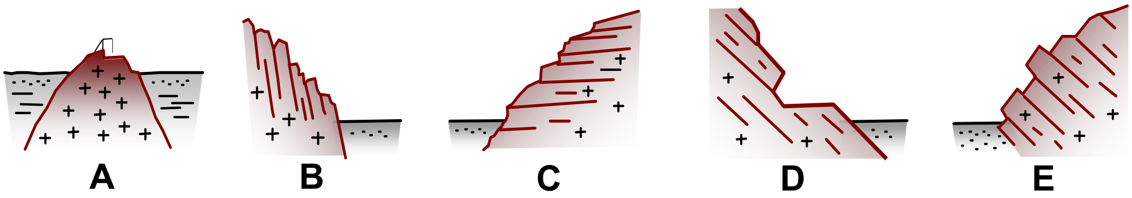


Figure 2. Different possible deposit sets, which influence the exploitation methods. A: plutonic outcrop; B: sub-vertical schistosity or stratification: sub-horizontal schistosity or stratification; D: down-dipping schistosity or stratification; E: up-dipping schistosity or stratification.

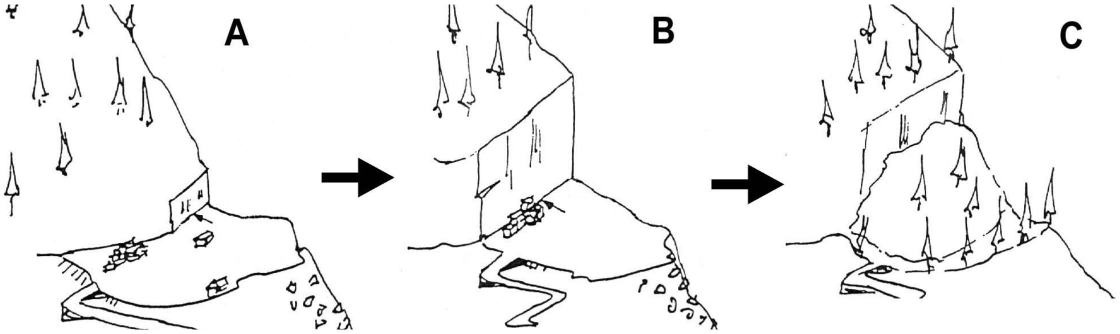


Figure 3. Exploitation by descending vertical slices (G. Zoppo).

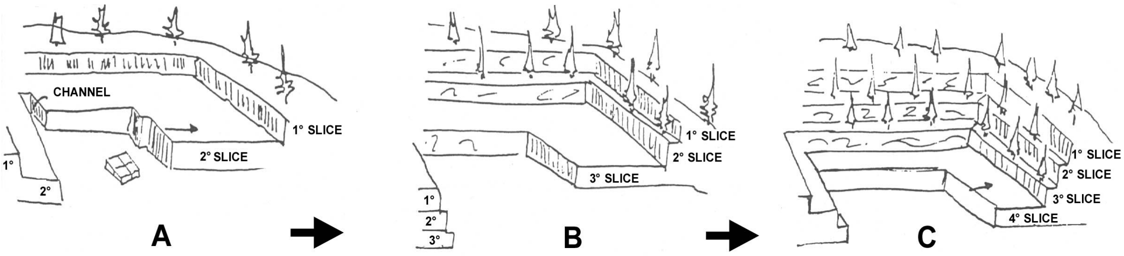


Figure 4. Exploitation by horizontal descending slices (idem).

Exploitation through a sequence of "vertical slices" which are progressively excavated by large banks, taken in "descending" order, is presented in Figure 5-1; every bank, with a volume of about thousand cubic meters, is split on the quarry floor, on a suitable "debris bed". Such stone mass is then divided in "benches", having a volume of about a hundred cubic meters and is subsequently cut in blocks of commercial dimensions, with a maximum volume of about ten meters cubes.

Quarry exploitation by horizontal slices is presented in Figure 5-2; a horizontal slice is excavated through a sequence of tiled banks on the same level; every bank, with volume bigger than a thousand cubic meters, is detached from the hillside and subsequently divided in benches, which are then overturned and cut in commercial volumes. A variation of this method is when high benches are detached directly from the slice (Figure 5-3). The horizontal slices are included between two "levels", whose difference of altitude corresponds to the obtainable heights of the benches (the method is usually called "high benches" exploitation).

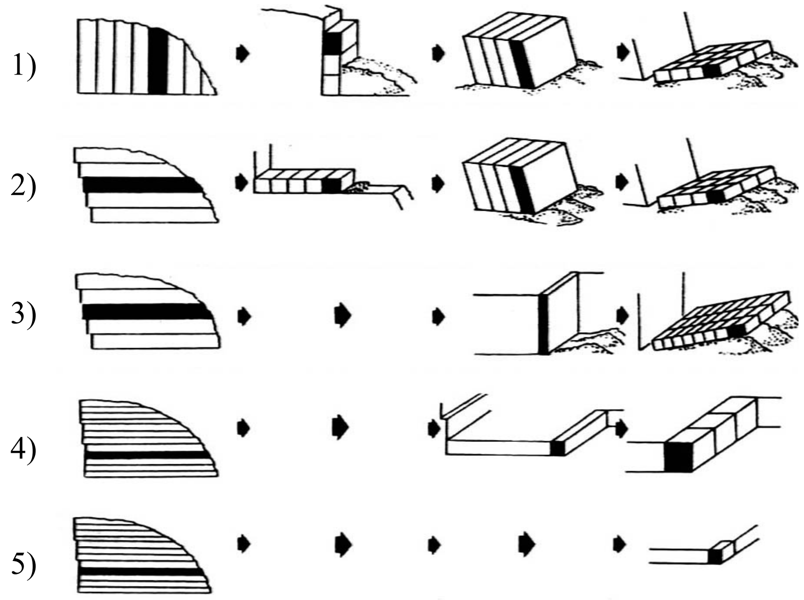


Figure 5. Different exploitation methods by slices (M. Pinzari).

Sometimes – as in the case of sedimentary deposits where the layers are quite thin, or in the case of massive magmatic rocks where there exists sub-tabular morphology and continuous and regular sub-horizontal discontinuity – "low step" exploitation can be adopted: the height of the benches corresponds to one of the commercial block's dimension (Figure 5-4 and 5-5). A low step exploitation fits to rocks with good uniformity and homogeneity and, above all, with little fracturation, in comparison to a high bench exploitation. In the low step case, in order to extract the same volume of rock, a bigger number of cuts is required and the choice could prove to be un-economic if a further selection of the excavated material is necessary, due to fractures, with consequent production of waste.

In the case of high bench exploitation, splitting great portions of rock allows reducing unitary cutting costs by sharing them to a greater volume, and inspecting wider surfaces after overturning (that obviously requires ample working spaces), thus isolating the most defective parts and optimising the block yield. On the other hand, a low step configuration corresponds to a safer and more manageable quarry layout, during both phases of operation and rehabilitation of the site, and allows, from a technological point of view, to use less "binding" machinery.

As far as underground exploitation methods are concerned, some outlines are given related to the most often cases of European quarries, particularly considering the exploitation of marble and slates. The most recent advances in this field will be examined thoroughly in Chapter 3. Generally, underground exploitation of dimension stones foresees the development of voids whose dimensions should allow the access and managing of machineries of standard dimensions. In order to guarantee the global stability of the structure, pillars or diaphragms of stone are left in place, designed basically on the geo-structural and mechanical characteristics of the material.

The underground exploitation method that sometimes develops in a single room, or more often, in succession of rooms and pillars, is usually referred as the "rooms and pillars" configuration. Pillars have either square or rectangular base and are left intact to support the stability of the roof. On the contrary, when the pillars are longitudinal, the exploitation is defined as "rooms and diaphragms (or rib pillars)". Thus, it is not as much a matter of different methods of exploitation, as a matter of different quarry configurations in accordance with the deposit characteristics.

In case of underground marble quarries, the exploitation starts with a first tunnel of access, usually excavated in the face of a pre-existing opencast quarry. In most cases, the opening proceeds from above to below, creating an "upper-void" which corresponds to the level of the roof of the future room and then proceeds through further widening and lowering: once a void of suitable size is created, it is possible to proceed with a production method entirely analogous to opencast exploitations, through descending horizontal slices (Figure 6). The voids must be planned in such a way to create the necessary spaces for the movement of equipment and the handling of excavated material.

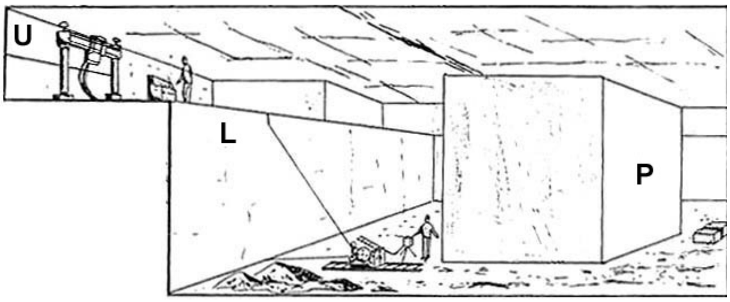


Figure 6. Underground marble quarry: development of a wide room by the "high bench" exploitation method. **U**: upper-void (chain cutter), **L**: lower cut (diamond wire cutter), **P**: pillar.

Several slate quarries are exploited underground with the rooms and pillars method. The geo-structural characteristics of slate deposits usually impose that the exploitation will start from above – e.g. from the contact with the host rock – and continuing by descending horizontal slices, until the bed-rock contact. The upper excavation of the bank, preferably in non commercial slate, may be carried out in different ways: in some quarries a chain cutter is used, freeing the usable underlying slate through a pre-cut; the demolition of the barren layer may occur through explosive or, whereas possible, by big hammers (Figure 7).

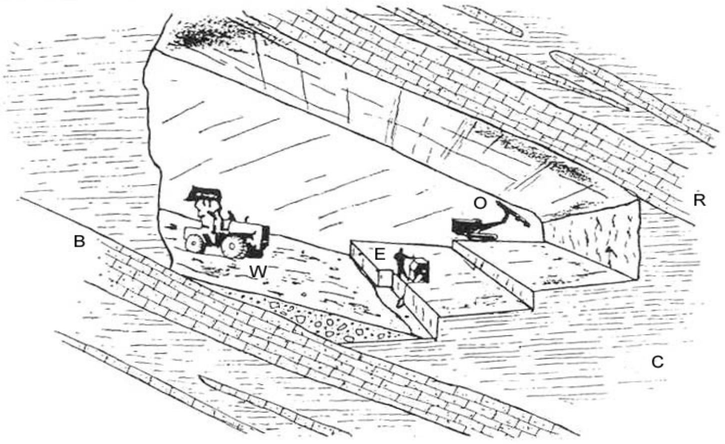


Figure 7. Underground slate quarry exploited by "descending slices" method, with wide voids and tilted benches. **O**: opening by explosive; **E**: exploitation by chain cutter; **W**: filling by waste rock; **R**: roof; **B**: bed of the bank; **C**: slate cleavage.

1.2. Cutting technologies

Cutting technologies include all the machinery, equipment and systems employed for the extraction and sectioning of stone blocks during the exploitation of a deposit.

If a quarrying method is seen like the “strategy” that will create a good mining recovery, with an acceptable visual impact during the quarry exploitation and an optimal final environmental rehabilitation of the site, then the cutting technology represents the “tactics” to choose, by selecting the most suitable equipment – for efficiency and safety – among those available.

In other terms, technologies may be selected in accordance with the material to be quarried, the capabilities of the personnel, the environmental surroundings and logistics bonds, the business choices and, obviously, the method of exploitation. In this paragraph the principles of operation, the main technical characteristics, and the range of employment and performances of the machineries widely employed in the quarries, will be illustrated.

The primary purpose of a dimension stone exploitation – unlike other quarrying activities – is to produce commercial blocks, that is, portions of sound rock with parallelepiped shape, with a volume generally varying between 2 and 15 m^3, proper for further processing (mainly finalised to slabs or other architectural elements). However, it should be stressed that some dimension stones (e.g., some quartzite, slates, porphyries, etc.), can not be extracted in form of blocks, but directly as slab-shaped elements.

The objective of a cutting technique is to create split surfaces, facing a reasonable cost and, in any case, without damaging the rock. After the removal of overburden rocks covering the deposit, the production cycle of a stone quarry may generally be outlined in four operational phases:

- primary cut
- overturning of the bench
- squaring in blocks
- material handling

In some quarries, according to the deposit characteristics (e.g. stratified deposits), the first three phases could be reduced to just one, when the blocks are directly extracted in their final dimension.

Technological progress (Table 3) for dimension stone quarrying has made available a lot of options for performing the different operational phases in a safe and productive way, allowing for various choices according to the typology and the size of quarries, the mineralogical, petrographic and structural characteristics of the rock and, last but not the least, the assets of the enterprises.

Every phase of the production cycle is characterised by the use of specific technologies, which subsequently differ from one another, according to the type of material under exploitation (Table 4). The applicability of a technology is fundamentally connected to the abrasiveness of the rock and, therefore, to the presence of silica in crystalline form (quartz). As a consequence, the following traditional classification of ornamental stones can be used as a reference:

- “marbles”: compact natural stone, mainly consisting of minerals with hardness between 3 and 4 on the Mohs scale (carbonates), hence definable as “soft”, e.g. metamorphic marbles, limestones, dolomites, travertines, serpentinites, etc.;

- "granites": compact natural stone, mainly consisting of minerals with hardness between 5 and 7 on the Mohs scale (quartz and feldspar), generally definable as "hard", e.g. granites, gneisses, porphyries, etc.

Table 3. Principal steps of technical evolution in the exploitation of dimension stones, with main regard to the Italian case.

I sec. B.C. - middle of XVII sec.	Manual excavation by "cesurae". Use of simple tools: clubs, chipping chisels, drills, etc… Transport through sloping planes and wagons hauled by animals.
XVIII sec. until middle of 1900	Introduction of exploding substances. Blasting of huge portions of material through massive employment of explosive (black powder).
Second half of 1700	Introduction of first steam machines. Use of steam pumps for water pumping and first sawing plants moved by hydraulic wheels.
1854	Introduction of the "sand wire" in Belgium.
1855	Development of the first pneumatic drill (Sommelier).
1861	First operative pneumatic drill (railway tunnel of Frejus).
1876 - 1890	Construction of the marble railroad of Carrara.
1897	Development of the "penetration pulley" Monticolo for the execution of blind cuts by helicoidal wire.
1960 - 1970	Introduction of trucks for transport operations.
1964	Abandonment of the marble railroad of Carrara
1965	First experiences through chain saws in Belgium, on marbles.
End of the '60s	Progressive advent of the hydraulic drilling.
'70s	Use of water-jet in the exploitation of coal and soft rocks in Germany.
1970 - 1980	Introduction and success of diamond wire cutting technology with electroplated beads and chain saw with widia tools in marble quarries (Carrara).
1978	Use of hydraulic rock breakers and expansive mortars in Japan.
1978 – 1980	First applications of the high pressure water-jet on granite.
'80s	Massive introduction of wheeled loaders.
1980	Introduction of first diamond wires with sintered beads.
1986	Introduction of diamond wire cutters in granite quarries.
Middle of the '90s	Introduction of the diamond belt cutter.
'90s	Consolidation of the employment of hydraulic drilling and use of the hydraulic excavators in stone quarries.
Beginnings of 2000	Spread of diamond wire cutters, with sintered beads, in granite quarries.

Such subdivision is mainly based on the different hardness of the principal minerals that constitute the stone, and it does not refer to a strict mineralogical and/or petrographic meaning. It is an empirical subdivision, but with an evident importance from a technological point of view, so that the technical-economical possibility of using the chain saw can be used as discriminating means between hard and soft stones. The main technologies and equipments employed in the different phases of dimension stone exploitation are illustrated in Table 4 and described in the following paragraphs, with a particular reference to the performances, advantages and disadvantages of the more commonly used and promising techniques, with respect to both quarrying productivity and environmental and safety aspects.

Table 4. List of principal technologies currently in use, related to different phases of the productive cycle and according to the stone to be quarried.

	Marbles	**Granites**
Primary cut	– Diamond wire cutter – Chain cutter – Diamond belt cutter – Disk cutter – Discontinuous drilling + explosive – Discontinuous drilling + wedges – Line drilling	– Discontinuous drilling + explosive – Discontinuous drilling + wedges – Line drilling – Diamond wire cutter – Flame-jet – Water-jet
Overturning of the bench	– Retracting cushions – Oil-pressure jacks – Hydraulic excavators – Fixed winches	
Squaring	– Diamond wire cutter – Diamond wire saw – Single blade gang saw – Chain cutter frame – Drilling + wedges – Drilling + expansive mortars	– Drilling + explosive – Drilling + wedges – Drilling + expansive mortars – Diamond wire saw
Handling	– Wheeled hydraulic loaders – Tracked hydraulic loaders – Tracked hydraulic excavator – Derrick crane	
Additional machineries	– Pressers – Self moving drilling wagons – Drilling dust aspirators – Pumps – Electric generator – Mobile cranes	

1.2.1. Diamond wire cutter

The introduction of diamond wire cutters has profoundly modified the way of working in stone quarries, allowing for very high productivity and improving aspects of health and – with the right precautions – safety at work. Cutting by diamond wire is the most widely spread technology nowadays in quarries of “soft” stones. On the contrary, in “hard” stones quarries, some problems mainly related to the abrasiveness of the materials to be cut are delaying the adoption of this technology.

The "standard" application of the cutting wire requires the creation of a loop of wire running at high speed, always cooled by water. Stone is cut progressively by the creation of an increasingly deeper slit (Figure 8). The realisation of the loop requires preliminary drilling of two intersecting holes, positioned along the edges of the rock portion to be extracted. The wire is inserted into this path and then it is closed as a ring and positioned around the external edge of the driving flywheel of the machine. During the cut the machine moves backwards, usually running on tracks, therefore maintaining the wire in continuous tension and in contact to the rock, thus producing a cut through progressive abrasion with the rock mass (Figure 9). The cutter is able to operate in various angles, simply by tilting the flywheel (Figure 10).

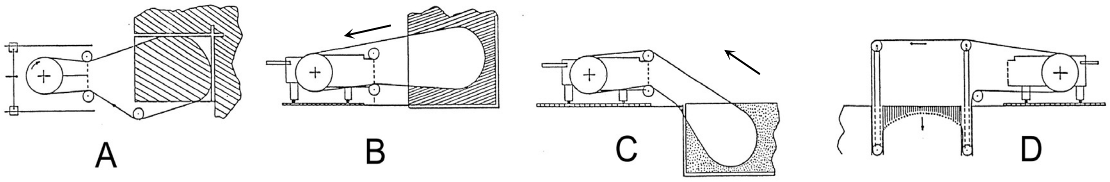


Figure 8. Different configuration of diamond wire cutting: A – horizontal cutting; B – vertical cutting through "descending" loop; C – vertical cutting through "ascending" loop; D – blind cut through "reversed catenary" arrangement.

The machine is an electromechanical unit automatically controlled, whose power is between 18 kW and 56 kW, and up to 90 kW in case of a Diesel fuelled motor. The most advanced types have an electronic device ("inverter") able to vary the speed of the wire in the different phases of the cut, according the wear degree of the beads: a real time electronic control of the tensioning applied to the wire is adopted, in order to maximize the productivity/wear ratio of the tool.

