DRAFT REPORT

STATE-OF-THE-ART: ORNAMENTAL STONE QUARRYING IN EUROPE

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Preface

This report is an attempt to summarize some characteristics of the ornamental stone quarrying industry throughout Europe and underline some challenges that this sector is facing. Furthermore, it seeks to highlight some of the most important innovative technologies and methods contributing to improve the viability and sustainability of ornamental stone quarrying. In addition to quarrying itself, the report also deals with other important aspects directly relevant to quarrying – such as exploration, some environmental issues, management of deposits and handling and use of waste rock. For other aspects related to the ornamental stone production, including environmental, the work by the other sectors within OSNET is recommended. These are: *Processing*, *Stone characterization*, *Tools and equipment*, *Risk assessment, safety and environment* and *Technology transfer*.
Ornamental stone quarrying in Europe is characterized by a great variation in traditions, extraction methods and, not at least, rock types. To give a complete picture of everything happening within the sector would demand far more pages and time than available, but we hope that we have not forgotten too much. The members of the OSNET quarrying sector come from Greece, Italy, Portugal, Sweden, Finland and Norway. Clearly, the report will be "coloured" by examples and case studies from these countries, but we hope – and believe - they have a more general validity.
In the report, the term "ornamental stone" includes all types of building stone, such as slate, marble, granite, soapstone etc. Some members would preferred to use "dimension stone" or "natural stone" instead, and there are obviously regional differences in Europe on how to use the terminology.

The authors wish to acknowledge the other members of the quarrying sector for important contributions and corrections.

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Summary

In Europe, more than any other part of the world, ornamental stone has been in history and is at present time, an important construction material. Worldwide use and production of stone is steadily increasing, and during the last 30 years, the technological development within the sector has been tremendous. Europe counts for approximately 35-40 percentage of world production and consumption of stone. The European stone quarrying industry show great variations in size of operation and thus the level of industrialisation and application of new technology. Nevertheless, the ornamental stone quarrying industry in Europe is facing great challenges in the years to come; the import of stone from low cost countries is increasing and the quarrying sector faces more and more regulations and environmental restrictions.

The quarrying of ornamental stone is generally not covered by mining laws in Europe, and there are no European directive on quarrying, mineral right claims and exploration. The practises and legal framework on mining vary significantly throughout Europe, including the way ornamental stone is treated compared to other mineral commodities. The commencement of ornamental stones exploitation activities, as well as, the production development of operating quarries, is today dependent on strict environmental regulations. The most important environmental issues for the ornamental stone quarrying are waste handling (rock fillings and dust), direct impact (noise, visual impacts, dust) and land use (competing interests). The EU Policy regarding waste focus on two aspects – handling and prevention. A directive for handling of mining waste is in progress, and Eco-labelling criteria for hard floor coverings, including stone, has recently been established. The document has raised discussions within parts of the ornamental stone industry. Regarding land use, the NATURA 2000 areas in particular can cause operational problems to any quarrying activity. Rehabilitation during and after quarrying has become a determined requirement and obligation.

Regional and quarry scale geological exploration, defines the rock type, the structure, the volume and quality characteristics of the economic target. Reserve estimation and feasibility study aim to optimize the quarrying operations to be undertaken. Rational exploitation plans aim to increase the recovery rate and minimize the waste production. Economic evaluation of ornamental stone deposits can be complicated, and require severe knowledge of the sector. At present, the education and training of geologists/mining engineers on ornamental stone is very limited throughout Europe, and (compared with other mineral commodities) the number of professionals working in the sector is small.

The future of the ornamental stone industry in Europe depends on a proper management of the resources. At the present time, the extractive industry is subject to a strong pressure from other needs of the society, ranging from urbanisation of traditional quarry areas to the formation of an increasing number of natural habitats, national parks and recreation areas. There are many examples of quarries that have been forced to close down, or concentrate their activity to smaller and less productive areas. Of importance for a better and less coincidental management of the ornamental

stone deposits in Europe would be easy available and useful information about the most important deposits.

In recent decades, there has been a tremendous development of new technology for dimension-stone quarrying, especially regarding sawing techniques, drilling and handling. Generally, sawing is substituting other methods for a variety of rock types, and is getting more and more usable also for the hard ones. However, there are still large differences in extraction methods, and there are probably a large potential both in the development of new, innovative technology (especially for hard rocks), further improvements of established technology and in the exchange of knowledge between different regions. A special challenge exists in the application of quarrying technology – optimising available methods to specific quarries, and selecting the most efficient, productive and environmentally methods.