The principal components of the wire cutter are presented in Figure 10:

- *the flywheel-motor unit*, constituted by an electric motor connected to an aluminium flywheel (diameter 550 to 1020 mm). For safety reasons, the flywheel-motor set is equipped with a protection carter against the possible projection of beads in case of accident. Likewise, the whole run of the wire is often covered by a rubber or teflon belt (about 40 cm wide and up to 20 m long) positioned above the wire at a distance of about 50 cm. In order to increase the force transmitted by the flywheel to the wire, sometimes two idle pulleys of aluminium (diameter 300 mm) are positioned near the motor flywheel to provide a better grip of the wire;
- *the control panel*, is kept separated from the machine and connected to the electric panel through a 10-15 m long cable, in order to allow the operator to place himself in a safe position during the cutting operation;

The cutting element is the diamond wire itself, which has passed through various stages of evolution and improvement. In its "classical" structure, it is composed by a cable of galvanized steel, 5 mm in diameter, which is formed by many strands of ultra-flexible steel; the cable has to carry the diamond beads and to sustain the static and dynamic stresses. The *diamond beads* are uniformly distributed along the wire, in varying numbers according to different stone types; 28-34 per meter in "marble" wires and 32-40 in "granite" wires. More details about the characteristics of the beads will be given in the following.

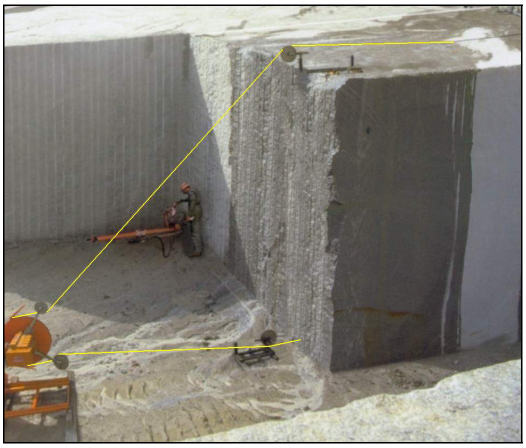


Figure 9. Cutting by diamond wire with traditional "descending loop".

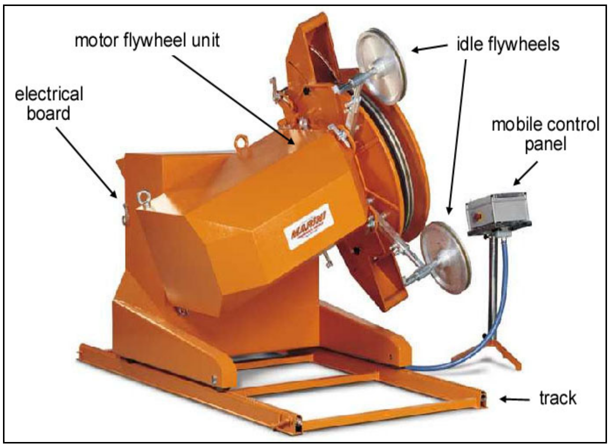


Figure 10. Diamond wire cutter, with indication of the main components (MARINI).

Besides the cutting tools, the diamond wire also includes a series of elements with different functions:

- *springs:* spiral-shaped, elastic, ultra-flexible steel elements, 8 mm in external diameter, interposed to the beads; their purpose is, beyond the protection of the wire, to perform a certain shock absorption of bumps and variations of friction that the beads may suffer in the cutting phase;
- *spacing rings:* segments of steel thin tubes, 4-5 mm long and 8 mm in external diameter, that allow for the maintenance of the appropriate position of the beads along the wire;
- *blocks:* metallic rings made embodied to the wire through pressure. Their function is to prevent the ejection of beads in case of wire breakage. Beads high speed would be an evident danger even for distant operators. A block is usually set every 4-5 beads;
- *joints:* used to close the wire in a loop and/or to join different pieces of wire to get the necessary length to contour the bench. The most widely used, for safety and practicality, are the copper or steel pressure joints. For this purpose screws are also used.

This wire configuration has been designed and is used to cut relatively "soft" materials, like marbles, limestones and travertines; in case of stones composed by harder minerals, like some metamorphic sandstones and "granites", the wear of the wire is excessively fast, because of the abrasiveness of the cutting sludge, so that the use of such wires is practically prohibited. To solve these problems, some "plasticised" and, more recently, "rubberised" wires have been introduced (Figure 11). In fact, the coating of the wire by a continuous wrap constitutes a good method to avoid its excessive wear and also guarantees a better anchorage and retention of beads in case of breakage. Plastic or rubber coating represents the standard configuration for "hard" rock wires.

In any case, water-cooling plays a fundamental role in diamond wire cutting. A lack of watering during the cutting phase causes a notable increase of heat, because of the friction between the rock and the beads, with consequent oxidation and graphitisation of the diamonds and fast reduction of cutting capability. Manufacturers of diamond wires advise to use from 15 to 50 l/min of water, according to the type of bead (less for the electroplated ones), the area to be cut and the speed of the wire.

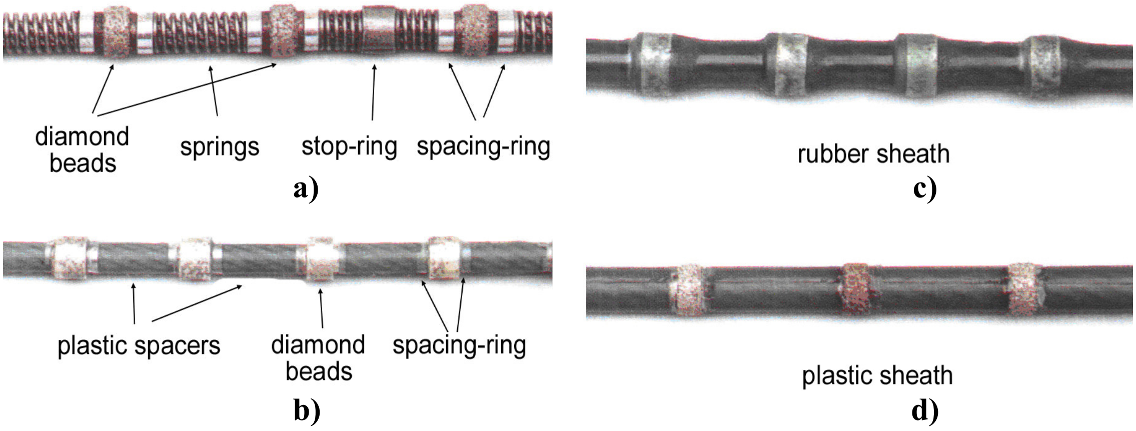


Figure 11. Different types of diamond wire. a) standard wire for marble with springs; b) plasticised wire; rubberized wire for granites; d) standard plasticised wire.

Diamond beads are the fundamental cutting elements. In the basic structure, the bead is a metallic cylinder, whose principal dimensions are: length 8-11 mm, inside diameter 5 mm and outside diameter 8 mm. On the external surface there is a 2-3 mm thick coat which contains the diamond grains (Figure 12). Therefore, the general resulting diameter usually reaches 10 - 11 mm. The beads are currently produced in two main types – electroplated or sintered (in concretion) – that differ from one another in the composition and in the technique of creation of the diamond coating.

Figure 12. Form left: an electroplated bead; one sintered; a microscope magnification of diamonds at the surface of a sintered bead.

The *electroplated* beads are the first ones that were introduced. The cylinder is covered by a coating of diamonds fixed at the surface through an electrochemical process and fastened to it with a nickel binder. The diamonds are usually synthetic, with an average grain size distribution between 40 and 60 Mesh. The concentration of diamonds may vary to some extend and this corresponds to differences in quality and performances (in marble beads, for instance, an average concentration of 0.4 carat/beads has been measured, where a carat = 0.2 g). The electroplated beads allow high cutting speeds, but with progressive reduction of their performance, with consequent wear of the surface diamond coating.

The *sintered* beads have been subsequently introduced, in order to obtain a tool that would last longer. The synthetic diamonds (grain size distribution 40-50 Mesh) are immersed in a sintered matrix composed by cobalt, with addition of bronze to calibrate its hardness, according to the material to be cut. The distribution of the diamonds is homogeneous in the whole thickness of the sinter (average concentration of 0,36 carat/bead) and only a part of these appears at the surface. The consumption of diamonds proceeds uniformly in the sinter, thus allowing the bead to maintain constant its cutting capability until its total consumption. Bead manufacturers, as well as quarry operators, are increasingly turning to, despite their higher cost. Sintered beads guarantee a greater versatility, as they allow the user to choose the type of their metallic sinter and/or the diamonds, in order to create "custom-made" beads for the material to be cut.

The cutting wire with electroplated beads and "traditional" structure is still broadly used for cutting calcareous stones, especially in the squaring phase, while, as mentioned above, in case of hard stones and for more difficult cuts, the coated wire with sintered diamond beads is used almost exclusively (Figure 13).

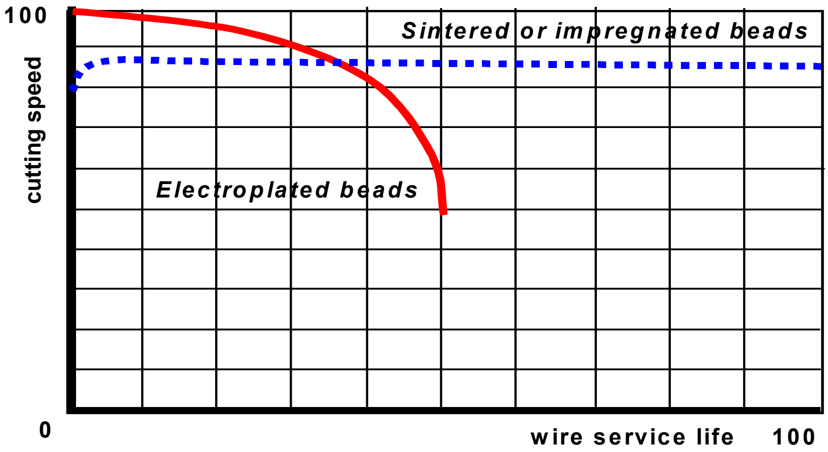


Figure 13. Qualitative comparison between cutting speed and wire service life in case of electroplated or sintered beads (DIAMANT BOART)

The principal parameters for appraising the effectiveness of diamond wire cutting are:

- cutting speed, expressed usually through the surface cut in 1 hour (m2/h);
- service life (or productivity or yield of the wire), expressed as the surface, cut by 1 meter of wire before it is completely consumed (m^2/m).

It is evident that only a simultaneous examination of these two parameters can lead to the selection of diamond wire as a cutting technique, and estimate correctly its contribution to the production cost. Nevertheless, in a general economic analysis, it is necessary to consider not only the operational costs, but other important aspects as well, mostly connected to the planarity and regularity of the cut surface, the absence of mechanic and thermal damages etc. Such evaluations are very important in case of materials with high commercial value: sometimes the "best" quarrying technology does not coincide with the most "economic" one.

The principal advantages of the employment of diamond wire are: versatility of use, reduced environmental impacts (vibrations, noises lower than 70 dB, dusts), reduction of waste - due to reduced cut thickness - absence of damaged and irregular surfaces. The greatest limiting factors are: the necessity of a very precise preliminary drilling, the necessity of skilled manpower and the necessity of having a continuous supply of water (a problem not to be neglected in dry areas).

1.2.2. Chain cutter

The chain saw technology comes from the development of machines originally designed for underground coal mining. Beginning since the ‘70s, this technology spread in marble quarries in Carrara and in a few years, it proved to be ideal together with the diamond wire cutters, in marble exploitation. Two types of chain cutters are produced, which differ in the technical solutions adopted to operate either on bench (Figure 14) or in advancement tunnels in underground quarries (Figure 15).

In the “bench type” chain saw, the machine is composed by an engine block mounted on a frame and connected to a mobile arm, along which runs a toothed chain. The machine has the possibility to move on rails through a rack. The engine unit, with power usually ranging from 44 to 52 kW, includes three electro-hydraulic systems, for the movement of the chain, the movement of the arm and the movement of the frame on rails, respectively.

Figure 14. Bench chain cutter.

Figure 15. Tunnel chain cutter.

The cutting tools consist of sharp prisms of sintered carbide (commonly called “widia”) or lined with polycrystalline diamond (“Stratapack” type), which are lodged on special supports fixed along the chain (Figure 16 and 17). The chain runs along the perimeter of the arm, continually lubricated by grease. The arm consists of a tabular-shaped steel element (about 40-50 cm wide and 34 mm thick), whose length does not usually exceeds 5 m. The arm is able to rotate by 360° on the head shaft that connects it to the motor and may perform both vertical and horizontal cuts.

The cut is created by the continuous passage of the sequence of tools, which removes a minimum partition of rock e.g. 0.45-1.5 mm by each tool. In fact, the tools are mounted on the chain in series of 6-8 elements, and positioned in such a way to create an angle. The cut has a width of 38-42 mm, a theoretically endless length (in horizontal), but a depth limited by the length of the arm.

The parameters that can be adjusted in order to optimise the relationship between cutting speed and tools wear are the advancing rate of the machine in cm/min and the rotation speed of the chain in m/s. The saw may advance to a maximum speed of 15 cm/min, while the chain has a maximum speed of 1 m/s; usually it is preferred to maintain a lower advancing rate, so that the produced debris can be removed by just one operator.

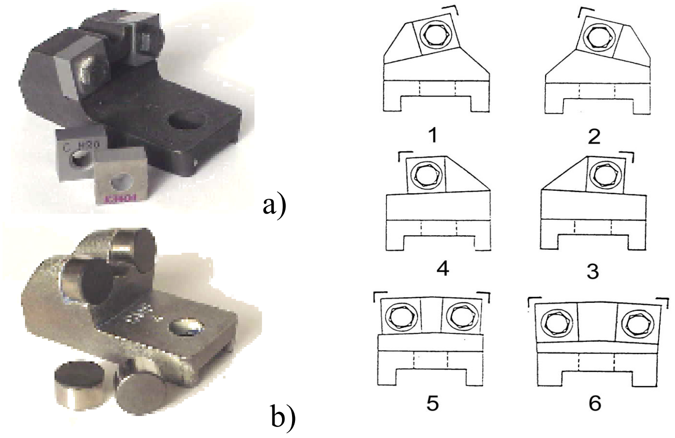


Figure 16. (a): Prismatic tools of widia bolted on the support; (b): cylindrical tools lined with polycrystalline diamond welded on the support

Figure 17. Complete series of 6 square tools, mounted on the chain

The hydraulic control for the movements permits the regulation of the working speed, while the control of the forces is done through pressure limiting valves. Cutting may be performed either in dry or in wet conditions: in the case of a dry cut, a higher speed of cutting is achieved, due probably to a better lubrication, but with a higher wearing of tools; cutting with watering causes the cooling of tools thus allowing their greater duration.

The chain needs a continuous lubrication for its operation; the recorded consumption is about 0.6 - 2 kg/h of lubricant. Problems connected to the release in the environment of mineral oils have led to the development of biodegradable oils and natural greases, in order to avoid the possible contamination of surface and/or underground water tables.

In the “tunnel type” chain saw cutter, the arm is mounted on a tubular frame, separated by the engine unit. The arm is usually 3.5 m long; the frame is 5-6 m wide and 3.2-4.5 m high. Due to the movement on the frame, it is possible to perform both horizontal and vertical cuts. To avoid problems of positioning and handling of this type of underground saw, a self propelled tunnel type saw has been recently introduced: the arm and the engine unit are mounted on a tracked carrier, which guarantees improvement in manageability and allows the management of the positioning operations to be carried out by just one operator (Figure 18).

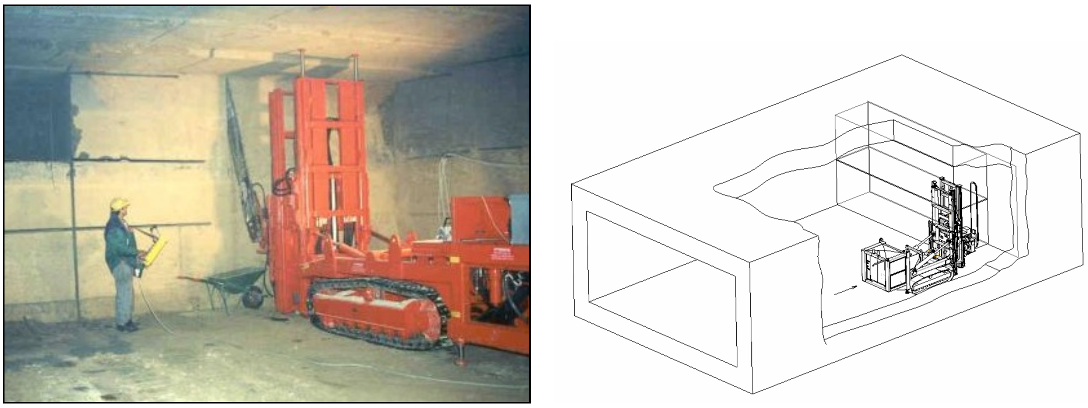


Figure 18. The self moving tunnel chain saw. Right: a schematic illustration of the operational possibility to perform the back cutting on blocks.

The most important advantages of the chain saw cutter are: versatility, good health and safety conditions during operation (absence of dusts, vibrations and contained noises), simplicity of the operation and necessity for little manpower (just 1 worker), absence of induced breakages to the rock mass, regularity and planarity of the cut (good inspection of the fronts and regularity of the extracted blocks). Furthermore, this technology is essential for the opening and exploitation stages of underground marble quarries.

The greatest drawbacks are: firstly, this technique can not be currently used on hard materials, secondarily, the reduced depth of cutting limited to the arm length, even if today, machines with 6 meter long arms are available (only for vertical cuts). As far as moving and positioning of the machine are concerned, apart from the self moving model, the availability of powerful loaders or excavators and the presence of at least two operators are required.

In case of layered deposits especially, with thickness lower than 4 m, the chain saw may be used as the only technology of exploitation, both for vertical and horizontal cuts. Otherwise, the most convenient and effective technique would require the use of chain saw together with the diamond wire saw.

Table 5. Technical characteristics of some models of chain saws (FANTINI).

	bench (70.RA.P)	**tunnel (G. 70)**	**self moving (GU 50/S)**
Power	49 kW	52 kW	45 kW
Weight	6500 kg	6000 kg	13000 kg
Arm rotation	360°	360°	360°
Chain speed	0.7 m/s	0.7 m/s	0.7 m/s
Width of cut	38 mm	38 mm	38 mm
Depth cutting	3.4 m (max)	2.4 m (max)	2 m (max)
Feeding rate	13 cm/min	7 cm/min	3-30 cm/min

1.2.3. Diamond belt cutter

The diamond belt cutter, introduced in middle ‘90s, was born as an “ecological” variation of the chain saw, from which it has borrowed the principle of operation and mechanical structure. The basic difference between the two machines relies in the belt (instead of the chain) equipped with diamond bearing inserts, which slides along the arm perimeter and is able to cut harder material (Mohs > 3), but not the granites. Unlike chain saw, the lubrication of the belt is exclusively achieved through water, distributed by channels inside the arm, excluding the use of oils or greases of any kind. In comparison to the chain, the masses in movement are notably reduced, allowing the diamond tools to work to a greater speed, without “centrifugations” and with less friction on the cutting elements.