Finding efficient and high–productive quarrying operations is of great importance. In this context, underground quarrying has great advantages, and is becoming more and more common for "soft" rock types. Interesting new technology and methods are preparing grounds for underground quarrying of also hard rocks.

One of the great challenges for the ornamental stone industries is the utilization of quarry waste. There are several interesting examples of developing commercial by-products from such, increasing the overall acquisition of the ornamental stone deposits. Turning waste into resources is one of the most important issues for the industry in the future, but also the proper handling and disposal of such and local/regional planning for alternative uses of waste and closed-down quarries.

1 Introduction

The exploitation and use of ornamental stone in Europe dates back to Antiquity. In Europe, more than any other part of the world, stone has been an important construction material throughout history, and stone is the primary material of which our rich cultural heritage is made.

It is difficult, probably impossible, to estimate the exact number of ornamental stone quarries throughout Europe. However, within the EU/EFTA countries, the number of unique stone types approach 2500. Not all of these are operating quarries, but most of them are, at present time, in production. A considerable amount can be characterised as “classic European stones”, meaning that they have been produced for more than a century and have contributed to the architectural heritage of Europe.

Some ornamental stone quarries are large-scale, comparable in size with large mining operations. Others are smaller, involving regular or periodic extraction of small volumes of stone. Others again, involve combined extraction of ornamental stone and other mineral products, such as rock aggregate or industrial minerals. Thus, the European stone quarrying industry show great variations in size of operation and thus the level of industrialisation and application of new technology.

The economically most significant part of the European ornamental stone industry is located in Mediterranean Europe – Italy, Spain, France, Portugal and Greece; these countries account for 90% of EU production[1]. This is partly due to the geology (large marble and granite resources), but also because of strong traditions for producing and using stone. In several Central and Northern European countries, urbanisation and a general decline in the stone industry in the Early to Mid 20th century led to closure of a large amount of quarries. However, at the present time, the ornamental stone industry is more vital than ever. Worldwide use and production of stone is steadily increasing, and during the last 30 years, the technological development within the sector has been tremendous. The European stone industry counts for approximately 35-40 percentage of world production (ca. 20 mill. Tons[2]). Europe's share of the world consumption is almost equal (37 percentage).

Nevertheless, the ornamental stone quarrying industry in Europe is facing great challenges in the years to come; the import of stone from low cost countries is increasing and the quarrying sector faces more and more regulations and environmental restrictions. Although the ornamental stone sector has deep roots in European history, these are important challenges that must be solved in order for the industry to be as successful in the future as it has been in the past.

This dual pressure on the industry from both increasing competition and environmental demands is expressed by the an EU Commission Communication[3]:

[1] Production quantities (European Minerals Yearbook 1996/1997)
[2] See http://www.immcarrara.com/stat/index.html and http://www.marbleandmore.com/econ/econ.asp

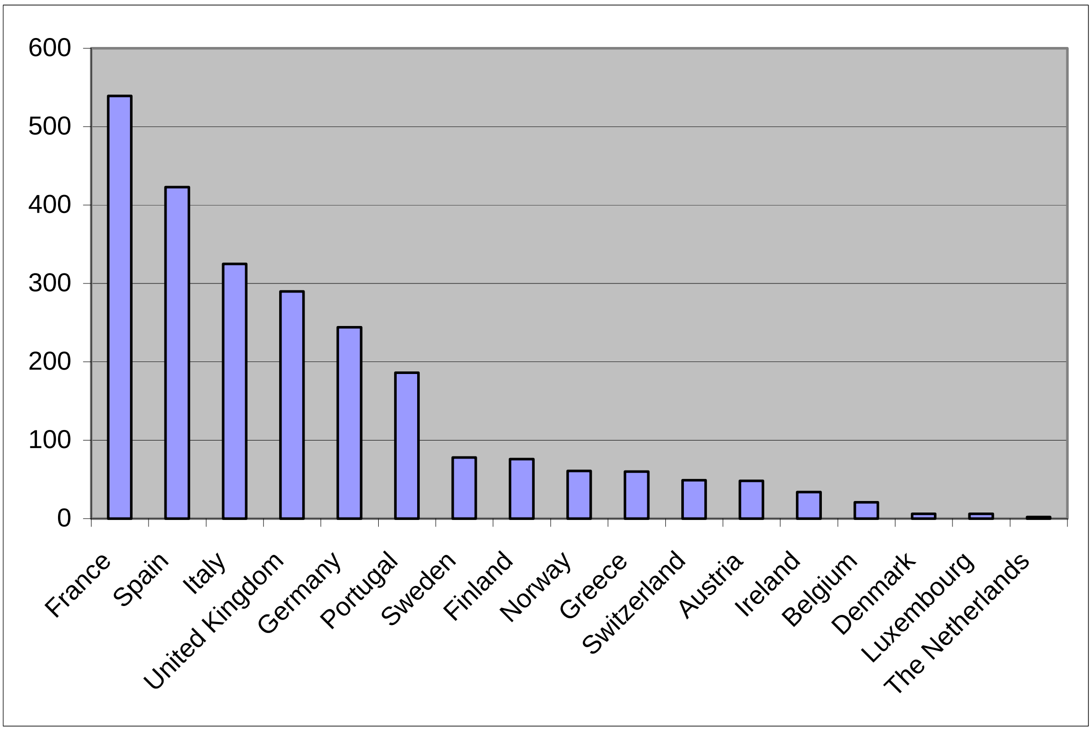
[3] Communication from the Commission: Promoting sustainable development in the EU non-energy extractive industry. COM (2000) 265

"The objective of this Communication is to set the broad policy lines for promoting sustainable development in the EU non-energy extractive industry by reconciling the need for more secure and less polluting extractive activities while maintaining the competitiveness of the industry."

On the competitiveness, the Communication says:

"The most important factors for the competitiveness of all sub-sectors of the industry includes human resources, land access, a stable and predictable legal framework generating legislation proportionate to the objectives sought, research and technological development, availability of infrastructure, including transport, low freight costs and energy supply."

This report – State of the art of European ornamental stone quarrying – places focus on some of the most important aspects of the quarrying sector: the legal framework, environmental aspects, geological investigations, quarrying technology and waste[4] handling. It addresses, furthermore, some key problems that could benefit from cooperation between industry and the R&D sector on a European level, either with respect to research, networks or technology transfer. In the quarrying sector, the main questions raising concern the quality upgrading of the exploitable resources, the increase of the recovery rate and the minimization of the quarry-waste production.



Number of ornamental stone types produced by country[5]

[4] "waste" is here defined as left-over stone in ornamental stone production, possibly usable for other purposes, not to be confused with hazardous materials.
[5] CEN EN12440:2000, annexe

2 Ornamental stone and legislations

2.1 Variations through Europe

The quarrying of ornamental stone is generally not covered by mining laws in Europe[6], and there are no European directive on quarrying, mineral right claims and exploration. The practises and legal framework on mining vary significantly throughout Europe, including the way ornamental stone is treated compared to other mineral commodities.

In most cases, the mining laws in European countries deal with metallic ore alone, or including a selection of industrial minerals commodities. The exploration and mining of ornamental stone (as well as aggregate, gravel and sand) is usually excluded from the national mining laws, and there are no national licensing systems for exploring or extracting such. Ornamental stone deposits belong, therefore, to the landowner, and not the "governments right". However, all mineral development and, in some cases, exploration usually requires planning permission from a mineral planning authority.

The procedure in most countries concerning exploration and extraction of ornamental stone can be summarized as follows:

- Initial investigations – agreement with landowner
- Exploration/pilot quarrying – exploration permission (local/regional authorities, mineral planning authority)
- Planning of extraction – environmental assessment/planning
- Quarrying

On a European level, the strongest attention is, at present, on the environmental side of quarrying (see below). Some countries have on their own initiative, changed their legislation framework (or are in a process of doing so) in order to increase the industrial activity in the mining and ornamental stone sector. Rationalisation of the mining legislation in Finland and Sweden in the early 90's resulted in a substantial increase in metallic ore and industrial mineral exploration activities.[7] However, these legislations only partly involve ornamental stone. A more detailed investigation and benchmarking of common practises/legislations on ornamental stone in European countries could help for finding "best practise" solutions for the future, and perhaps improve the overall competitiveness of the industry. However, the legislations can, occasionally, be extremely complex.

[6] Some exceptions exist. In Finland, marble and soapstone are treated within the mining law, whereas granite is not. The reason for this different treatment is probably that the mining of marble and soapstone building stone often are closely related to extraction of industrial minerals from the same sources.