The belt is composed by a metallic core (a series of thin steel wires), covered by a very hard plastic coat. From the belt, emerge diamond tools, which are steel segments of rectangular shape (usually 32 mm wide and 15 mm thick), covered on the exposed side by a coat (6 mm) of sintered diamonds.

On average, 13 sharp sectors are mounted on one meter of belt. As for the sintered beads, the metallic composition of the sinter matrix (cobalt/bronze) and the type of diamond may vary according to the material to be cut. When the cutting elements are consumed, the whole belt is replaced. This substitution though, represents a constant economic burden.

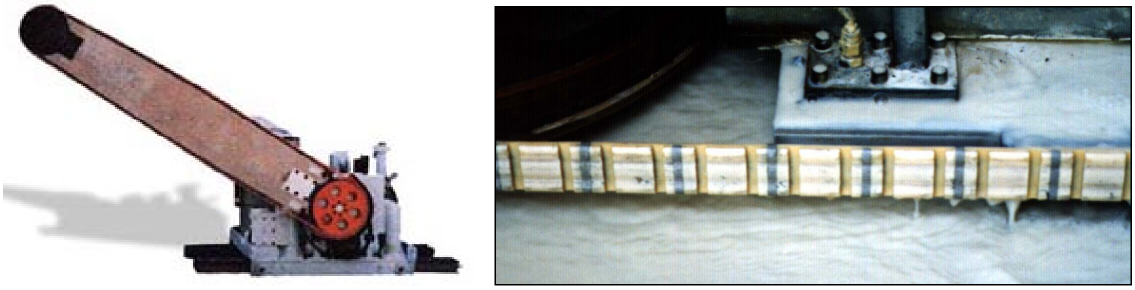


Figure 19. A diamond belt cutter (left). On the right, a close-up of a belt with diamond tools.

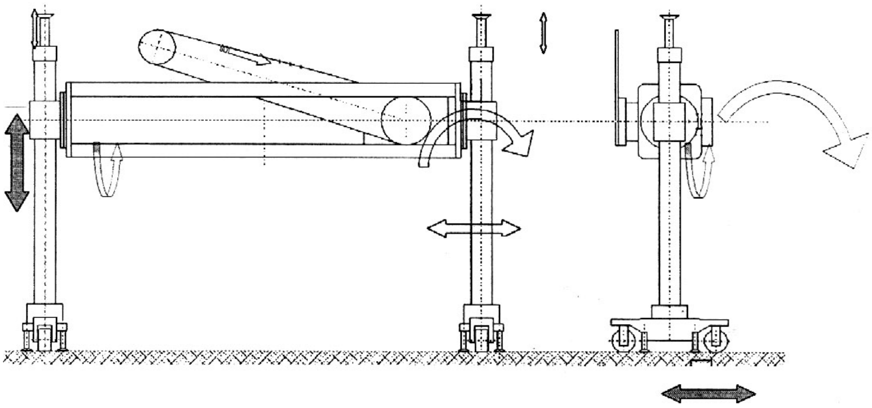


Figure 20. Tunnel belt cutter (BENETTI). Axes of rotation and directions of movement are indicated with arrows.

The belt cutter is produced in three types, which in chronological order of development, are: a “bench” type for vertical cuts only (Figure 19), a “bench” type for both vertical and horizontal cuts; a “tunnel” type for underground exploitation (Figure 20).

Regarding performances, the cutting speed is 4-5 m^2/h (according to the length of the arm), corresponding to an advancing rate of 2,5 cm/min. The advancing rate may automatically be controlled according to the load. The belt sliding speed is about 20 m/sec, which is remarkably higher than that of the toothed chain. The service life of the diamond tools, as measured in Carrara white marble exploitation, is about 120 m^2/m (for a ten metre long belt).

The advantages of this technology are the same with those of the chain saw described in the previous paragraph, with the addition of the complete exclusion of lubricant use, allowing for the exploitation of more abrasive materials and reducing the frequent maintenance of the cutter, required by the traditional chain saw[8]. The drawbacks are also analogous, to which the higher investment cost, given the present purchase cost, has to be added.

1.2.4. Flame-jet

The flame-jet operation is based on the thermal shock induced to a material by a high temperature flame mixed with gases, projected at high speed on the line of cutting. This technology takes advantage of the difference between the thermal expansion coefficients of minerals that constitute the rock and, therefore, it is particularly effective in rocks mineralogical inhomogeneous, like granites with high percentages of quartz. Actually, the flame-jet is suitably applied only in some quarries of granite, mostly for vertical cuts orthogonal to the quarry front, for the first lateral isolation of the benches.

The flame, which has a maximum temperature of 2000°C and a jet speed of 1300 m/s, causes the separation of chips from the rock mass, thus creating a channel at least 8-10 cm wide. The high temperature may induce an undesired vitrification of the rock around the cutting plane, with consequent loss of physical-chemical and aesthetical characteristics of the stone.

The flame-jet machine is constituted by two pipes, feeding respectively compressed air and fuel to a combustion chamber, from which the flame jet comes out; an operator manually maintains the position of the torch, directing downward the flame and progressively deepening the cut. The ordinary operation of the flame-jet requires a consumption of 4.5-8.5 m^3/min of compressed air and 30-70 l/h of gas-oil. The maximum depth of cutting is 4-5 m with a speed that varies between 1 and 2 m^2/h.

The advantages of this technology stem from its simplicity and immediateness of use, the need for not skilled operators and the relatively low cost of investment. However, the greater advantage is connected to the possibility to create cuts without necessity of preliminary operations.

Nevertheless, there are numerous disadvantages: as mentioned before, this technology is effective only in some types of granites and produces a damage on the rock to a remarkable thickness; the environmental impact is noticeable, in terms of energy consumption, increased noisiness (more than 120 dBs), aero-dispersed dust, exhausted

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[8] A specially designed tunnel cutter for underground use, incorporating diamond belt technology, capable of working on hard and abrasive types of marble by high fracture characteristics, has been developed within a Brite-Euram 3 project completed in 2001. The diamond belt cutter has been tested in the Portuguese pink marbles.

gas, etc.; finally, the productivity is very low, and depends on the ability of the operator to manage and direct the welding torch on greater lengths. For all these reasons the flame jet is becoming obsolete.

1.2.5. Water-jet

This technology, while still considered experimental in dimension stone extraction, is a mature and widespread method in stone processing and in concrete demolition. It is based on the cutting power produced by a water jet (about 1 mm in diameter) with great speed due to very high pressure (up to 400 MPa). The cutting mechanism combines the breakage of the mineral grains and the separation of the rock components. The water-jet machine consists of two parts: the pressure generator, or the pump, and the cutting machine (Figure 21).

The pressure generator provides a water flow of 5-80 l/min under the pressure of 100-400 MPa. For pressures up to 200 MPa and large flow rates positive-displacement single-stage pumps are normally used. For higher pressures and lower flows, a two stage system is used: a positive-displacement single-stage pump, providing a pressure of 10-20 MPa, and a pressure intensifier. The intensifier consists of two cylinders of different diameter and a single piston: the cylinder of greater diameter is fed at 10-20 MPa by the pump, while the cylinder of smaller diameter acts on the output, raising the water pressure from 10-20 to over 200 MPa. The single-stage pump without the intensifier is more reliable than the second method though, because it is simpler and subjected to smaller stresses; besides this, the experimental studies conducted up to today have proved that the best conditions for cutting are obtained by larger flows and not excessively high pressures. Consequently, the current trend is to use the single-stage pump system without amplifier.

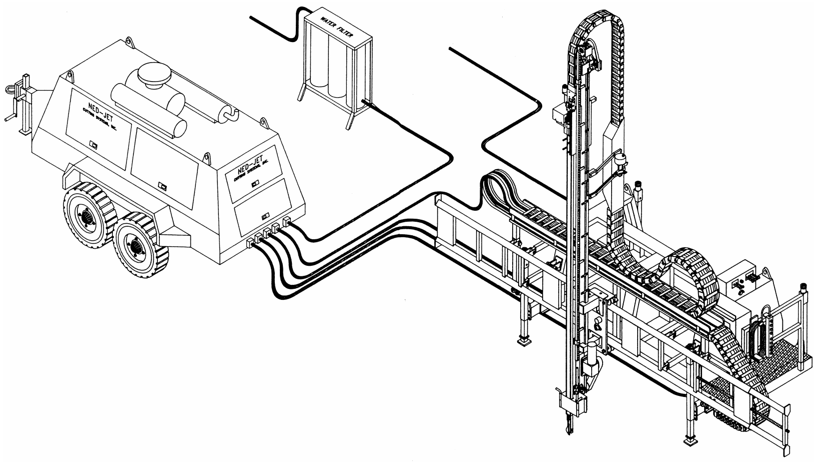


Figure 21. Water-jet machine: mobile pressure generator (left), rod with nozzle (right).

The pressure generator operates with an electric motor or Diesel engine. The installed power varies in the range of 20-300 kW. The water is projected through a nozzle, into which the hydraulic pressure of the water is turned to kinetic energy. The nozzle is normally mounted on a rod, which gives the ability to move it accordingly. The rock-nozzle gap is maintained approximately constant. Different “nozzle-units” are available; they differ from one another in the number of nozzles and the cutting motion. The most widely used consist of 1-2 nozzles mounted on an oscillating head. As already mentioned, the cutting head is supported by a rod, which must bear the recoil of a jet flowing through the nozzle at supersonic speed (up to 800 - 900 m/s). To allow passage of the rod in the cut, the latter must be some centimetres wide, normally 4 to 8 cm.

In Table 6, some data of performance recorded in different types of material and with different configurations are presented: it is observed that, currently the speed of cutting, directly affected by the structure and texture of the materials, is relatively low. In marbles, generally, the hydro-jet is not competitive in comparison to other technologies of cutting with analogous end result (essentially, chain saws); on the contrary, in granites and sandstones, the technology is interesting and competitive enough.

Table 6. Performances of the water-jet in different lithotypes and with different operational configurations (R. Ciccu).

Material	Pressure (MPa)	Flow (l/min)	Power (kW)	Speed of cutting (m^2/h)
Granite (USA)	280	11	52	1,17
Granite (USA)	310	5	26	0,6
Granite (Canada)	140	76	175	1,15
Granite (France)	200	70	330	1,5
Granite (Italy)	200	18	60	2,4
Gneiss (Italy)	350	8	47	1,7
Sandstone (France)	80	60	160	6,5

From the operating point of view, the cut is created by the penetration of the rod with the nozzle through successive passes along the selected direction. The advancement of the machine is automated and allows for non-stop operations without continuous presence of an operator. The obtainable depth of the cut is 2.5 – 3.5 m, reaching 8 m through a rod extension.

Finally, the water-jet introduces several points of interest that make it in prospect, surely interesting for the quarrying activity of dimension stones:

- it performs a very precise cut, allowing for a good recovery in comparison to other cutting systems (is more accurate in particular, than explosives and more productive than flame-jet), especially in hard rocks (granites, gneiss etc.);
- cutting phases can be highly automated, allowing the operator to stay at a safe distance;
- it has a low environmental impact: scarce or null vibrations (especially in comparison to the methods that foresee the use of explosive), null release of polluting substances in the environment;

On the contrary, this technology still presents some important problems:

- low cutting speed;
- high specific energy of cutting;
- elevate noisiness especially in the initial phases of cutting;
- very high costs of initial investment;
- necessity of a constant maintenance;

- necessity of a large water supply, and water recycling.

From the point of view of evolution in quarrying activities in “hard” stones, the water-jet represents a technology with high potential, because it can allow, in combination with the diamond wire, undertaking underground exploitations with operational formality analogous to those of diamond wire and chain saw in the marble sector.

1.2.6. Drilling + splitting devices

The drilling may be considered either as an auxiliary and preparatory technology to other methods of cutting, as in case of the diamond wire, or an autonomous technology. In this last case, a distinction must be made between the continuous drilling (a line drilling directly produces a surface of separation) and the discontinuous drilling (mechanical or chemical or hydraulic devices are needed to complete the separation).

Line drilling

Through the continuous drilling, splitting surfaces are created without resorting to auxiliary elements of separation. Such technique can be used with effectiveness in compact or particularly vulnerable to explosives rocks.

Drilling + blasting

The use of explosives as a splitting technology, is probably the most traditional, consolidated and “cheap” technique in the exploitation of “hard” stones. It is less and less applied today in the exploitation of marbles, because of its low yield and the drawback of fracturation of the rock mass, mostly in comparison to wire and chain saws.

This technique, usually called dynamic splitting, can be considered as an extreme application of controlled blasting concepts and precision drilling techniques. Very thin linear charges, represented by strands of detonating cord (6-15 g/m of PETN), are placed in parallel, closely spaced drill holes (about 32-34 mm in diameter and 15-40 cm distance between centres), filled with a suitable shock absorbing material, like water, and simultaneously detonated by a master cord (Figures 22 and 23). Fracture happens due to tensile stresses in the rock inter-hole bridges and excess energy from the blast provides the required small displacement of the separated mass. In well conducted operations no extra cracking occurs that would damage the stone block.

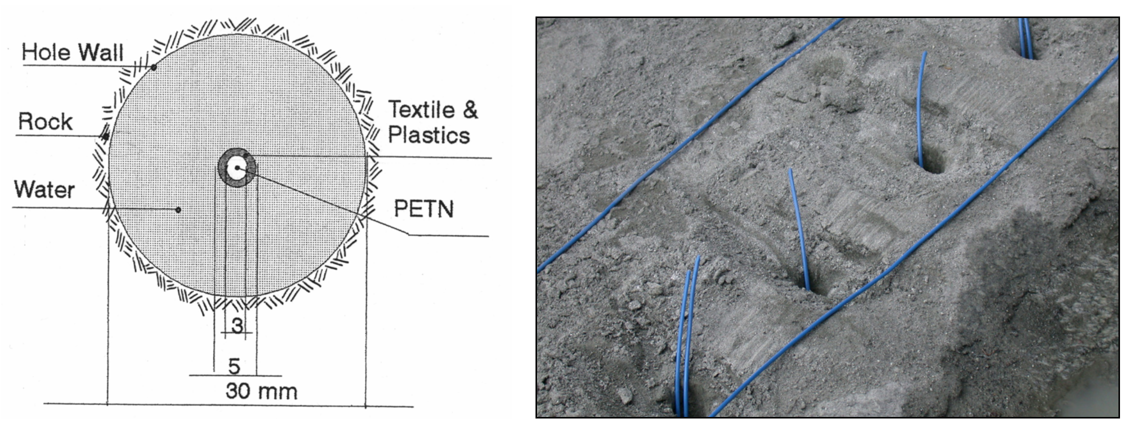


Figure 22. Drill holes charged with detonating cord and filled with water.

Figure 23. Splitting by explosive of a great bank of gneiss (Val d' Ossola - Italy).

The described technique finds its best application in opencast quarries with regular step geometries, where the benches are cut in a parallelepiped shape. Splitting by explosive can be employed for both cutting of great banks and squaring of blocks, and it represents an adaptable technique to compact rocks of any hardness. This technique is certainly versatile and flexible, and provides an acceptable recovery in blocks, with limited operative costs.

The greater disadvantages of this method are connected to the use of explosives (noises, vibrations, fragment projections, induced fracturation in the rock mass, etc.) and to the subsequent irregularity of the cut surfaces. This last aspect has a negative impact on the processing phases of the blocks, when regular surfaces guarantee a better recovery of slabs. In fact, many quarry operators agree on the point that explosive cutting brings out a 7-10% waste of material due to cracks which may occur near the splitting surface, while only a 2-2.5% waste is produced by diamond wire sawing.

On the other hand, the exclusive use of the diamond wire is not currently practicable in hard stones, where operational problems and costs of production make this method non-competitive in comparison to the dynamic splitting method. Good results are obtained, in different quarrying situations, by combining dynamic splitting with diamond wire cutting: usually, the vertical back cut and the horizontal one are performed by explosives while the side cuts are performed by diamond wire.

Drilling + "rock breakers"

An ancient system, but still applied today in different situations, especially in the phase of sectioning of benches. It causes the creation of a surface of separation by inserting and hammering wedges in the holes. Wedges cause a fracture along the plan determined by drilling. The wedge dimensions vary from 135 to 800 mm in length and from 12 to 40 mm in diameter.

A "mechanized" version of the wedge system is composed by "rock breakers": metallic "cylinders" (up to 6 in common models) that exert when inserted in the holes, through an oil-pressure system (50-60 MPa), and exercise pressure on the walls inducing a fracture along the plan predetermined by drilling. These techniques can be employed in all the lithotypes, but they are especially applied in the exploitation of hard stones.

Drilling + "physical-chemical devices" (other than explosives)

When local laws make the use of explosives or other mechanical means of cutting impossible, some special expansive mortars (or expansive cements) can be used. Such mortars, poured inside drill holes, produce pressures up to 80 MPa and cause breakage of the rock among the holes.

According to the type of mixture and the temperature, the time of action varies between a minimum of six to over 24 hours, with evident limitation of productivity. Furthermore, such technique loses effectiveness in case of fractured materials, in which case there is, also, an uncertainty effect. On the contrary, whatever problem connected to vibrations, noises, projections and dusts is completely avoided.

Shape memory alloys

Finally, a new technology that deserves a reference is the use of "shape memory alloys", which is still in the phase of experimentation for cutting dimension stone. It consists of cylinders of small diameter, made by "shape memory alloys" (SMA). SMA are novel materials which have the ability to expand to a predetermined shape when heated, generating large forces and displacements. The cylinders of SMA, electrically heated by the Joule effect, expand themselves exerting notable pressures on the rock and then return to their original shape by means of springs. This technology will eventually replace the explosives in the exploitation of dimension stones.

1.3. Conclusions

In conclusion, the present state of application of cutting technologies is given in relation to the exploited material, in the following tables. The compatibility of technologies is given together with the different methods of exploitation, always distinguishing among "marbles" and "granites", and also indicating possible prospects of application.

Table 7. Present state of technologies used for dimension stone quarrying.

	TRADITIONAL TECHNOLOGIES					**ALTERNATIVE TECHNOLOGIES**		**INNOVATIVE TECHNOLOGIES**	
TYPE OF ROCK	*drilling + explosive*	*flame jet*	*drilling + rock breaker*	*diamond wire*	*chain saw*	*continuous drilling*	*drilling + expansive mortars*	*water jet*	*diamond belt saw*
MARBLES	scarce		frequent	very common	very common	occasional	scarce		occasional
GRANITES	very common	local	frequent	frequent		scarce	scarce	experimental	
SANDSTONES	common		frequent	frequent	frequent	occasional	scarce	occasional	

Table 8. Exploitation method and application of technologies in marble quarries.