[7] Promoting sustainable developments in the EU non-energy extractive industry. Communication from the Commission, COM (2000) 265 final.

2.2 Important environmental issues

The Extraction and use of **mineral resources in general** raise several concerns regarding the environment:

- Use of non-renewable resources may cause limited availability for future generations
- Direct impacts on the local or global environment, such as dust, noise, visual impact, disturbance of natural habitats, eco-toxicological pollution and effects on ground water levels
- Indirect impact on the environment, e.g. use of energy in the production process and life-cycle patterns of the materials
- Risk of disasters during extraction and distribution

These concerns vary significantly depending on the type of mineral resource and characteristics of the production site. **Regarding ornamental stone**, the first and third points are almost irrelevant: although stone is a non-renewable resource, there is no risk of a future lack of such resources. Furthermore, the indirect impacts are considered to be much lower than many other construction materials. The consumption of energy for production and transport of stone is low, even for the most sophisticated ornamental stone products. The material itself is durable and long-lasting, and the recycling ratio is high. As the eco-toxicological pollution from ornamental stone production is small or absent, the main direct impacts relate to noise, dust, visual impact and effect on landscape and natural habitats.

The recovery rate for ornamental stone quarrying vary from 5 to 50 percent. This is high compared to metallic ore, but lower than aggregate and some industrial minerals. In addition to the actual use of land for quarrying, the handling of waste rock is considered to be the ornamental stone sector’s largest environmental issue. Although the waste rock has the same composition as the surrounding bedrock, and does not contain any toxic additives, the huge waste dumps seen in many quarry areas cause a significant visual impact on the environment. The quarrying technology is improving, contributing in increasing the recovery. However, the strong international competition as well as demand for better quality raw material in the processing industry has driven recoveries in the opposite direction. As a consequence, the recovery of ornamental stone resources has not improved significantly during the last decades.

The utilisation of waste rock for other products, such as aggregate or industrial minerals, is increasing, and this issue is perhaps one of the most important future developments towards a more sustainable and eco-efficient ornamental stone production. The handling and utilisation of waste will be treated separately in chapter 7.

The most important environmental issues for the ornamental stone quarrying can be summarized as follows:

- Waste handling (rock fillings and dust)
- Direct impact (noise, visual impacts, dust)
- Land use (competing interests)

Waste or by-product?
What is called "waste" by some, are called "by-products" by others. According to Commission Decision 2000/532/EC, waste rock from ornamental stone quarries belongs to the category called *"waste from mineral non-metalliferous excavation"*. A recent decision by the Court of Justice of the European Communities made clear the legal meaning of such leftover stone. The judgement (18. April 2002, case C-9/00) was based on a case from Finland, regarding a dispute between a company (Palin Granit) and the local authorities:
"Palin Granit and the joint board brought an appeal before the Korkein hallinto-oikeus challenging the classification of the leftover stone as waste. Palin Granit submitted that the leftover stone, whose mineral composition was identical to that of the basic rock from which it was quarried, was stored for short periods for subsequent use without the need for any recovery measures and did not pose any risk to human health or the environment."
However, this view did not reach through to the court, which concluded:
"The holder of leftover stone resulting from stone quarrying which is stored for an indefinite length of time to await possible use discards or intends to discard that leftover stone, which is accordingly to be classified as waste within the meaning of Council Directive 75/442/EEC of 15 July 1975 on waste."
Furthermore,
"The place of storage of leftover stone, its composition and the fact, even if proven, that the stone does not pose any real risk to human health or the environment are not relevant criteria for determining whether the stone is to be regarded as waste."
Although the legal side is made clear, it is obvious that considering the quarry waste as a potential resource and stimulate for uses, is the best practise from an environmental point of view.

2.3 European directives and policy

The activities of the ornamental stone industry are governed by EU Directives on waste/landfill, water, air quality, nature conservation, birds, habitats and Natura2000. The Directive on environmental impact assessment covers quarries where the surface of the site exceeds 25 hectares.

Details on environmental issues will be treated separately by the OSNET Sector ……. In this report, only some of the **key factors** involving exploration and quarrying will be discussed.

The EU Policy regarding **mining waste** focus on two aspects – **handling** and **prevention** of waste. Regarding handling of waste (at present covered by the Landfill Directive), a new directive on *"Management of waste resulting from prospecting, extraction, treatment, and storage of mineral resources"*[8] is in progress (second draft in circulation). Comments on the draft proposal from several institutions and organisations reflect some controversy regarding the view on waste from aggregate and ornamental stone quarrying. Such "waste" has the same composition as the soil and bedrock of a specific quarry site, no toxic constituents are added (the waste is inert) and it could be viewed as "leftover stone" with possible future use rather than

[8] http://europa.eu.int/comm/environment/waste/mining.htm

"waste". Such arguments are also reflected in various practises throughout Europe on the handling of waste from ornamental stone quarries. For example, in Sweden, waste rock from quarries has to be disposed in a way that secures a future utilisation of the material. In other words, the "waste" is viewed upon as a possible future resource. On the other side of the scale, Portugal has a different practise, considering the leftover stone material which is not immediately used in the quarrying process, to be waste and nothing else, and to be buried and covered with soil once and for all.

Other reactions to the draft directive include the proposed procedures for documentation and monitoring waste; it could be questioned if a small enterprise disposing small volumes of inert waste each year should need to do the same amount of documentation and monitoring as a sulphide mine. Problems related to handling and utilisation of waste will be further treated in the last chapter of this report.

Regarding waste prevention, some important goals can be read from the documents preparing the 6th Environmental Framework Programme[9]:

- Identify and encourage substitution of the hazardous substances that present the biggest problem in different waste streams
- Integrating waste prevention objectives and priorities into the Community's Integrated Product Policy
- Encouraging the use of economic instruments, for example, eco-taxes on resource- and waste-intensive products and processes
- Influencing consumer demand in favour of products and processes that give rise to less waste e.g. via green procurement policies, eco-labels, information campaigns, and other tools.

The first point is not very relevant for ornamental stone, since the waste in no cases can be defined as hazardous. Of great importance to the ornamental stone industry, however, are the guidelines for *"Eco-labelling of hard floor coverings"*[10]. This has been voted upon in the Regulatory Committee (of the Eco-label Unit of the European Commission) meeting of 5 December 2001. The Decision will be translated into the 11 official European languages, adopted by the Commission and published in the Official Journal. Eco-labelling is voluntary, and is meant as a tool for stimulating *"ecological behaviour"* among producers and consumers. It differentiates between *"Natural products"* (ornamental stone) and *"Processed products"* – hardened (agglomerated stones, concrete paving units and terrazzo tiles) and fired products (ceramic and clay tiles). For natural products, the criteria are largely concentrated on the raw material extraction operations, e.g. quarrying. The criteria for the processed products, are, one the other hand, more focused on the processing stage of the production.

Among the most important criteria for ornamental stone production are the following:

- *Recovery of commercial blocks* (marble 20%, granite 30%, other stone 10%[11])

[9] On the sixth environment action programme of the European Community: "Environment 2010: our future, our choice". Proposal from the Commission to the European Parliament and of the Council. COM (2001) 31 final.
[10] http://www.europa.eu.int/comm/environment/ecolabel/producers/pg_hardfloor.htm
[11] Exclusion hurdle

- *Natural resource appreciation* or total recovery of the deposit, including uses of leftover stone as aggregate, industrial minerals etc. (marble and granite 35%, other stone 25%)
- Water recycling ratio >80%
- Rehabilitation simultaneity degree
- Air and water quality
- Noise (<60 db along border of quarry area)
- Visual impacts
- Working conditions of operating equipment

The document has raised discussions within parts of the ornamental stone industry, especially regarding the block recovery criteria, which possibly will exclude a significant part of the European stone industry. The critics emphasize that the criteria "discriminate" natural products, and that they are not well adapted to the real situation in ornamental stone quarrying. In several countries, there are now ongoing studies on life-cycle analyses for ornamental stone. Such studies will perhaps bring new aspects into the discussion, and contribute to improve the eco-labelling criteria for the next revision in a few years.

<u>Life cycle studies</u>

Ongoing project in Finland[1]: *"Development of an environmental database management system for natural stone industry and the life cycle of natural stone production".* This cross-scientific project aims to find out about the actual environmental impacts of Finnish natural stone production by measuring the environmental loadings of natural stone production during its life cycle (impacts on ground water, noise, tremor, radiation, production release and production residue impacts). The project will build an environmental GIS- and Internet-related database management system for the small-scale Finnish natural stone industries. Using the gathered information, a life cycle analysis/assessment (LCA) concerning natural stone production will be made.