METHODS OF EXPLOITATION & OPERATIONS IN MARBLE QUARRIES	TECHNOLOGIES											
	drilling + explosive		*drilling + rock breaker*		*diamond wire*		*chain saw*		*diamond belt saw*		*continuous drilling*	
	application and perspectives											
	actual	future	actual	future	actual	future	actual	future	actual	future	actual	future
OPENCAST great benches - high step configuration												
primary vertical cuts	small	marginal	marginal		very common	very promising	marginal	promising		small		
primary horizontal cuts	marginal		marginal		frequent	very promising	very common	very promising	marginal	promising		
secondary cuts sectioning			frequent	frequent	very common	very promising	scarce	marginal		marginal		
OPENCAST direct extraction of the block - low step configuration												
vertical cuts	marginal		frequent	marginal	frequent	very promising	very common	very promising	marginal	promising	marginal	
horizontal cuts	marginal		marginal	small	frequent	promising	very common	very promising	marginal	promising	marginal	
squaring			frequent	frequent	very common	very promising	marginal	promising	common	promising		
UNDERGROUND												
Initial phases of opening	marginal	small	scarce		marginal	diffused	very common	very promising	marginal	promising	occasional	
Lowering of the rooms	scarce				very common	very promising	very common	very promising	marginal	promising		

Table 9. Exploitation method and application of technologies in granites quarries.

METHODS OF EXPLOITATION & OPERATIONS IN GRANITE QUARRRIES	**TECHNOLOGIES**											
	flame jet		*drilling + explosive*		*drilling + rock breaker*		*diamond wire*		*hydro- jet*		*continuous drilling*	
	Application and perspectives											
	actual	future	actual	future	actual	future	actual	future	actual	future	actual	future
OPENCAST ***high step configuration***												
vertical cuts ⊥ to the front	common	local	marginal	scarce			frequent	very promising	experimental	.promising	small	
vertical cuts || to the front			very common	occasional	marginal	small	marginal	promising		promising	scarce	
horizontal cuts			very common	promising	marginal		scarce	promising		promising		
secondary cuts			very common	occasional	frequent	occasional	scarce	very promising		small	marginal	small
OPENCAST ***low step configurations***												
vertical cuts	scarce		frequent	occasional	frequent	occasional	scarce	promising	experiment	promising	marginal	small
horizontal cuts			frequent	small	marginal	discreet	marginal	promising	experimental	promising	marginal	small
squaring			frequent	marginal	very common	promising	frequent	very promising		scarce		
UNDERGROUND ***initial phase of advancement opening of the rooms***												
frontal cuts				small		small	experimental	promising	experimental	very promising		small
back cuts				small		small	experimental	promising				
UNDERGROUND ***Lowering of the rooms***												
exploitation cuts				occasional		small	marginal	very promising		promising		small

2

Operational aspects

MARILENA CARDU, ENRICO LOVERA

Considering that every quarry site has unique characteristics, it can be observed that only with the application of specific techniques and the employment of advanced technologies, good levels of productivity with acceptable costs of production can be achieved along with safe working conditions and, at the same time, protection of the environment and the surroundings.

Consequently, the methods of exploitation and the available technologies must be applied in a suitable way, according to the different geo-morphological configurations of the deposit and the lithological characteristics of the material. The operational aspects of the exploitation of stone deposit are described in this chapter, by applying a "mixed" classification, based on the material nature and the geo-morphological configuration, combined with the relative methods of exploitation and the fittest technologies; it is not possible, of course, to cover every possible case, in a undoubtedly various reality as the one represented by the European stone quarries.

By simplifying as much as possible, a reference can be made to the following situations:

1. Stratified deposit in mountainous area, benches presenting a fairly steep dip, with reduced overburden in relation to the exploitable thickness (Figure 24).

In this context, it is possible to distinguish between:

1.a. Calcareous rocks, namely "soft", like metamorphic marbles, polishable limestones, etc. (Figure 25);

1.b. Siliceous rocks, namely "hard", like granites, gneisses, etc. (Figure 26).

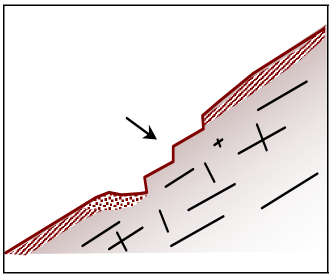


Figure 24. Scheme of cases 1.a and 1.b.

Figure 25. Marble quarry (Central Alps - Italy) with inclined benches.

Figure 26. Gneiss quarries (North Western Alps – Italy) with very inclined benches

Concerning the exploitation method for case 1.a, a "descending horizontal slices" quarrying method is easily foreseeable. The slices – according to the dipping of the layers – are exploited through a sequence of inclined benches, which are detached from the hillside and finally subdivided in blocks. The cutting technologies are usually the diamond wire saw and the chain saw, often combined for greater productivity and higher block yield.

In case of overlapped layers with different characteristics and in order to have different commercial products, the quarry can be organised simultaneously to more productive levels. Work organisation must guarantee the operational safety in potentially interfering stopes. A slight downward dipping of the layers may be favourable to the primary splitting of big volumes of stone, but the local stability of the bench during the cutting phase should be carefully monitored.

The typical mountain morphology often involves a layout with rather steep layers position. This is the case (point 1.b) of many alpine gneiss quarries, in which the presence of systematic structural discontinuities may facilitate the primary detachment, on one hand, but on the other hand, it is a source of constant potential danger. In such cases, the method of "lateral attack" of the stopes allows the avoidance of worker presence under the potentially instable quarry faces while, it makes possible the timely reclamation, from above, of the upper step; hence this method should be extended as much as possible to the active quarries, and should be imposed as a rule to new activities. If ramps are created in a lateral safe position since the beginning of a quarry operation, benches can be exploited sideways, also using the diamond wire for opening the first channel.

2. Morphological plain context, with different exploitable deposit thickness in relation to the deposit extent, and with little or absent overburden. The following situations can be observed:

2.a. Outcropping sedimentary calcareous deposits, with limited useful thickness (Figure 29);

2.b. Calcareous rocks, for instance of chemical or organogenic nature, with a weak overburden (weathered rocks) and a notable exploitable thickness (Figures 27 and 30);

2.c. Hard, quartzite rocks in form of "erratic boulder" of magmatic origin, or sedimentary and metamorphic bodies (e.g., quartzite or quartzite sandstones) outcropping with strongly heterogeneous characteristics, or sub-horizontal outcrops of thick massive granite banks (Figure 31), or sub-vertical schistose bodies (e.g., porphyroids or serpentinites), emplaced among sedimentary or metamorphic rocks (Figure 28).

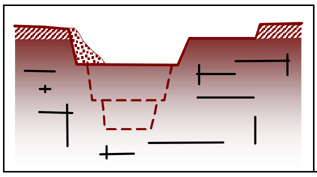


Figure 27. Cases 2.a -2.b.

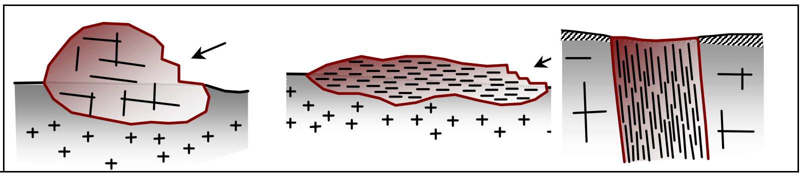


Figure 28. Different possible cases for point 2.c.

Figure 29. Flat land quarry of calcareous stone with limited exploitable thickness (Croatia).

Figure 30. Quarry of calcareous stone in flat land with very deep pit layout, exploited in many levels (Italy).

Figure 31. Flat land quarry of pink granite, with stepped layout (Spain).

The situation described in point 2.a is relatively “simple”: in fact, overburden removal is not a binding operation and the mechanical characteristics of the soft rock make it “easily” exploited by all current technologies; besides, the ample availability of space allows the most complete mechanisation with the fittest means for quarrying operations.

In case 2.b, an opencast exploitation, through progressive lowering of the quarry floor, will be the most common option. Some difficulties – typical of pit exploitations – could be arise by the necessity of water pumping from the bottom of the pit; nevertheless, such quarrying units can be fully mechanised and rationally organised in highly productive exploiting levels. The situation becomes progressively more difficult in case of deepening of the pit, until it assumes a “good” configuration. In this case, vertical lifting of materials becomes essential, as the operational spaces at the bottom of the pit are increasingly reduced. In both cases, the cutting technologies mainly used are the diamond wire saw and the chain saw.

In the first case of point 2.c, the material is “hard” and abrasive, but the exploitation does not present difficulties in primary detachment: in fact, the boulders can be progressively reduced in dimensions by diamond wire cuts or by explosives. Such “squaring boulders” method is still common in many developing countries, because above all, it does not require any particular equipment or specialised manpower; in Europe, boulders are often considered as an obstacle to be eliminated, in order to get a stepped layout of the main rock deposit. More common is the case of massive and wide deposits, productively exploitable by progressive descending horizontal slices, using the splitting by explosives and/or diamond wire.

3. Hillside context, with exploitable bodies of regular shape and good volume, emplaced in the slope, more or less steep, whereas other materials of different nature and geomechanical characteristics are present. The following cases are evidently different:

3.a. Embanking rock – on top and eventually beside the exploitable body – with good geotechnical characteristics, thus being able to guarantee the general stability of the quarry (Figure 32 and Figure 34);

3.b. The exploitable body is emplaced in host materials, with poor physical properties, thus a preventive removal of barren materials and isolation of the useful deposit is required (Figure 33 and Figure 35).

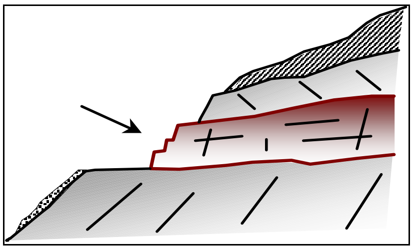


Figure 32. Scheme of case 3.a.

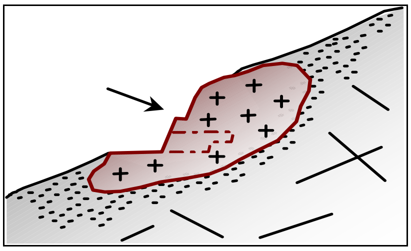


Figure 33. Scheme of case 3.b.

Figure 34. White granite hillside quarry (Italy).

Figure 35. Ophicalcite underground quarry (Italy).

In case 3.a, where the deposit difficult to access, quarries are traditionally drawn hillside, with the need for removal of large quantity of overburden. In recent past, exploitations used to proceed by vertical ascending slices, with residual fronts difficult to be managed. Today quarries should be worked through a stepped layout, adopting descending horizontal slices methods.

Finally, in case 3.b, where sound and sizable rock bodies are placed within rock masses of deep weathering or even within loose material, the need for a complete preventive removal of the barren materials above the stone bodies is clear, for creating working conditions of global stability of the hillside. The exploitation, also in this case, can proceed through descending horizontal slices.

In case of calcareous material, the strategy of underground exploitation by tunnel chain cutters and diamond wire saws has been notably developed. On the contrary, the underground exploitation of siliceous stones still presents great difficulties basically of technological nature, since an equivalent of the chain saw able to cut through hard materials does not yet exist.

2.1. "Soft rock" quarrying

Referring to the traditional differentiation between "hard" and "soft" stone, for the extraction of the latter it can be stated that the use of diamond wire saws and chain saws has proved itself as the most flexible and productive practice, advantageous also in terms of block yield. Precision of cutting, regularity of the obtainable surfaces and lack of undesired stresses lead to high percentages of regular and sound blocks. Such mixed technique presents today relatively low costs and above all has demonstrated great flexibility in its applications, being able to fit to every stope layout: it is directly usable even in underground quarries.

For a rational exploitation through an opencast, stepped layout, a preliminary operation is the opening of a "channel", that is the creation of a third free surface, besides the vertical front and the horizontal upper plane, necessary to facilitate the following phases of exploitation by wire saws and/or chain saws.

Operating by exclusive use of wire saws, two different ways for creating the channel are possible (Figure 36):

- the opening of a "V" channel requires 3 convergent drill holes of reduced diameter (from 36 - 40 mm for a manual pneumatic hammer or 85-110 mm for a hydraulic drill or "down the hole" hammer, according to the depth of drilling). The horizontal base cut is carried out first and, subsequently, two side cuts with "descending loop" are made. Such type of opening has the disadvantage of creating a surface not perpendicular to the other, creating consequent losses of volume during blocks squaring. On the contrary, it reduces to a minimum the number of drill holes and necessary cuts, consequently saving time, manpower and money. This operation would be convenient in the "defective" parts of a deposit, where a low block yield would be more accepted.
- the opening of a "U" channel requires 4 drill holes, of which the two vertical must have large diameter (205-255 mm for a hydraulic drill) for the preliminary creation of the blind back cut. Although this way of channel opening demands greater effort in terms of drilling and surfaces to be cut, it creates a geometrical channel which corresponds to the maximum recovery of commercial volume. Therefore, for non-

defective or highly valued material, higher operative costs can certainly be compensated by a better block yield.

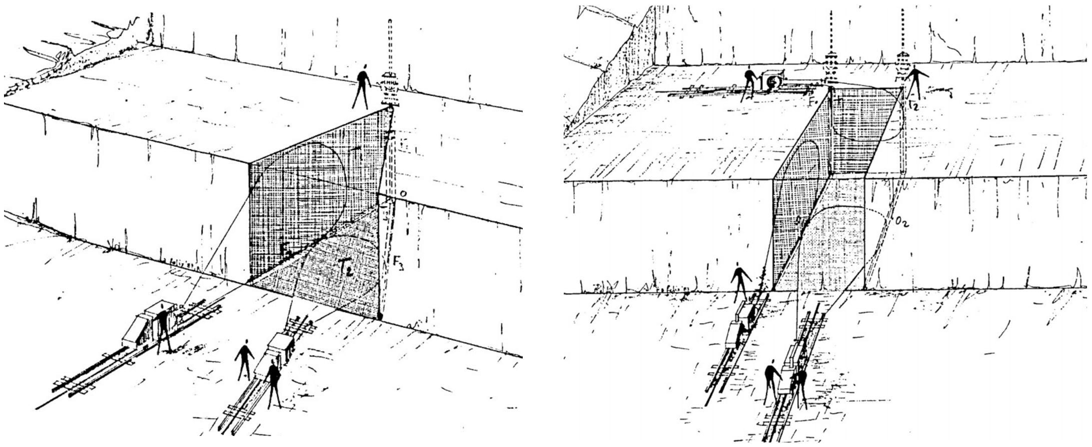


Figure 36. Opening a “V” channel (left); opening a “U” channel with diamond wire (right).

If chain cutters are available, the opening of the channel can be executed in a decidedly more comfortable way, according to the scheme of Figure 37. Horizontal drillings are avoided; in fact, the base horizontal cut is carried out first by the chain saw that does not need any preliminary operation of drilling. Then two vertical back holes (usually 110 mm in diameter) can be drilled, evidently co-planar and intersecting the horizontal surface just made. The plane, already freed at the base, and the vertical holes, allows the cut by wire (through a loop configuration) of side and back surfaces too.

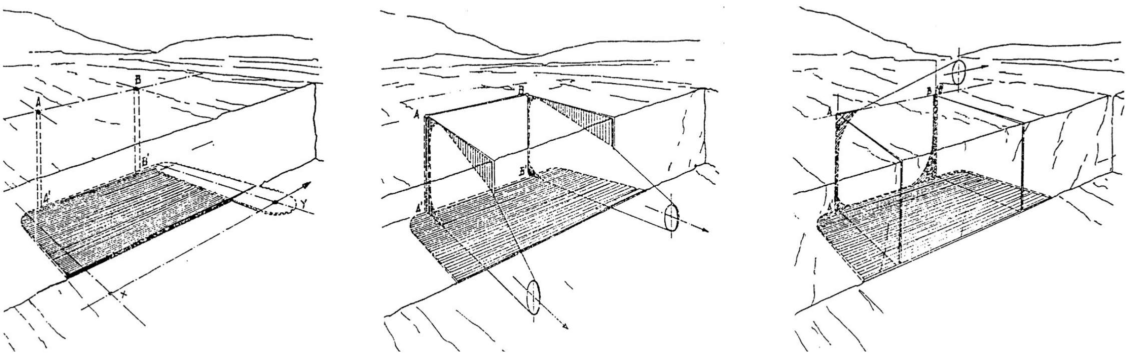
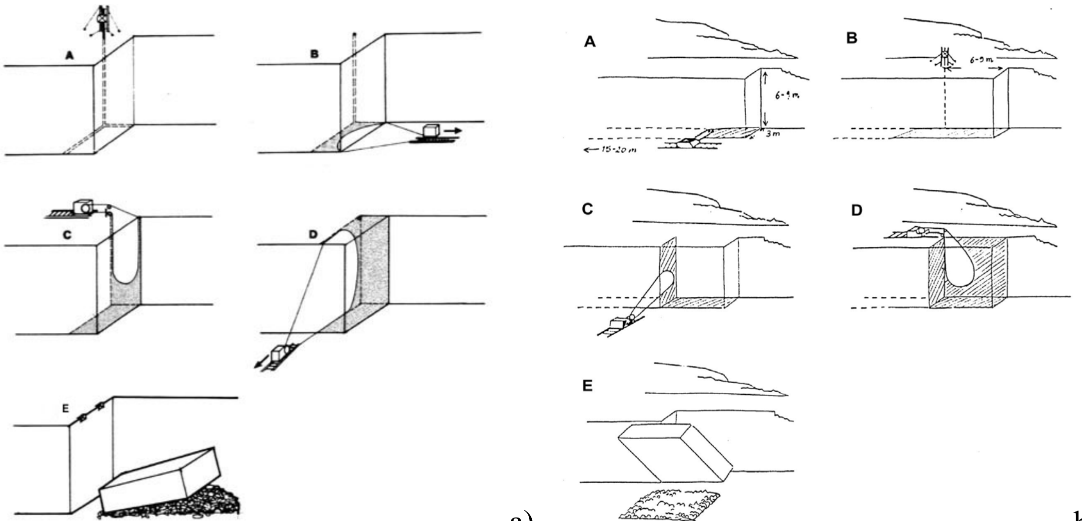


Figure 37. Opening creation by chain saw and diamond wire.

After opening the first channel, it is possible to perform the whole operation of separation of benches through the exclusive employment of the diamond wire (Figure 38 a.), even if the most “efficient” cutting method foresees the contemporaneous use of wire and chain cutters, for the same considerations already described.

Combined use of chain saw (for horizontal cuts) and diamond wire (for vertical cuts) leads to production optimisation by reducing the number and the diameter of the holes (only vertical) (Figure 38 b.). Obviously, in this case, the bench depth is limited to the length of the chain cutter arm. Whenever the structural conditions of the deposit suggest maintaining low steps, with a maximum height of around 3 m, it is possible to reverse the roles of the two technologies, realising the vertical cuts by chain saw and the base cut by diamond wire. Often, especially in fractured deposits, it is preferred to make the first horizontal and vertical cut (phase B and C in Figure 38 b.) notably ampler in comparison to the dimension of a single bench and then proceeding with a set of vertical lateral cuts (phase D), positioned according to the fracture set of the rock (Figure 39).



a) b)

Figure 38. Sequence of operations for quarrying a bench: a) diamond wire cutter is the only technology adopted; b) chain and wire saw are combined. (F. Bradley mod.)