Source: http://kiviteollisuusliitto.gsf.fi/environmental.html

Like all extractive industries, ornamental stone quarrying is dependent on **access to land**. The mineral industry is often one of a number of competing land uses, and has in an increasing amount of cases, lost the "battle" on land access. During the last decades, restrictions have been put to any industrial use of an increasing part of the areas in Europe, either through national legislations (national parks, nature conservation areas) or through EU directives[12].

The Directive (92/43/EEC) **on the conservation of natural habitats and of wild fauna and flora** addresses the establishment of a network of sites for the conservation of natural habitats. These sites are known as **NATURA 2000** areas. The directive sets out the framework for site conservation and protection, and includes proactive, preventive and procedural requirements. A Community list of such areas is established, and member states shall act in a way to ensure that the aims of the directive is not jeopardised. Furthermore, Member States are advised to abstain from

[12] EU documents on nature protection are found at http://europa.eu.int/comm/environment/nature/home.htm

any activity that can cause deterioration of a site on any national list, or a site that, on the basis of the criteria, ought to be on a list. NATURA 2000 areas also include sites under protection according to Directive (79/409/EEC) **on the conservation of the wild birds**. Extractive industry within NATURA 2000 sites is not excluded, but the sites are under strong protection[13].

However, although the number of protected areas in Europe is increasing rapidly, the is still, in many places, a lack of integrated land planning framework that seeks to balance competing interests between national and local levels, and between mining and conservation. In this context, the industry could work together with planning authorities and governments and find *"better practises that can help achieve a better relationship between protected areas and other land uses, such as how to incorporate areas of known mineral potential into decision-making about new protected areas"*[14]

Visual impact? Quarry and scenery.

http://europa.eu.int/comm/environment/nature/natura.htm

[14] Breaking new ground: the report of the mining, minerals and sustainable development project, may 2002. http://www.iied.org/mmsd/

3 Geological Exploration /Prospecting – Economic target selection

3.1 Ornamental stone – the aesthetic mineral resource

Ornamental stone differs from other mineral resources in several ways. First of all, stone quarrying is about the art of collecting whole, massive pieces of rock, without the need for crushing, grinding and separation of individual minerals. Furthermore, stone processing does not include removal of “unwanted” components from the rock; it simply deals with a more or less advanced way of shaping pieces of rock into finished products. Stone products of excellent quality may readily be produced using simple tools and manpower, although the extraction and processing may equally involve the use of highly sophisticated machines. Applications vary from crudely shaped blocks for local housing to polished slabs cladding skyscrapers in the cities around the world.

The market for stone products depends highly on the consumer’s personal taste and on fashion trends. Thus, the aesthetic properties of the rocks are often more important than physical and chemical properties. Predominantly, rare colours such as blue, yellow, pure white and deep black are highly priced, whilst rocks of more ‘ordinary’ colours obtain lower prices. For rough blocks, the most exclusive rocks may be 20 times more expensive than the cheapest.

Building stones are often classified according to their technical quality and usability. A standardised, international classification scheme does not exist, but it is common to differentiate between massive stone (extracted in large blocks) and slabby stone, extracted as slabs which are cleaved along a planar structure, such as sedimentary layering or metamorphic foliation – e.g. slates. Massive stone is further divided into ’soft’ varieties such as carbonates and serpentinite, and ‘hard’, essentially quartzo-feldspathic rocks.

3.2 Important aspects in the evaluation of ornamental stone deposits

The evaluation of ornamental stone deposits differs significantly from other types of mineral resources, especially since the quality of the deposits rarely can be established only by objective measurements. The market value depends on the colour and texture of the stone, and minor variations in the deposits can have great impact on how profitable the production is. Furthermore, since ornamental stone quarrying depends on extracting large blocks without cracks and fissures, the distribution and spacing of fractures in the rock is of vital importance, but can in many cases be difficult to predict.