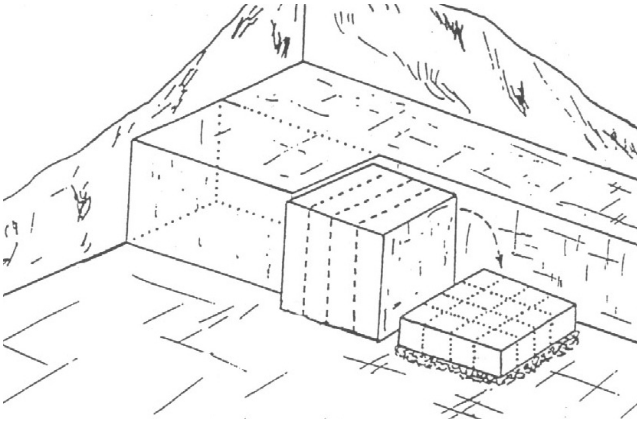


Figure 39. Side cuts and sectioning of a great bench (R. Ciccu et al.).

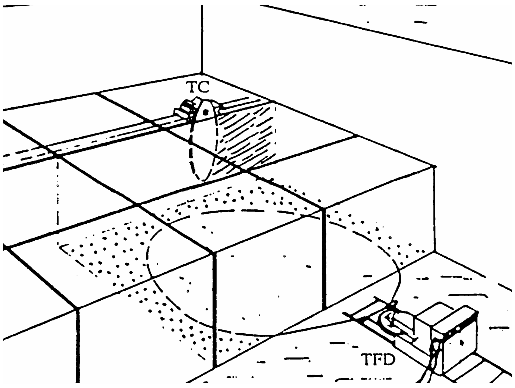


Figure 40. Low step quarrying, using chain saw and diamond wire.

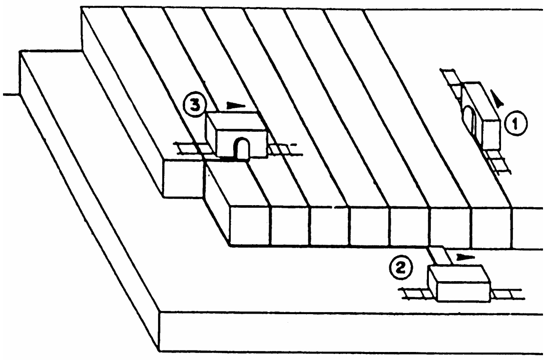


Figure 41. Low step quarrying, only by chain saw (P. Primavori).

Usually, through this operative methodology, the extracted volumes coincide to the dimension of the block (Figure 40). Sometimes the chain saw alone may be used (Figure 41 and 43). In layered limestone quarries, characterised by benches of limited height, the primary cut is sometimes performed by combining wire saws (or chain saws) with splitting (drilling plus explosive or rock breakers). These operations are exemplified in Figures 44 and 45.

Figure 42. Marble quarry: overturning a high bench, cut with diamond wire.

Figure 43. Tuff quarry exploited only by chain cutters (Italy).

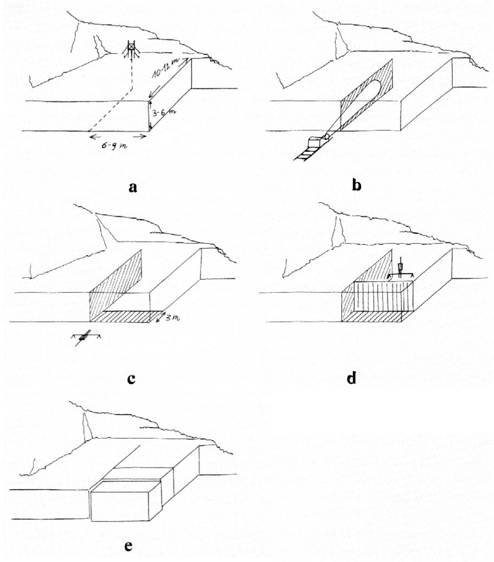


Figure 44. Cutting by diamond wire saw and splitting (F. Bradley).

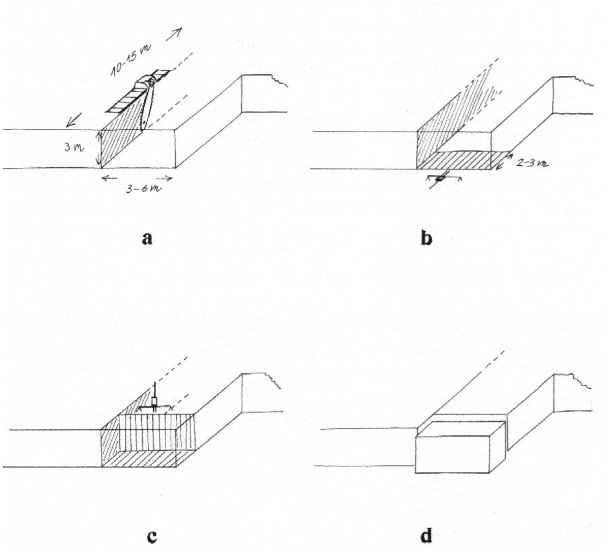


Figure 45. Cutting scheme by chain cutter and splitting (F. Bradley).

2.2. "Hard rock" quarrying

The most widely used cutting technology in quarries of hard and abrasive materials, such as massive granites or stratified gneisses, is certainly the dynamic splitting by detonating cord. Diamond wire is increasingly adopted, at least for the execution of primary cuts (e.g. the vertical side cuts, perpendicular to the quarrying front).

Figure 46. A typical alpine quarry of gneiss, exploited through dynamic splitting technology.

Nevertheless, it is necessary to remember that in very abrasive rocks, like some quartzite rocks, the use of the diamond wire is not suitably applicable. In such cases, quarrying is conducted simply by separating from one another the slab-shaped elements, opening the existing fractures and developing the latent ones as far as possible, without inducing any damage in the rock. In such cases, the technique of "drilling and blasting" (by black powder and dynamite, the latter mostly acting as "booster") and the resort to heavy hammers (acting perpendicularly to the schistosity) still result the most suitable options.

In some quarrying units, particularly of porphyries, the exploitation is traditionally carried out through blasting of mines located at the base of the front, which cause the detachment of great volumes of rock (Figure 47). Anyway the recovery of this method is very low.

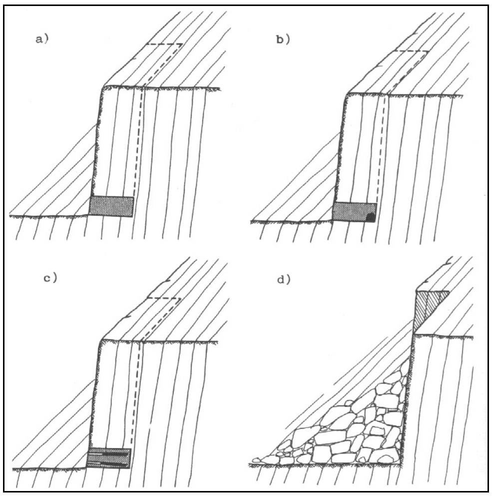


Figure 47. Blasting rounds in porphyries (P. Berry). a) indication of the volume to be removed; b) concentrated charge; c) "plane mines"; d) result of the blasting round.

A comparison among different cutting technologies can be made on the basis of some objective parameters that surely influence the cost and the applicability:

a. volume of rock to be destroyed per unitary surface of cutting (m^3/m^2);

b. average productivity: cut surface per energy consumed in an hour (m^2/kWh);

c. usual range of power of a single machine (kW);

d. limits of height (or depth) *h* and of length *l* of the obtainable cut (m).

Indicative values for the above parameters for soft and hard rock are given in Table 10.

From the point of view of a pure unitary cutting cost, referred to 1 m^2 of surface, dynamic splitting is nowadays cheaper than mechanical cutting. It must not be neglected though that the unitary cost for splitting have to be correctly appraised with reference to the volume of useful blocks produced.

In comparison to other mechanic cutting methods, dynamic splitting causes a greater percentage of waste, whose economic effect depends on the intrinsic value of the material produced. The material value depends on the type of stone but also on the phase of the productive process to which reference is made: since the commercial value of the stone grows with the processing progress, a less “precise” method, in case of highly appreciated material, could be advantageous only in the first stages.

Table 10. Comparison among cutting technologies. S.R. = soft rocks; H.D. = hard rocks

Parameters	**Technology**					
	Splitting		*Line drilling*		*Diamond wire*	
	S.R.	H.R.	S.R.	H.R.	S.R.	H.R.
a. (m^3/m$^{2)}$	0,005	0,005	0,05	0,05	0,005	0,005
b. (m^2/kWh)	0,3	0,15	0,03	0,015	0,2	0,05
c. (kW)	100	100	100	100	50	50
d. (m)	8·∞	8·∞	8·∞	8·∞	10·20	10·20
bxc: (m^2/h)	30	15	3	1,5	10	2,5

- in the case of splitting the diameter ϕ assumed, is the one more commonly adopted for long holes performed through heavy drill (50 mm) and with a distance between centres of about 10ϕ; resorting to smaller diameters, or to greater centre distances, can involve a reduction of the destroyed volume but not necessarily an improvement of the result.
- net production of 1 hour of machine operation is considered; time losses due to installation, changing of tools, charging of holes in case of splitting, etc. are not considered.
- the usual value of the installed power on a single machine is reported; in case of splitting, several machines can easily be employed in a single operation, while this rarely occurs to other methods;
- the symbol ∞ indicates the case in which a theoretical limit does not exist; obviously, also in these cases, the necessity of repositioning the machine to the progress of the cut should be considered in practice;
- the product b×c is the net productivity of a single machine (installed power).

Undoubtedly, the simplicity and the relative inexpensiveness of a method are important factors for its adoption. Nevertheless, other aspects have to be considered as well. Firstly the safety and following the operative flexibility and the adaptability to the characteristics of the rock, along with the minimization of the environmental impacts (Table 11). Furthermore, the most crucial element in evaluating a technology is its ability to maximise the block yield.

Currently, diamond wire is employed in many “hard” stone quarries (Figure 48). Plasticised or rubberised wires with sintered beads (34-40 per meter) are always used, whose performances, both in terms of productivity (m^2/h) and service life (m^2/m) have been notably improved in the last years, passing from non acceptable values (average cutting speed of 2 m^2/h and service life of 2 m^2/m) to results decidedly competitive (4-5 m^2/h and 6-10 m^2/m), recorded in different quarries of gneiss and granite.

Table 11. Comparison between detonating cord, diamond wire saw and mixed methods.

Comparison Elements	Detonating Cord	Diamond Wire	Mixed
Cut accuracy	Low	High	High
Cut productivity	High: 7 – 10 m^2/h	Average: 1 – 4 m^2/h	High: 10 m^2/h
Energy consumption	Low	Average – low	Average – low
Capital cost (Mechanical Equipment)	Low	Average	Average
Tools consumption	Low	High	High
Environmental impact	High	Low	Average
Recovery on primary blocks	92%	98%	95%
Possibility of mechanization process	Low	Average	Average – low
Working conditions	Low	Average	Average
Water consumption	Low	Average	Average
Influence of ore body	Low	High	Average

Figure 48. Examples of lateral cuts by diamond wire in different hard stones quarries. From left to right, coarse grained gneiss, gneiss and granite (Italy).

Besides the wire characteristics, the specifications of the saw machine and the operator’s skill are of great importance. Particularly, the possibility to automatically regulate the tension applied on the wire and to vary with continuity the speed, will allow the maximisation of the yield, avoiding excessive consumptions or breakages of the wire.

The most frequent applications are for vertical side cuts of great benches; horizontal cuts are frequent too, while the employment of the diamond wire in sectioning phases is not yet “profitable” (Figure 49). Therefore, in the medium-term, the mixed employment of dynamic splitting and diamond wire, through a progressively widening of the use of the latter, seems to be the fittest technique for an optimisation of the block yield and a reduction of rock wastes (also in the following phases of processing in laboratory), consequently limiting the increase of operational costs.

It should be considered that "drilling & blasting" for hard stone primary cutting will not result great improvements, mainly because the productive cycle does not allow a serious automation, thus keeping high labour costs. Moreover, problems linked to noise, vibrations and unexpected rock projections impose restrictions to the method, especially close to towns or roads. As detonating cord splitting is a simple and mature technique, progress is expected only in the drilling phase of the production process: more productive drills and, above all, more accurate guidance[5].

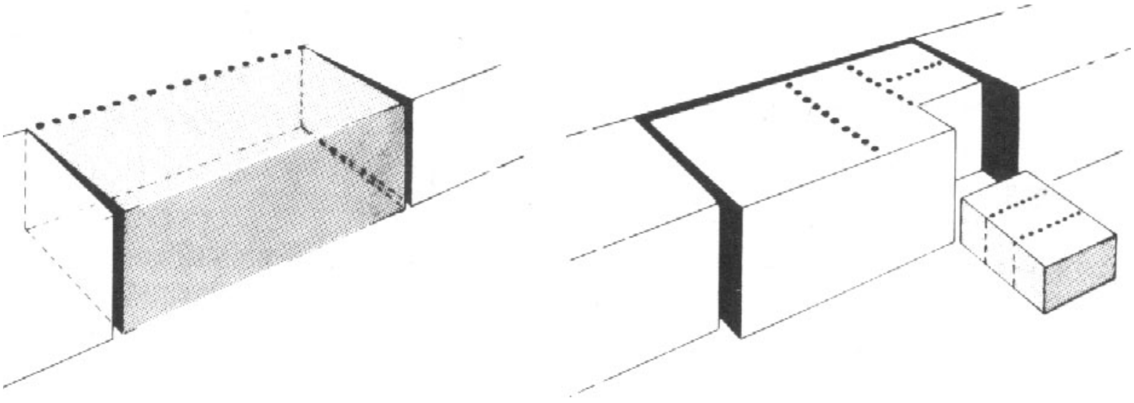


Figure 49. Cutting scheme in hard and abrasive rock through the creation of lateral cuts by diamond wire.

As far as diamond wire sawing is concerned, the wire itself is the biggest part of the total production cost but substantial progress is still possible: for instance, researches are carried out about the optimal bead matrix for different rock types[6], the rubber coat quality to avoid metal cable wear, etc. Further efforts should be made, in order to improve safety conditions of diamond wire use; accidental wire breakages are still very dangerous because of wire lash and throwing of beads or other metallic parts. Finally, global reliability and service performances of diamond wire could still improve in abrasive stones.

2.3. Handling technologies

With "handling" are referred all the operations of loading, unloading, lifting, moving, etc. that concern either the extracted material (marketable or waste) or the operative

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[5] A radical innovation could be, in the future, the employment in quarry of ultrasonic drills, currently employed, still at the experimental stage, for the drilling of glass and ceramic materials (IFW – University of Hannover).

[6] This aspect is very important, in fact, analysing the characteristics of the recovered diamonds, by chemical dissolution, from the flood water produced during different cuts by wire, it has been observed that averagely around 40% of the diamonds shows dimensions not much reduced in comparison to those original, therefore indicating that they have been prematurely detached from the bead (a phenomenon defined as "pull-out") because of the excessive wear of the matrix, without having completely developed their "work".

machines. The equipment universally used for these operations are loaders and hydraulic excavators (Figure 50).

The tracked loaders – slower and with a more limited range of operation in comparison to the wheeled loaders – are preferred when a good traction and the ability to act in narrow spaces are needed. Vice versa, the wheeled loaders have a very wide range of operation, showing good flexibility of use. Together with the wheeled loaders, the hydraulic excavators are essential for quarrying activities of a certain dimension and elevated productive level, being usefully employed in every phase of the quarrying cycle (Table 12).

Figure 50. Wheeled loader equipped with "fork" for loading of marble blocks on truck.

Table 12. Possibilities of use of earth-moving machines in quarrying operations.

Job	Wheel loader	Track loader	Excavator
Removing and dumping earth and debris	effective	effective	effective
Making and maintaining quarry yard and ramps	effective	effective	fairly adequate
Making debris bed for bench tipping	effective	fairly adequate	effective
Tipping benches	effective (with ropes)	effective (with ropes)	effective
Block handling	effective	fairly adequate	fairly adequate
Equipment handling	effective	fairly adequate	not suitable
Wastes handling	effective	fairly adequate	fairly adequate
Removing portions of fractured rock	not suitable	not suitable	effective
Crushing shapeless blocks	not suitable	not suitable	effective (demolition hammer)
Installing drilling equipment	not suitable	not suitable	effective

Finally, an outline about the "derrick crane" lifting system is worth to be made, as it is still used in many stone quarries both hillside and flat land pit (Figure 51). In some quarries, where the morphology does not allow for a traditional access through ramps, it is an irreplaceable mean. Some models with a 70 m long arm, can serve an area of over 6.500 m².

The principal limitation of the derrick is its fixed installation: therefore, its position should be very carefully decided according to the development plan of the exploitation. Furthermore, as far as impact to the landscape is concerned, the presence of a derrick may cause a certain temporary visual impact, but reparable in some extend with "camouflage" painting.

Figure 51. Derrick crane in a hillside marble quarry (Italy).

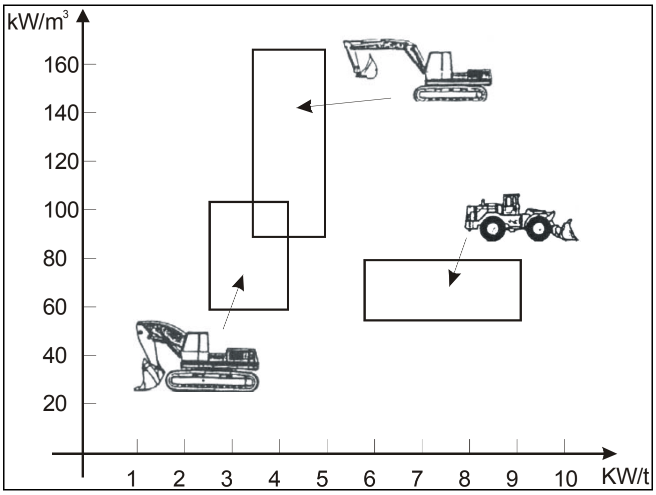

Figure 52. Usual ranges of the relation power/weight and power/capacity of some types of machines commonly used in dimension stone quarries (R. MANCINI, M. CARDU, 2000).

2.4. Conclusions

In conclusion, a synthetic description of some representative cases of European stone quarries is given (Table 13), indicating the geo-morphological situation, the method and the technologies of exploitation adopted.

Table 13. Synthetic description of some representative cases of European stone quarries

Location	Rock type	Quarrying methods	Technologies
Ylämaa - Finland	Rapakivi granite – Massive deposit	Surface pit	Hydraulic drilling machines, K-pipes, detonation cord, hydraulic wedging machines
Juuka - Finland	Soapstone – Massive or schistose deposits	Surface pit	Electric chain saw machines with abrasive hard-metal segments
Larvik and Porsgrunn - Norway	Monzonite (Larvikite) - Massive deposits	Opencast hillside and surface pit	1-2 directions wire cutting, horizontal and/or one vertical cut by dynamic splitting
Eigersund and Hå - Norway	Anorthosite - Irregular vein shaped deposit	Opencast hillside	1-2 directions wire cutting, horizontal and/or one vertical cut by dynamic splitting
Fauske - Norway	Calcite-dolomite marble - Inclined vein	Opencast hillside	Diamond wire cutting
Oppdal - Norway	Quartzitic schist/semi-schist - Inclined vein	Opencast hillside	Dynamic splitting
Granitis, Drama - Greece	Dolomitic marble	Surface pit	Diamond wire sawing, hydraulic wedging
Thassos - Greece	Dolomitic marble	Surface pit	Diamond wire sawing, hydraulic wedging
Luserna S.G., Bagnolo P.te, Rorà - Italy	Leucogranitic orthogneiss - Sub-horizontal vein, with a marked foliation	Opencast hillside	1-2 lateral wire cutting, vertical back cut by dynamic splitting, wedging
Valdossola - Italy	Orthogneisses	Opencast hillside	Dynamic splitting, 1-2 lateral wire cutting
Carrara - Italy	Metamorphic marble – Massive deposit	Opencast hillside, surface pit, underground rooms and pillars	Diamond wire sawing, chain cutting
Sardinia - Italy	Granites – Massive deposits	Surface pit	Dynamic splitting, primary cuts by diamond wire
Alicante - Spain	Dolomitic marble – Massive deposit	Opencast hillside	Diamond wire sawing, chain cutting

3

New quarrying methods and technological progress

MARILENA CARDU, ENRICO LOVERA, GEORGE V. CRASSOULIS

3.1. Introduction

An analysis of the technological evolution in the last years points out that the greatest improvements are more due to refinements and optimisations of systems already employed, than to the introduction of technologies based on completely new principles of operation.

In the quarrying practice, the use of the diamond has been the protagonist of the technological development, together with the spread of powerful loading machines and hydraulic excavators, which has allowed for great increases in productivity. From a conceptual point of view, the only innovative technology of the last years, based on completely new principles of operation, is the water-jet, which however still needs improvements to make it competitive in a quarrying context, from an economic point of view.

Apart from the introduction of new materials, the most important technical evolution has to be attributed to the use of electronic components and automatic control devices in the cutting machines. To appraise the impact of the technological evolution on the stone production, the case of the exploited deposits in Carrara (Italy) can be observed. About the 30% of the whole quarried material in 1000 years has been produced in the last 20 years; that is after the introduction of the diamond wire and the spread of powerful handling machines.

Consequently, since the ‘70s, the absolute production has progressively grown to over 1.000.000 t/year (Figure 53). The comparison between the number of workers and the productivity is very interesting too: technological progress has led to a drastic decrease of workers employed in quarrying operations, dropping from over 9.000 employees in the ‘30s to less than 1.000 today, with an increase of productivity at the same time, from about 10 ton/worker to around 1.500 ton/worker per year (Figure 54).

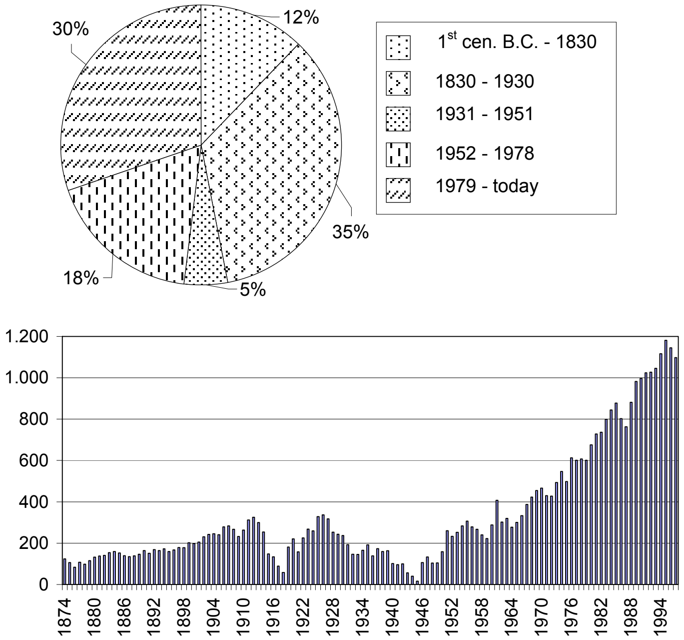

Figure 53. Trend of the production of Carrara marbles since the 1st century B.C. (upper figure) and annual production (thousand of tons) since 1874 (lower figure).

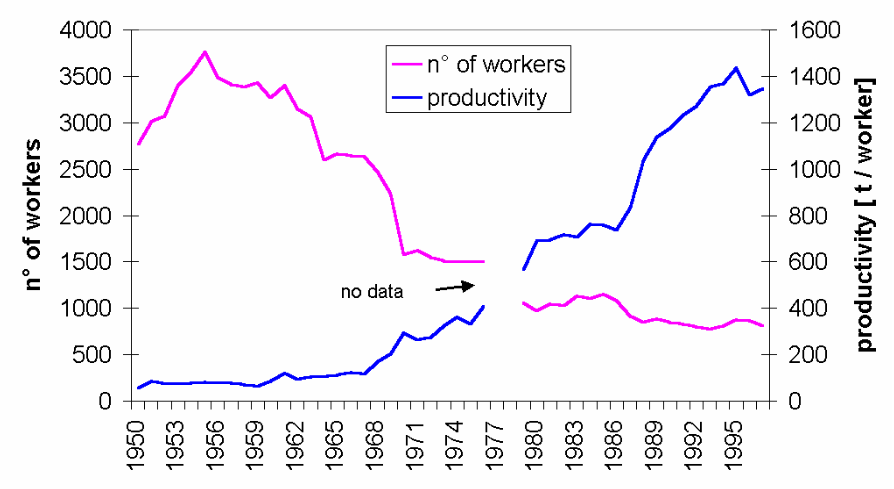

Figure 54. Trend of the number of quarry workers, compared to the productivity.

In “soft” stone quarrying sector, the modern practices described in the previous chapters and used in the most modern situations are a good foundation for the optimisation of production and yield; however, further improvements can be expected.

Researches currently in progress, particularly on diamond wire and chain saw, actually converge on the general objective of predicting the performance of a certain machine on a certain rock type and the variations of this performance caused by changes of the rock characteristics, modifications of the machine and the relative tools, and finally by simple variations of the operation parameters. In short, research aims to introduce and test some cutting operation models, in which all the variables can be set in order to predict their influence on the productive goals.

The possibility of resorting to more efficient technologies, specifically developed for the quarrying of a certain lithotype, is progressively becoming an essential presupposition for the exploitation of stone deposits in a rational way, in order to reduce waste production and maximise the recovery.

For “hard” stone quarrying, the mechanisation is not yet completed. In fact, in primary cut and sectioning operations traditional techniques are still frequently applied. Such technologies, even if “refined” by long experience and applied correctly, are less “precise” and often proven to be neither efficient nor appropriate for maximising deposit performance.

As already pointed out, the mixed use of dynamic splitting and diamond wire, whereas applicable depending on the characteristics of rock and the climatic conditions, seems to be, in the medium-term, the best technique for optimisation of the block yield and reduction of produced waste. Nevertheless, the use of diamond wire, especially in abrasive rocks, requires skilled workers for its optimal use and, therefore, only its systematic use can make it competitive.

3.2. Underground quarrying

Underground exploitation of dimensional stones has ancient origins: it was used more than one thousand years B.C. in some Egyptian quarries; the statuary marble from the island of Paros in Greece, was extracted by underground exploitation; in the Roman age many underground quarries were operated in the limestones of the Italian Karst. Probably, the technical impossibility to remove thick overburdens, suggested to the ancient quarrymen the method “follow the rock with the best qualities in the mountain”. Today, the reasons that can lead to an underground exploitation are manifold. This method may as well present several technical difficulties and involve greater (at least initial) costs (Table 14).

Firstly, one reason for adopting the underground method is the bad structural condition of the rock body which can make the opencast quarrying problematic. High superficial fracturing or occurrence of non-exploitable cap rocks above the exploitable rock demand selective exploitation. In this case an underground method allows quarrying the marketable materials, with a higher overall block yield. Besides, the elimination of costs connected to the removal of cap rocks and the general reduction of materials to be disposed in dumps are certainly positive aspects, to which less impacts on the landscape and local environment should be added: actually, only adits and possible buildings on the quarry yard will be visible.

Another reason is that underground operations could be carried out independently of the weather conditions, avoiding unproductive pauses of operation. Finally, the creation of stable wide spaces can be an economically positive factor in the future, since the spaces can be reused at the end of the exploitation. For example, waste rock could be relocated into the created spaces helping in the long term stability of the voids and representing a final solution to the visual impact problem caused by waste dumps that grow along the slopes or over flat areas around the quarries.

Table 14. Main positive and negative aspects of underground exploitation.

Motives	Positive aspects	Negative aspects
characteristics of the rock body	- more selective exploitation - impossibility of an opencast exploitation	- more accurate prospecting and geotechnical investigation; - difficult characterisation of the rock body - possible complication during the exploitation (presence of faults, ground water, etc...)
technical and operational	- no stability problems of high and steep slopes - possibility of working independently on weather conditions	- detailed studies for the opening stages - stability analysis of rooms and pillars - need for technical direction with underground experiences
economical	- removal of overburden is avoided - less production of waste rock and possibility of disposing it into the created voids - reduction of costs for environmental rehabilitation - possible economical re-use of the voids - nearly unchanged value of surface soil	- higher cost of the project - higher cost and less production in the early stages - bigger investments - cost for possible systematic works of consolidation (bolting, etc.)
environmental	- less visual impact - reduction of rock volume to be disposed in dumps - possibility of quarrying even in protected areas	- possible long term stability problems - possible interference with ground waters

The application of an underground method though requires the consideration of various aspects concerning the creation and control of the underground structure. Obviously, long term stability of the voids must be guaranteed, demanding for suitable rock mechanics studies and assessments, monitoring and control during operation, which could not depend only to the experience or sometimes irresponsibility of the workers.

Higher costs in the early stages of the activity should be expected, considering also that a part of potentially exploitable material has to be left in pillars. Moreover, lighting and ventilation systems are needed in underground quarries, and safety and health problems, which could be amplified in confined spaces, should not be neglected.

However, the relatively smaller cost of an opencast exploitation has to be re-evaluated considering the limitations that are generally imposed to extractive activities, in a continuously more domineering way. For instance, the costs of a satisfactory environmental rehabilitation of an opencast quarry are definitely not negligible in the budget and, above all, they must be evaluated from the beginning of the activity. Furthermore, in a situation in which the available areas are small and the authorised quarry sites are strictly defined, a surface excavation can lead to unacceptable situations (e.g. pit configurations with high and potentially unstable fronts), from both a technical and safety point of view. A consequence of such environmental and technical bounds can be the progressive reduction of opencast quarrying activity and, on the other hand, the development of underground activities.

As before mentioned, this trend is already marked for soft stones – for instance, in the extractive basins of Carrara, where about 100 quarries are active, 30% of them are working underground – while for hard rocks only a few quarries are exploited underground all around the world. The principal reason is connected to the available cutting technologies: in fact, while diamond wire and chain saws are directly usable in underground spaces, the methods traditionally used for the exploitation of “granites” (dynamic splitting and flame-jet) are not easily usable in closed and confined spaces.

A further development of the water-jet technology, combined with the diamond wire, will be probably able to guarantee, in a next future, economically sustainable productions in hard stones, realizing an operative system potentially equivalent to the chain saw in “marbles” (Figure 55).

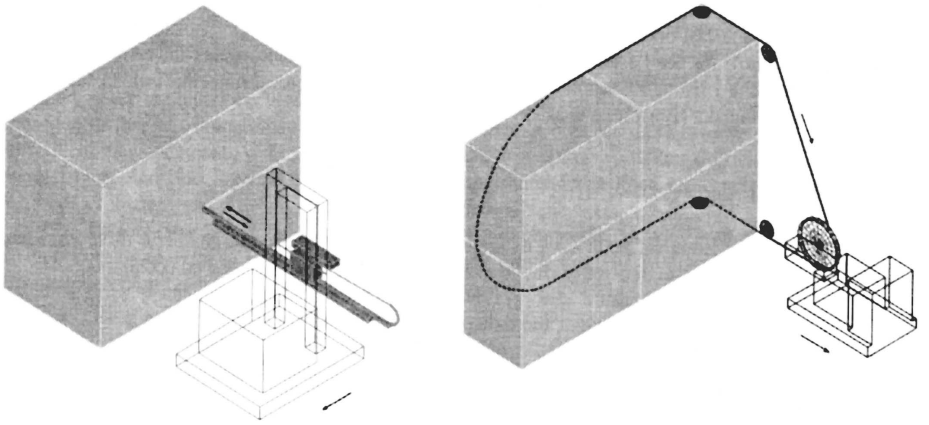

Figure 55. Possible underground quarrying scheme through the use of hydro-jet and diamond wire saw (R. Ciccu et al.).

In the following paragraphs, two examples of optimisation of underground exploitation for dimension stones are presented; in the first one, a detailed description of the underground experimentation in the green quartzite of the Spluga (Italia) is given[7]; in the second one, the results of a European project (Brite Euram Project – BE 5005) on “Development of an integrated computer aided design and planning methodology for underground marble quarries” are reported.

3.2.1. Experimental underground quarry of abrasive and hard stone

The quarry is located in the Chiavenna Valley, in the central Alps (Italy), at an altitude of around 1.500 m. The exploitation has been conducted opencast until two years ago, when the morphological and structural conditions of the deposit along with some limitations connected to the visual impact, because this zone is highly appreciated from

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[7] The initial phases of this experimentation have been described in the OSNET Edition – Volume 2 “Dimension stone quarrying in Europe and stability of quarrying operations” (page 49).

a tourist point of view, have not allowed for further surface developments. The quarried stone is a metamorphic green quartzite commercially known as “Verde Spluga”. The deposit forms a 30 m thick bank within an 80 m high vertical slope.

A blind drift was first driven, in the direction of the quartzite bench, with a height of 6 m, a width of 5 m and a length of 5 m. The excavation advanced with heading, lowering and widening of the first tunnel. Today a long room has been created, 10-12 m wide, 20 m high and 30 m long. First of all, the experimentation has allowed verification of the technical feasibility of underground quarrying in such material, identification of a certain variability of the “ornamental” characteristics of the rock and confirmation of the deposit “unpredictability”. Therefore, considering the results of the continuous geomechanical control that will be conducted progressively, the project choices related to the quarry layout have to be definitely “flexible”, without though escaping from the aim of guaranteeing the operational safety and the long-term stability of the structures.

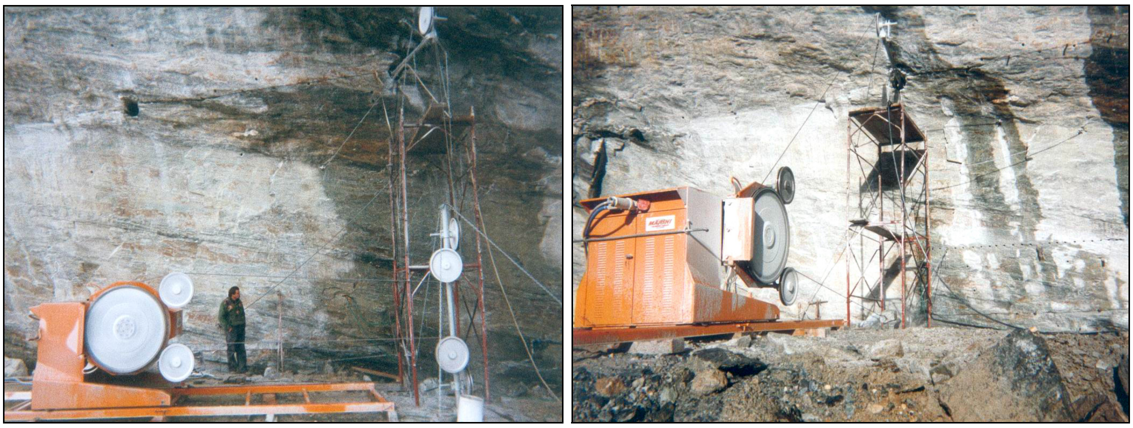

Figure 56. The first vertical cuts of the experimental underground quarry: on the left, lack of space for the machine positioning lead to setting a special idle pulley structure at an angle of 90° to perform the cutting.

Regarding the exploitation technologies, experimentation has allowed reaching a good level of optimisation, verifying different operational solutions. The combined use of diamond wire and dynamic splitting proved to be the most reliable and productive technology. The diamond wire employed is the standard type for the cutting of abrasive rocks, with 40 sintered beads per metre and covered by a rubber coat, while the explosive used is the 12 g/m PETN cord is used. Operationally, the underground exploitation of the quartzite foresees the quarrying of a primary wedge of rock (Figure 57), beginning from the roof of the future room, which coincides in this case to the natural surface of discontinuity. The presence of such sub-horizontal surface allows the detachment of the upper part of the wedge, without resorting to further cuts, hence guaranteeing the creation of a “clean” roof.

However, the continuity and the “regularity” of this natural surface had to be progressively assessed, and in some cases proceeding to local supporting of potentially unstable portions of the roof (bolting) was needed. The side surfaces of the upper wedge are cut by diamond wire, through descending loop configuration: the loop for the passage of the wire is created by two convergent holes, one parallel to the roof of the tunnel, the other one inclined. Because of the narrow angle that the wire is forced to complete during the cutting, it is imperative to maintain a high speed of rotation of the wire (around 30 m/s), reducing in the meantime the traction transmitted by the withdrawal of the machine, in order to reduce the wear of the wire and diamond beads.

Figure 57. The tunnel-quarry in the first productive phases. On the right, a detail of the cut of the upper wedge.

In the opening phases, a rather low cutting speed is recorded (about 1 m²/h), because of the difficult operational conditions. The inclined face of the wedge is made through the blasting of detonating cord placed into a series of parallel aligned holes (30 mm in diameter, distance between centers of about 200 mm) (Figure 58).

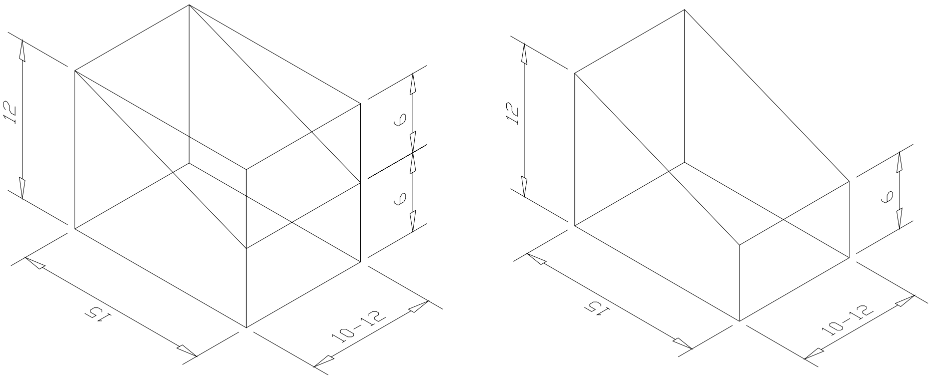

Figure 58. Geometric scheme of typical wedge extraction – first phase of the “upper void” creation. The vertical development of the room is related to the presence of other underlying exploitable quartzite banks.

Once the wedge is “blasted” (a reduced block yield is obtained from it), it is possible to square the bench and turn back to a stepped exploitation (Figure 59). The two side cuts, for the productive extraction of the underlying volume, are always performed by diamond wire, through descending loop configuration: a loop is realized by two convergent holes at an angle of 90°, coincident to the bottom and lateral edge of the advancement. In these phases, maintaining the speed of the wire at around 20-25 m/s, a cutting speed of 2,5 m²/h has been recorded, with a service life of the wire of about 10 m²/m.