Generally, one differs between general, geological and industrial features when investigating ornamental stone deposits. The general features include:

- Ownership (landowners, mining rights)
- History of operation
- General environmental issues, land use

- Size of quarry/concession area

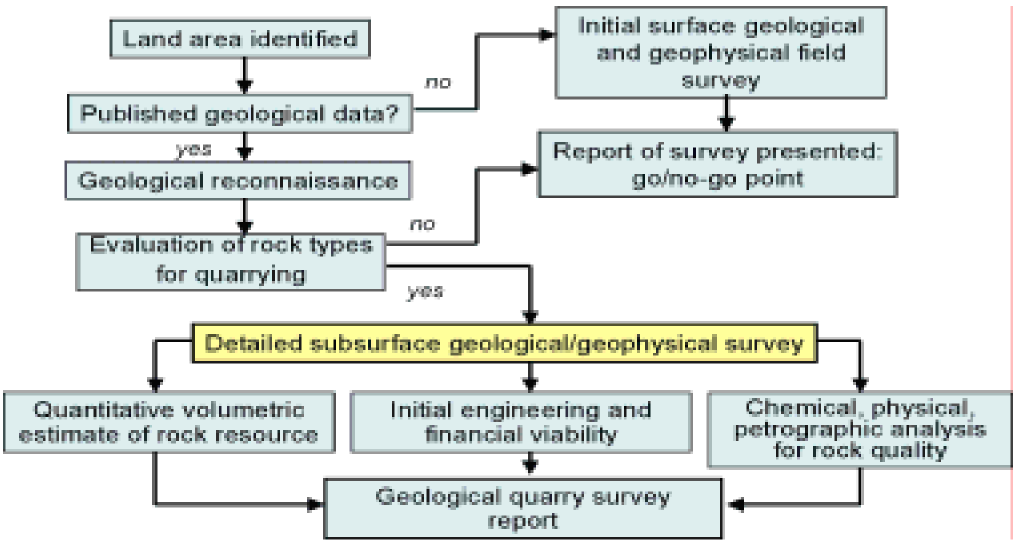
The geological features can be summarized as follows:

- Regional setting and occurrence
- Geometry and structure (stratigraphy, structural geometry, contact relations)
- Size (realistic depth and area of workable part of the deposit)
- Petrographic characterization (minerals, texture and fabric)
- presence of imperfections (segregations, pyritization etc)
- Quality (durability aspects, physical properties)
- Fractures and faults (spacing, distribution, relations to block yield)

The industrial features include the following:

- Commercial value, market (colour, market concept)
- Access and logistics (roads and infrastructure)
- Use (experiences, references to architectural applications)
- Workability (cutting directions, production properties)
- Working facilities (topography, climate, other activity in the area)
- Area for present and future movement of machinery, explosive magazines, statutory safety zones and basic amenities
- Area for disposal (far from deposit/near to workings)
- Availability of semi skilled and skilled personnel in the region

An investigation program of ornamental stone begins with regional investigations and selection of economic targets, based on introductory geological evaluation and market studies. A more detailed study of one or several targets follows, applying geological mapping, core drilling or other specialized methods and sampling. The last step is pilot quarrying.



Example of evaluation scheme for ornamental stone deposits. Source: Institute of Geology and Mineral Exploration, Greece.

3.3 Regional scale exploration and surveys

A regional ornamental stone survey is often focused on locating potential economic deposits within a geological province – e.g. a granite pluton or a sedimentary limestone basin. A good geological model of the province can be extremely helpful, especially for predicting where the most valuable rock types can be found, and for developing an **exploration model**. The methods applied vary depending on the rock types in question. Field reconnaissance is important, following pre-selected targets, such as valuable formations or granite bodies. In some cases, geophysical techniques (generally airborne geophysics in regional surveys) can be valuable; magnetic anomaly maps can, for example, be of use when exploring certain igneous rocks and soapstone. Arial photographs and/or satellite images may give valuable information for separating fractured from non-fractured rocks.

<u>Exploration models</u>

A good geological model can be useful for regional ornamental stone surveys. The Orivesi granite in Central Finland can serve as an example; the granite is divided in two parts by a fault, and geological investigations by Selonen (1998) concludes that the most interesting stone potential is in the western fault block. The eastern one exposes a higher level of the granite body, which has a less homogenous appearance, containing more dykes, veins and fine-grained granites.