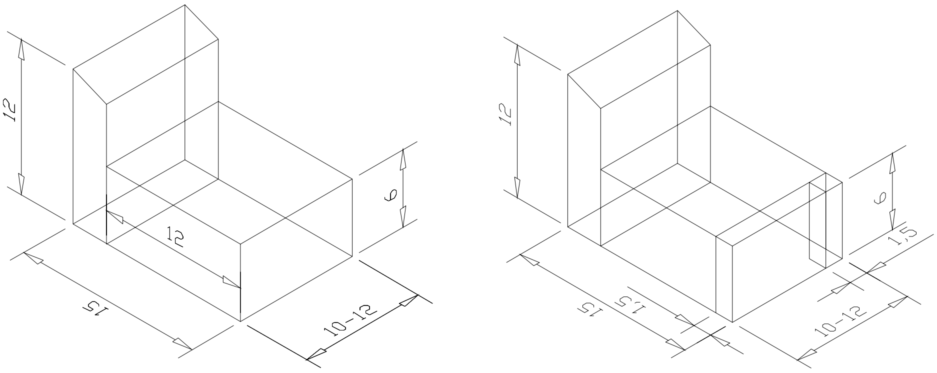

Figure 59. Geometric scheme of typical tunnel advancement – second phase of room exploitation. Right, scheme of opening cut of the side "block" and indication of the first "slice".

The back cut and the base cut of a slice is done by dynamic splitting, through analogous principles to an opencast exploitation. The detached slice has the following average size: 6 m high, 1,5 m deep and 10-12 m wide. The following separation of 7-8 "slices" exhausts the single advancement, with a total depth of about 12 m (Figure 60).

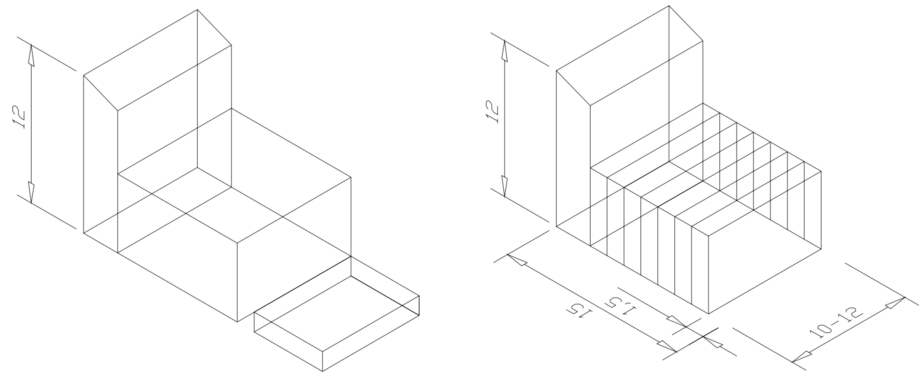

Figure 60. Geometric scheme of typical tunnel advancement – third phase of exploitation of the room: left, overturning of the first slice; right, exploitation of the bench through the cutting of a sequence of slices.

3.2.2. Optimisation of marble underground quarries

The project started in October 1998 and was completed in March 2002, with the participation of some of the biggest marble companies and the most prestigious academic institutes.

The research project is addressed to both already operating underground marble quarries and quarry owners that intend to go underground, and it can provide new, improved design and planning optimisation techniques for underground quarry exploitations. These techniques, will allow prediction of the most cost effective and safe quarry layouts that will lead to maximum block yield of such sizes and quality that the market demands.

Through the project a Decision Support System was developed, which given all the necessary input, can provide accurate answers to questions that make decision makers reluctant to proceeding to underground exploitation, such as: “Will underground exploitation be profitable to my company? Will the underground quarry be safe? Which are the optimum quarry layout, so as to have the maximum recovery and safety?” The project comes to give answers to these questions and help the businessmen of the quarry industry to rationalise their decisions.

Optimised underground marble quarrying depends in the first place on the geological conditions, secondly, on the technical possibilities of marble recovery and lastly on economic factors. Like other mineral deposits, all marble deposits appear to be characterised by an individual property pattern. Consequently, there is no generally binding formulary solution to the optimisation of marble recovery, but only the consideration of a complex system of geological and geotechnical conditions that vary from one deposit to another.

In evaluation and optimisation of underground quarry sites for marble mining, the role of the overall geological situation must take priority. The geological evolution of a marble deposit decisively influences the volume and quality of the rock to be exploited. In order to take into account and to predict such volume and quality variations in a marble deposit, the availability of small-scale geological maps is urgently needed. Existence of such detailed maps with lithologic and tectonic information is, therefore, important for a decision process.

Figure 61. Underground marble quarry in Greece.

The following aspects should be considered regarding position and orientation of the underground quarry site with respect to the geological and geo-morphological situation:

- <u>starting point of the excavation:</u> in order to proceed from existing surface quarries to underground quarrying, the definition of the entrance or starting point of the excavation is important. Optimisation of the starting point must take in consideration the geometry of the productive marble layer, the geo-morphology and the access to roads.

- slope effects influencing the excavation in near surface positions: the existence of a-tectonic fractures more or less parallel to the slope, is interpreted as the result of stress release in the vicinity of open quarries which (together with karsts) will reduce stability and block size in near surface areas of the underground mine.
- karst effects influencing marble quality and rock mass stability: In near-surface places the impact of karstification processes and products to the marble quality and quantity and on marble mass stability can be serious. Due to ground and surface water activity occurring in fractures, calcium carbonate resolves in water and enriches non-carbonate, often clayey, substances. Another important effect is the discolouration due to iron oxide formation. As a consequence of karstification-related opening of fractures and due to clayey infillings the mobility of blocks in the marble mass is increased and consequently the stability decreased.
- type of overburden and contact or transition between marble and overburden: type and thickness of overburden and the transition between marble and the overburden are important parameters in planning the position of a future underground excavation. Transition zones, e.g. between marble and schist, may result rocks of low quality and low stability.
- primary vertical and horizontal marble quality distribution and shape of the deposit: on the basis of detailed mapping of the marble deposit in neighbouring surface quarries, the vertical and horizontal distribution pattern of marble qualities at the underground site can be assessed. Likewise, the possible geometric shape of the productive marble bodies can be derived from geological mappings.
- structural features (e.g. folding of the productive marble layer): quality distribution is not only influenced by the primary faces differentiation but also by the structural character of the deposit.
- existence of fault zones affecting continuity of the marble deposit and the intensity of karstification: the existence of fault zones in the marble deposit area could influence the continuity of the productive marble horizon which on the other hand would result increased density of discontinuities and reduced block sizes. In addition, fault and shear zones tend to increase the depth range of karstification.
- influence of the discontinuities pattern to the preferred orientation of the excavation: in order to produce an optimum amount of large rectangular blocks, the orientation of the excavation rooms should be adapted to the prevailing discontinuity pattern.
- existence and orientation of schistosity and its influence to marble block quality and workability: schistosity is one of the structural features of marble, that is less easily and frequently observed but may strongly influence the workability of the marble blocks. In order to detect any preferred orientation of the marble calcite grain and accessories, petrological studies under the microscope will be advisable.

One of the most important aspects in designing underground quarry exploitations is the knowledge of the strength and deformability characteristics of the rock mass to be exploited, besides the geometrical and mechanical characteristics of major individual rock joints. The size, orientation and shape of the underground rooms are strongly influenced by the bearing capacity of the natural support structures (e.g. pillar, rock wall, and roof). In order to provide a sound experimental basis to the planned program of the quarry excavations, a wide set of experimental tests on rock specimens was carried out (Table 15). The data from laboratory characterisation tests were required in order to correctly interpret and evaluate the signals from the monitoring system (which will be also installed), to model the mechanical behaviour of the structures under study and, generally speaking, the design of the experimental stopes.

Table 15. List of the specimens requested to perform the tests.

Test	Sample shape	D (mm)	H (mm)	L (mm)	S (mm)	Number of samples	Number of Tot. samples
Uniaxial compressive strength	cylinder	54.74	150			10 x 3	30
Pseudoelastic Constants	cylinder	54.74	150			10 x 3	30
Deformability Moduli	cylinder	54.74	150			10 x 3	30
Triaxial compressive strength	cylinder	54.74	110			20 x 3	60
Uniaxial tensile strength	cylinder	30.10	90.3			10 x 3	30
Indirect tensile strength	disk	54.74			27.4	10 x 3	30
Shear test	cylinder	54.74	110			10 x 3	30
Toughness	beam		82	320	40.5	10 x 3	30
JRC	prism		120	120	120	3 x 3	9

If the preliminary study were positive, a pilot gallery would have to be excavated. The objective of this stage was to create a room around a pillar, in order to install the appropriate instrumentation system. The dimensions of the pillar and room were decided, according to the local conditions of the quarry, by the institutes which undertook the consultancy service. Normally the dimensions of the pillar were between 15x15 - 20x20 m and the cross section of the gallery was 4,5x6 m^2.

The equipment that was required for the underground works differs from the surface exploitation. Thus new machinery was purchased for the creation of the pilot gallery. The most important machines for the project were: a tunnelling chainsaw machine (Figure 62) which has the ability to perform vertical cuts of 4,5 m height and horizontal cuts, one at the floor level and one at the ceiling level (4.5 m), a drilling machine which is capable of installing rock bolts. Rock bolting is the most effective and simple support system for underground works. A typical bolt is 3 m long and it is anchored with resin capsules.

Ventilation system was installed in the underground site (Figure 63). The selection of the proper fan and the design of the ventilation system are of vital importance for the creation of the proper conditions of health and safety. The factors that have to be taken into consideration are the cross section of the galleries, the quarry layout, the galleries' length, the total horsepower of the diesel engines and the number of the workers.

Except for the above machinery, equipment used at the surface quarrying was also used for underground works, such as wire saws and jackhammers.

While excavation of the experimental site was in progress, thorough investigation of the rock mass geomechanical properties through both field surveys and laboratory tests took place. Based on the data collected, development of the 3D rock block models and of the appropriate numerical models of the system roof-pillar-floor commenced. The development of the computer simulations continued until both the 3D rock mass block structure and the observed behaviour of the test pillars were replicated and calibrated the computer simulations. At that stage the most possible rock block data base and the rock mass mechanical behaviour models were available for use at the optimisation stage.

Figure 62. Tunnel chain caw on tracks.

Figure 63. The intake (fan) of the ventilation system.

The developed rock block data base was used in planning the optimal quarry layout for maximum block yield of such sizes and quality that market demands. This was achieved using the computer based decision support system (originally developed in the Project). Input information for the system was the rock block data base, alternative quarry layouts (i.e. orientation of the exploitation, and pillar and span size), exploitation plans and the value of the exploitable blocks in relation to their size, their natural characteristics (i.e. discontinuity free blocks, colour heterogeneity, anisotropy) and the exploitation cost. The decision support system, suggested the most possible cost effective quarry layouts, by examining all possible combinations of the above factors. These possible quarry layouts were then checked from the stability point of view using the appropriate discrete element model, based on the calibrated numerical models developed during the previous stage. Thus, for each underground opening the optimum layout which satisfied cost reduction, safer conditions and maximum saleable block yield was predicted. The main benefit from the application of the methodology described is the introduction of scientific knowledge to the design of the quarry layouts with all the aforementioned benefits.

Until now there was no alternative to the application of the methodology, except the empirical methods used in the past. These methods can not give accurate information about the expected recovery, the optimum dimensions of the room and the pillar, the optimum gallery orientation and the support system. This has the following disadvantages:

- parts of the deposit may left unexploited due to bad planning. Because of the nature of underground marble exploitation (from the upper floors to the lower) is extremely difficult to exploit the remaining part, if not impossible.
- the support system might be either inadequate or exaggerated. The first case leads to reduced safety and the second to increased cost. With the application of the described methodology though, balance between safety and cost can be achieved.
- the dimensions of the room and the pillar are not optimised. It is possible to have too small rooms and too large pillars, which lead to lose of valuable irreplaceable material. On the other hand if the mechanical strength of the rock is overestimated it

is possible to have critical conditions, which will lead to the direct abandonment of the quarry, since almost nothing can guarantee the safety of the personnel and the machinery, after a pillar has started to fail. An example of bad estimation of the situation at the Carrara area is very recent. At that quarry a pillar reached 65 m height without any additional support, or crown pillars. This, combined with the surrounding works, which did not take into consideration the existing opening, led to failure of the pillar and the direct cease of all works.

- the insecurity that exists about the underground conditions holds back many exploiters from expanding their works to underground.

Underground quarrying is in many cases the only way for a quarry to proceed, for two reasons:

- big thickness of overburden, which gives a too high reveal ratio that makes the exploitation not profitable.
- reduced environmental impact of underground works. Underground works have less waste, since there is not overburden to remove. Additionally the recovery is higher at underground exploitations because the parts of the deposit with the lower quality can be left as pillars. Finally they are sound-proof and the noise never causes disturbance to the nearby residents.

Thus if it is considered that marble is irreplaceable natural resource it is easily understood why the exploitation should be performed rationalistically and the only way to achieve this is by the application of a scientific methodology.

3.2.3. Conclusions

It is necessary to underline that, independently from the method of exploitation and the extracted lithotype, one of the principal problems to be faced in underground quarries, either during planning or quarrying, concerns the stability of rooms and pillars.

Therefore, in the creation of great underground voids, the investigation on the geologic and structural formation holds a fundamental role: besides recovery, and apart from operational risks consequential to possible falls of rocks and uncontrolled separations of blocks, the completeness and the precision of the rock mass characterisation is directly proportional to the accuracy of the campaign of preliminary investigations. These factors affect in a decisive way the reliability of the “geomechanical model”, on which every project calculation and/or stability assessment of the exploitation has to be based. Particularly, in case of complex geometries, the behavior of the rock must be studied by applying an approach that integrates the numerical methods to the continuous control and geomechanical monitoring. On these important aspects, for a specific close examination that is beyond the purpose of this edition, it is suggested to refer to the OSNET Edition, Volume 2 – Part B “Dimension stone quarrying in Europe and stability of quarrying operations.”

However, the underground quarrying should not be seen as a universal “solution” for the stone quarries, but only as a possible quarrying technique, feasible in some geo-morphological configurations. In fact, the consequences of “adventurous” choices are already verifiable during the exploitation, in form of scarce performances and higher operating costs. But the most disastrous effects can be found at possible instabilities of the produced excavations – both underground and surface.

Finally, for new quarries the underground option should always be preventively considered, after the necessary prospecting, in order to plan it with technical correctness and without prejudice, neither for the original morphology nor for the integrity of the deposit. On the contrary, a systematic turn of opencast quarries to underground can not be always considered as a correct application of mining methodology and a sustainable strategy of quarry planning, especially where the voids have a potential interference with the stability of the natural slope.

However, without the wrong generalisations, probably in many quarrying basins, today characterised by very high fronts and not much safety for the workings, a further development will be possible only through underground exploitations.

4

Waste management and environmental rehabilitation

MARILENA CARDU, ENRICO LOVERA

The social concern about environmental aspects, which is increasing constantly in the European countries the last twenty years, has led authorities to impose various rules and norms to the stone productive activities. Among other industrial sectors, quarrying is also a target for preventive measures of "censorships" due to its impacts on environment and landscape; impacts that are the inevitable results of quarrying.

In the particular case of dimension stones exploitation, quarries most of the times are gathered together in areas where the stone resource is present with the quality and the quantity required. This fact has serious effects to the environment such as: visual impact from the fronts and the huge stone dumps, water and acoustic pollution, dusts and vibrations, territorial disarrangements, etc. On the other hand, there is the economic and occupational importance of the sector and its consequent activities, especially in areas deprived of other important productive alternatives. Another fact is the cultural importance of widely appreciated and traditional materials. All these must serve towards the search for a point of sustainable balance among socio-economic demands and protection of the environment.

The constitution of huge set of rules, complex and not always coordinated, seems to create a tight framework in which quarry operation is practically impossible. The result of such politics may be anything but positive. Closing-down stone quarrying activities imposes shrinkage in local, social and economical development. As a result, quarrying activity is pushed towards developing countries, which are environmentally unprotected, hence putting off the problem to the near future.

Therefore, it becomes necessary to conduct constructive dialog between norm and routine, so that the predisposition for a precise normative frame and the adoption of up-to-date and efficient technical procedures will lead to the sustainability of the stone quarrying activity. A correct methodological approach for a rational management of the stone quarrying activity can be found in the followings points:

- correlation of geo-deposit situation, territorial planning and economic management;
- planning of the exploitation program and rehabilitation measures for the quarrying area, in accordance with the impacts (procedures for assessment and verification of the environmental impact);
- management of the activity according to the authorised program, adopting the best operative procedures and available technologies, in terms of productive efficiency, operative safety and environmental control;
- realisation of the environmental rehabilitation at the same time with the exploitation phases, with final rehabilitation of the quarrying area according to the surrounding territorial dynamics.

In other terms, there are three different subjects from the integration of which the profile of an optimised and sustainable stone quarrying activity can emerge: the assessment of compatibility in the project phase; the sustainability of the operative phases; the necessity of the rehabilitation and the opportunity for after-use of the quarrying sites. Among the issues that the European quarrying industry has to face, the most urgent are probably the low yields of exploitation and the consequent production of huge quantities of waste.

Recent data about the world production of stone indicate that, consequently to a gross quarry production of over 65.000.000 ton of dimension stone, the quantity of waste has amounted to around 65.800.000 ton. However, considering also the waste of the following processing phases, the total stone waste production that have to be managed, comes to a total of 90.000.000 ton per year (Table 16).

Table 16. Worldwide production of dimension stones, with indication of the quantities of produced waste (source: Stone 2002).

Activity	Parameter	ton	m^3	%
Quarrying	gross extraction	130.800.000	48.450.000	100
	gross production	65.000.000	24.080.000	49
	quarry waste	65.800.000	24.370.000	51
Processing in laboratory	gross processed	65.000.000	24.080.000	100
	neat production	38.350.000	14.210.000	59
	processing waste	26.650.000	9.870.000	41

A low output of usable ornamental material leads inevitably to a larger presence of open stopes and the creation of great waste dumps in proximity of these stopes, residual of the quarrying activity. Such dumps are often an obstacle for the rational development of the activities. In fact, they may cover some portions of potentially exploitable deposit. Another negative impact is the "visual pollution", caused by the waste deposits accumulated along the slopes of the mountain or mounted in flat land areas, which are also connected to problems of interference with other human activities or, in general, with the environment.

Improvement of the present situation can be obtained by pursuing two parallel strategies: to seek and apply techniques and quarrying technologies that can reduce production of waste; to promote economic reuses of the wastes, in order to create some alternative possibilities in comparison to the simple practice of dump disposing. The spread in Europe of rational, modern and efficient techniques has to be further promoted because, besides the benefits on an environmental and safety level, it can also lead to the reduction of production costs, thus allowing for a greater competitiveness of the stone industry. The reduction of waste is the objective of projects aimed at the integral exploitation of the stone resource. In fact, producing a reduced quantity of waste, the total consumption of waste as a “secondary raw material” will be more viable.

For waste, which is produced anyhow and is not otherwise usable, a technically correct disposal must be anticipated, planned and realised, taking into account long-term stability and progressive restoration of the environment and landscape. For example, in a hillside configuration, disposing of waste material along the slopes should be forbidden. The dumps should be formed starting from the bottom, operating by overlapped “horizontal stripes” thus creating stable scarps accessible for every following act of re-naturalisation and maintenance.

4.1. Waste management: from stone wastes towards by-products

The problem of waste management in the exploitation of dimension stones – either produced in the past or currently – introduces some particular aspects in comparison to aggregate or industrial mineral quarries. In fact, in these last cases, the waste usually consists of earth-rock mixtures, allowing only extemporaneous usage in the quarrying area (e.g. the creation of quarry floors or ramps) and in operations of morphological remodeling for the environmental rehabilitation. Besides, the waste volumes generally involved are not important in comparison to the extent of the deposit volume.

On the contrary, quarries of dimension stones introduce a special situation concerning both the nature of the waste and the huge quantities of this material in relation to the total production. The greatest part of the waste has mineralogical composition and chemical properties identical to those of the useful rock; consequently, the distinction between “saleable product” and “waste” presents a notable degree of elasticity, according to the different uses and possible reuses.

From a wider perspective, appropriate for the politics of sustainable development, it seems that it is more convenient to refer to management of waste in terms of “treatment” rather than “disposal”, in order to favor for a recovery as extensive as possible (Figure 64).

With reference to the terminology of Figure 64, re-employ stands for a re-qualification of the waste, through a revocation of the “waste” attribute; the recycling is the employment of waste to recover secondary raw materials, alternatively in comparison to other natural resources, and to insert them in the same cycle of production from which the waste originates; the reutilization is the employment of the waste, after physical-chemical treatment, for uses different from those of the starting productive cycle, eventually in competition with other materials.

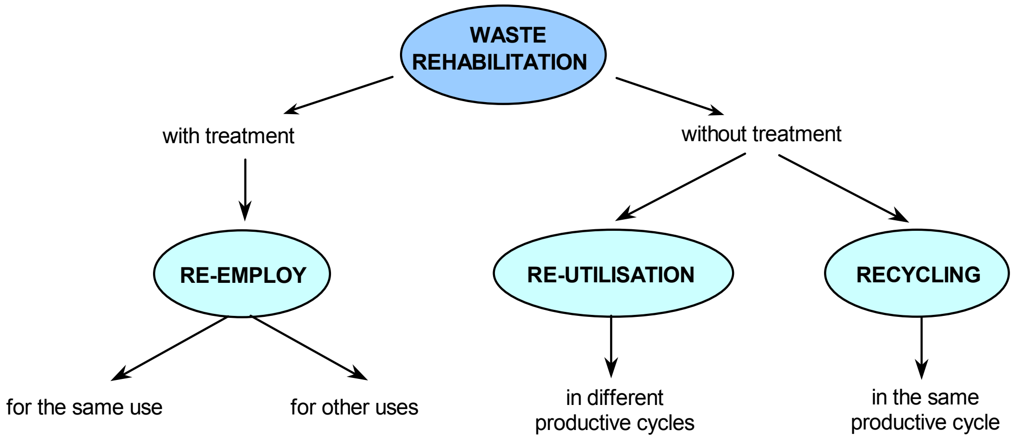

Figure 64. Different types of waste recovery.

For example, "re-employ" of stone waste is the case of direct use of big shapeless stone blocks as armour stones, without any intermediate treatment. An example of "recycling" is the production of "artificial stones" or aggregates by crushed rock wastes; finally, a case of "re-utilisation" is the production of concentrated mineral through specific physical-chemical treatments.

Materials which present shape, size, structural and/or aesthetical defects can not be introduced in the productive cycle of ornamental stones and are normally destined to dumps. Therefore, some principal categories of waste can be pointed out, whose characteristics condition the possibilities of recovery:

- "third choice" or defective blocks, regular-shaped, but poor from a technical-aesthetical point of view or not appropriately sized for the demands of the processing plants;
- shapeless large blocks, which, given the excessive irregularity of form or volume, cannot be generally sawed in slabs;
- shapeless small blocks, deriving from the quarrying of particularly fractured portions of the deposit or from the blocks squaring;
- debris and fines, deriving from drilling and cutting operations (by wire or chain machine).

Technically, some uses that will allow waste redefinition as "by-product" or "co-product" can be found for almost all the types of quarry waste. However, the essential condition for a correct realisation of this technical possibility with economically acceptable results is the primary selection of waste during its production (Figure 65) along with effective organisation of its disposal, in order to minimize handling and transportation costs.

Referring to the above listed categories, some of the options for waste recovery, currently in use or in phase of experimentation, are reported as follows:

The defective or "third choice" blocks are used in the production of serial and low price products, as some elements for external floorings, urban furnishing, etc. Non first-quality blocks can be stored and then profitably processed on the occasion of frequent orders that quickly ask for great quantities without qualitative standard of excellence.

Figure 65. The selection of different waste types is an important presupposition for reuse opportunities.

Figure 66. Rock debris of small size, mixed with dirt, is used without further process for fillings and ramp construction.

The shapeless blocks of great size, whenever present appropriate physical-mechanical characteristics, have been in the last years widely used as armour stones, reducing the necessity to open new quarries for this purpose. Most granite shapeless blocks (volume bigger than 0,2 m^3) can find an application in this field, while in the case of marbles, shapeless blocks of good quality can be sawed in tiles for coverings and floorings. The introduction of splitting machinery, specialised in the production of "little blocks" for road paving and sidewalks, has subsequently widened the possibility of reuse of the shapeless blocks, in relation to the renewed interest for local stone materials in the restoration of the urban historical centers.

For small sized shapeless blocks (e.g. with linear dimension lower than 0.5 m), the most suitable choice for reuse is crushing and classification for the production of aggregates (Figure 67). However, this is not a universal solution: in fact, experience matured through many years of tests and applications have shown some restrictions.

Figure 67. The installation of a mobile or fix crusher in a area next to the quarry can reduce the costs of transport of the material and realize an integral reuse of the quarry waste.

Other fields for reusing certain types of quarry wastes are the production of artificial stone materials and the production of mineral concentrated in special plants. The "artificial stones" are obtained through agglomeration of rock fragments by suitable binders. These products can reproduce the aesthetical lines and the mechanical characteristics of the natural material, but usually they are not directly set in competition to the natural material, but are rather directed towards particular applications concerning aesthetical homogeneity demands, exact reproducibility, possibility to face important orders in brief time, etc.

Minerals for industrial use can also be extracted whenever the lithotypes are suitable, through appropriate processes of separation and ore concentration. Different experiences have shown that, the realisation of such processing is certainly possible. For example, from granites is possible to get (once the minerals based on iron are eliminated through magnetic, gravimetrical processing, or flotation) selected feldspar concentrations (sodic and potassic) for the ceramic industry, and quartz for the glass industry. Nevertheless, from an economic feasibility point of view, marketability of these products can be hindered by the availability in the market of the same products obtained with lower costs.

For calcareous wastes, due to their high contents of $CaCO_3$, various possibilities of recycling have already been proposed in different industrial sectors, making their reuse decidedly more "desirable" in comparison to the granite waste. The potential uses of the carbonates obtained by treating "marble" wastes can be in the following sectors: cement production, paper production, glass production, in the productive cycle of water paints, in the chemical industry, in the production of fertilizers and amendments for the agriculture, in the desulphurization of electric plants fumes, etc.

In order to make reusing and the consequent exploitation of quarry waste a current practice, beneficial for the environment and profitable for the enterprises, organisation and good coordination among the different interested parties is required. Public administrations, for their part, have to stimulate the reuse of the waste materials. They can encourage it for example by giving prizes or facilitations to enterprises that use stone wastes for the construction of public infrastructures. Nevertheless, it is essential that the contract specifications for such jobs are thoroughly studied and well defined in order to technically allow a correct and safe employment of the available materials. Therefore, research centers owe to establish technical specifications on the formalities of treatment and reuse of the stone wastes, promoting innovations that will widen the range of possible applications.

4.2. Environmental rehabilitation

Exploitation of a natural stone deposit can not leave behind the appropriate environmental rehabilitation. Nevertheless, the term "environmental rehabilitation" expresses an extremely generic concept, sometimes used in ambiguous ways. It is hence, proper to specify different particular meanings (Table 17).

Starting from the general definition of environmental rehabilitation, some important concepts can be underlined. First of all, the quarrying activity is carried out for a limited and mostly predetermined time. In the majority of cases, the administrative limitations or the specific technical and geo-morphological situations, allow foreseeing the time when the quarrying activity will finish, thus permitting to schedule all the interventions for the rehabilitation.

Table 17. Definition of specific meanings, in the generic concept of environmental rehabilitation.

Term	Definition
Environmental rehabilitation	A total of interventions able to guarantee that, after the quarrying activity, the site can usefully be integrated again to the territorial system and the existing environmental context, at any qualification, productive or naturalistic, foreseen by the current laws.
Reclamation	Particular strategy of rehabilitation aiming in obtaining, at the end of the quarrying operations, a site having characteristics substantially similar to the original ones, so that it will be able to resume to its prior uses.
Remodelling	Operational tactics, performed at the same time with the quarrying phase, in order to prepare the site, from morphological and hydrological point of view, for the final rehabilitation, guaranteeing the stability and the environmental safety.
Re-naturalisation	Particular arrangements of the quarry area, generally executed at the end of the activity, in order to allow a quick action of the natural agents – physical, chemical and biological – intentionally giving back a more natural aspect to quarry areas.
Reuse	Transformation of a quarry site in order to host different uses or facilities from the ones present before the exploitation.

Effective realization of rehabilitation is not always found in practice, mostly because of the frequent lack of an integrated plan, on the basis of which the rehabilitation operations would become a real phase of the quarrying process. From a quarrying point of view, it can be maintained that a "good" quarry management is not incompatible to the general principles of land protection; analysing some recurrent situations (Table 18), a substantial convergence of goals can be observed.

Table 18. Convergence of goals and finality in the quarrying production and in the environmental and land protection.

Goals	Principles	
	Quarry Activities	*Land*
Stability of the fronts	Safety of production; Safety at work	Essential pre-requisite for the environmental rehabilitation
Exploitation of the whole deposit	Maximise turnover	Minimise the area of exploitation
Integral exploitation of quarried material	Maximise turnover	Minimise the area destined for dumping
Management of the dumps	Quarrying production	Arrangement of the sites
Reduction of the emissions	Maximise the efficiency	Reduce damages to the surrounding environment

From the previous assertions is certified that proceeding to rehabilitation, or at least to an arrangement of the quarry area simultaneously with the extractive operations, in order to reduce the “exposed” areas in phase of exploitation, guarantees a quick and effective environmental rehabilitation at the end of the activity. The practical implementation of these operations though, is often difficult, because the different phases of “preparation”, “exploitation” and “arrangement”, in view of a definite release of the quarry areas, are submitted to rigid conditionings, dictated not only by the morphology of the place and the deposit, but also from primary safety issues.

Therefore, the concept of quarry rehabilitation at the same time with extractive operations must be understood rather as an opportunity to arrange those quarry parts that are already under “mature” conditions, that is, they do not coincide with areas under exploitation. In any case, the rehabilitation of the stone quarries will take place (from an economical point of view) on a long time basis, taking advantage of all the opportunities that will eventually arise (Figure 68 and 69).

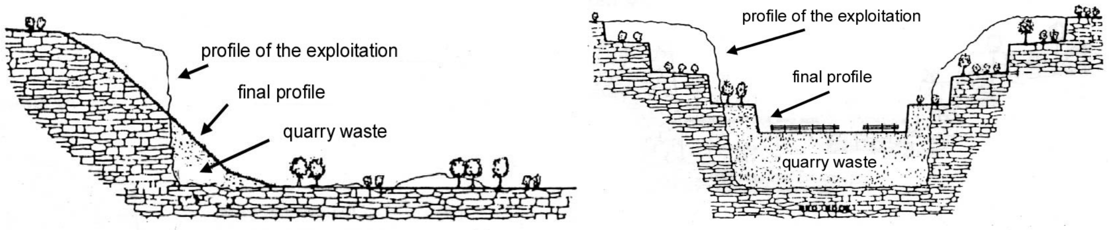

Figure 68. On the left, scheme of a rearrangement of the quarry front. The filling is material removed from the dump. On the right, a scheme of partial refilling of a pit quarry. (G. Gurnari).

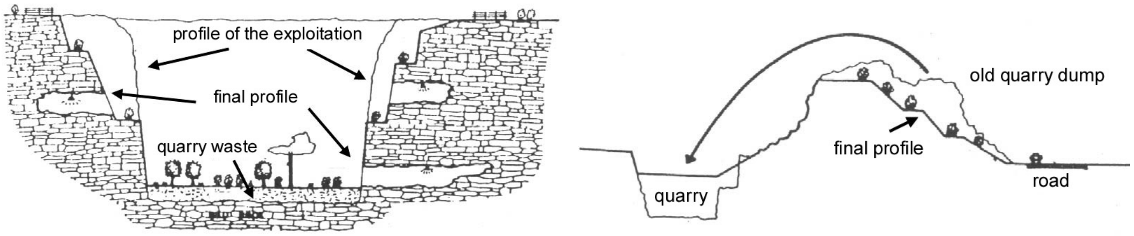

Figure 69. On the left, pit quarry transformed into a tourist-recreational area, due to interesting karstic formations, revealed by quarrying. On the right, the material of refilling can be recovered from the unstable dumps that impend on public infrastructures.

Operation of stone quarries, damages the landscape in a way that can not be completely reversed. Consequently complete elimination of the traces of the quarrying activity is unattainable. Realistically considering the fact that, after years of quarrying activity in an area it is not possible for this area to return to its original natural state, the primary objectives for a correct strategy of rehabilitation should be:

- safety from the hydro-geologic and geomorphologic point of view;
- starting of a process of re-naturalization;
- reinstitution to the community the areas for a plurality of collective uses.

Quarrying areas should not be considered as wastelands but as areas able to offer important opportunities for reorganisation of the land. It should be noted that this perspective underlines the serious bond existing among raw materials, quarrying systems, architectural planning of the quarry spaces and modeling of the land. In case of quarries operating in environmental and ecological context of particular value, the rehabilitation plan should foresee actions mainly focused on the restoration of the typical morphological and vegetation characters of the area, in the shortest time possible. Optimal conditions for the indigenous species should be created, following thorough studies on the composition of the vegetable associations naturally existing on the site. It is finally stressed that solutions adopted with the single objective of relieving visual impact, thus reducing the measures to just "aesthetic" actions, are not long-term effective. Stone quarries often create peculiar geometric spaces that may offer stimulating project alternatives for rehabilitation and reuse, in comparison to the simple return to a "natural" landscape. As a reference, two European cases are reported, in which the rehabilitation of stone quarries led to the creation of particularly significant places, from the point of view of public recreation, as museums, parks, show places, etc.

S'Hostal quarry (Minorca, Spain) – The rehabilitation, finished in 1996, involved a complex of opencast quarries, in which up to 1994 quarrying of small blocks of sandstone was conducted (Marés's stone of the Balearic islands). The spaces on the ground level are currently endowed with an area of access and a parking, an informative center, an expositive path on the history of the stone and its processing, a conference room and a refreshment area. From that point visitors can go down to the lower level of the quarries, where some gardens have been planted and an amphitheater has been created in the wide, regular spaces left by mechanical quarrying by disc cutter. The same traces of the cutting operations constitute a typical "decorative pattern" on the walls (Figure 70).

Dyonissos quarry (Attica, Greece) – The rehabilitation of Pentelic Marble quarries (closed in 1986) included remodeling of the slope underlying the quarry fronts, by building a "natural" area, strongly influenced by man at the same time, through laying down marmoreal elements to form harmonious surfaces. The quarry fronts, reached by the principal pathway, create a sculptural composition that is well matched in this "marble landscape". The rehabilitation measures (1994-1998) wanted to maintain the elements of quarry workmanships, as a proof of the environmental molding by human activity, which lasted for ages.

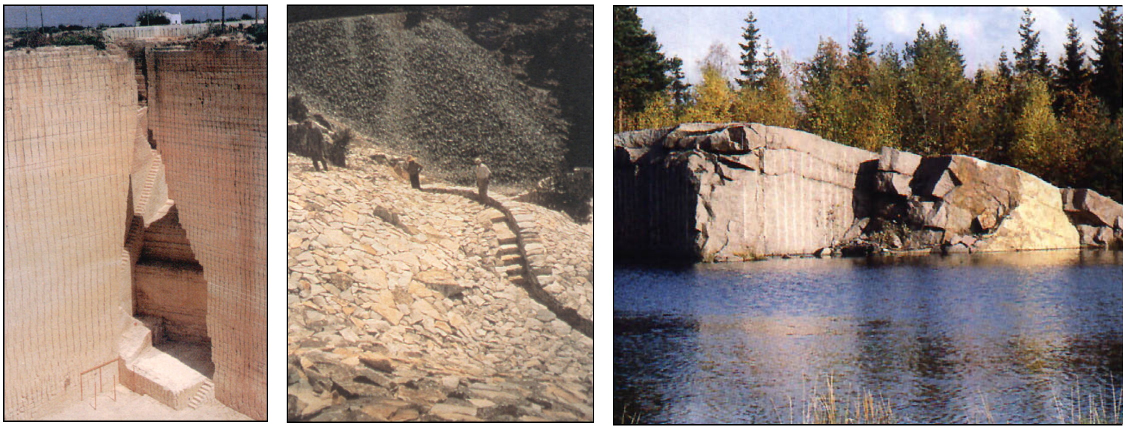

Figure 70. Images of rehabilitations of stone quarries and dumps (left to right: sandstone quarry in Spain, marble dump in Greece, granite quarry in Sweden).

5

Concluding remarks

MARILENA CARDU, ENRICO LOVERA

Ornamental stone quarrying presents particular characteristics in comparison to the other extractive industries, such as the exploitation of primary mineral resources (metalliferous minerals, energetic resources, etc.) or other common materials destined to the constructions industry. Indeed, even though advanced techniques and automated procedures are used, the quarrying process can be hardly defined as "industrial" in a strict sense. Apart from production numbers, the sector is generally represented by small or medium enterprises which employ a rather small number of workers.

On the contrary, ornamental stones products are characterised by an international wide market and above all they get quite high commercial prices, which can balance the high production costs typically faced by the quarrying enterprises. The value of stone products, shaped partially by the fact that market supply and demand balance to rather increased prices, is also justified by the "cultural" meaning that they include. They are a part of our historic-artistic heritage, as their use as a construction material still characterises and ornaments most of the public and private places throughout European cities.

In order to achieve an effective continuation of this traditional and important economical activity, source of wealth and employment, the following issues have to be faced:

- the necessity of "planned management" and better organization of the activity; in practice, starting from a better knowledge of the mineral resources, it is essential to plan the use of land and manage the activities, in such a way so that the stone resources can be exploited efficiently, protecting the environment and getting good productive performances;

- the urgent demand, to reduce the production of waste “to the source”, through the adoption of the best available methods of exploitation and the introduction of more “precise” technologies and to exploit profitably through possible reuses, the stone wastes either way produced;
- the demand to guarantee the environmental compatibility of the quarrying activity, through an effective assessment of quarry programs and project, the improvement of environmental performances during the activities and a full rehabilitation of the site at the end.

The progressive optimisation of quarrying techniques and practices is essential to match the final goal of stone quarrying sustainability and competitiveness. This edition is intended to be a small contribution to such an important challenge.

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