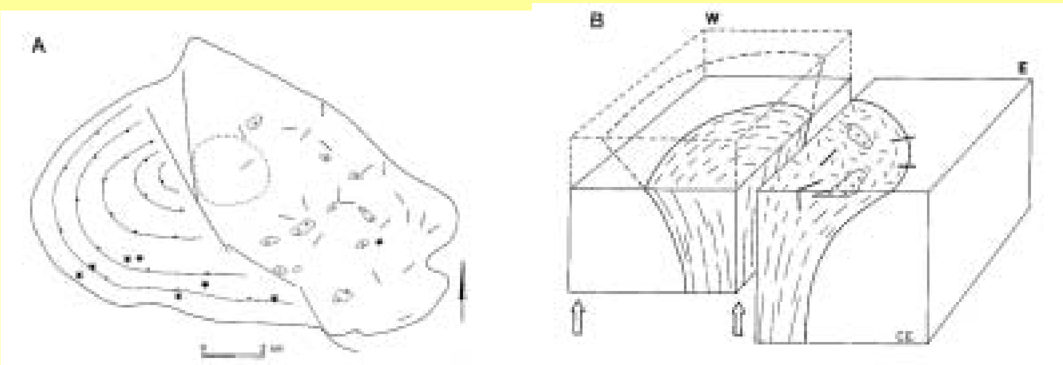


Figure: Map and perspective model of the Orivesi granite, Finland. Left: map image. Right: 3D interpretation. Stars (left image) show positions of ornamental stone quarries and potential deposits.

Source: Selonen, O. 1998: Exploration for dimension-stone deposits – geological aspects. PhD thesis, Åbo Akademi University, 64 pp.

<u>Airborne surveys</u>
Magnetic anomaly maps have shown to be of great value for the mapping of larvikite resources in Southeast Norway. The larvikites contain magnetite and ilmentite, and the internal relationship between these two minerals decides the magnetic properties of the rock. The deposits are composed of several ring-shaped bodies, and this pattern is reflected clearly on the magnetic anomaly map. The most important larvikite resources (Blue Pearl, Emerald Pearl and Sea Pearl) are found in intermediate anomaly levels. The geophysical survey also revealed the existence of two large faults, which have divided the larvikite complex into three fault blocks with different quality assortments. Combined with field mapping, the geophysical survey contributed significantly to making an interpretation map of the distribution of different commercial larvikite types.

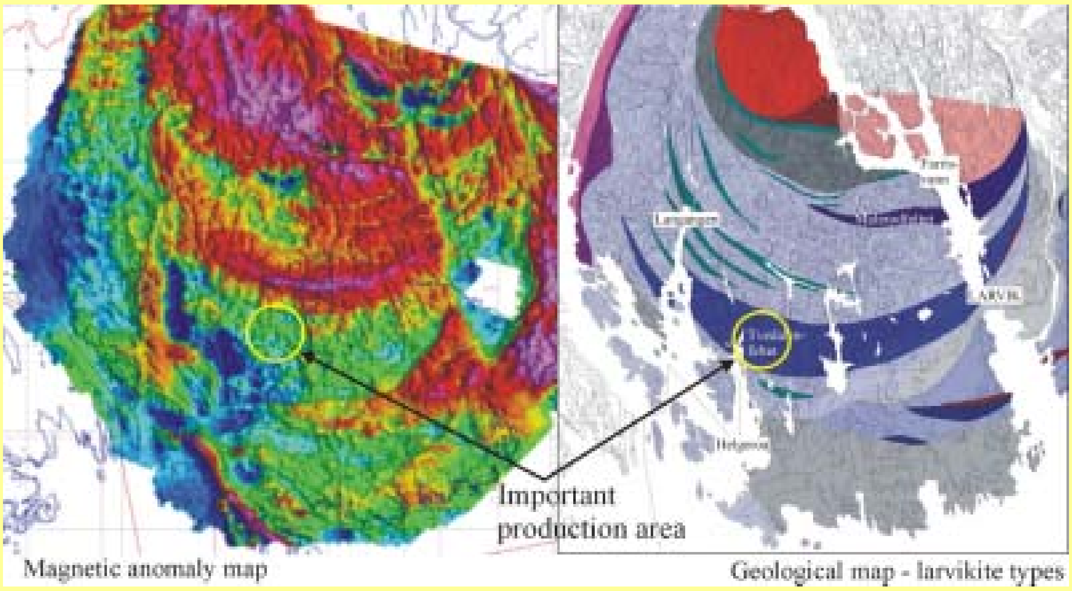


Figure: magnetic anomaly map (left) and geological map of larvikite resources, Southeast Norway. The main quarry area ("Blue Pearl" larvikite) is marked with circles.

Source: Geological Survey of Norway (NGU)

3.4 Exploration methods

In detailed surveys of ornamental stone deposits, there are two aspects that are of specific importance; the uniformity of the rock (homogeneity of appearance and quality through the workable part of the deposit) and fracturing (size of blocks limited by natural fractures).

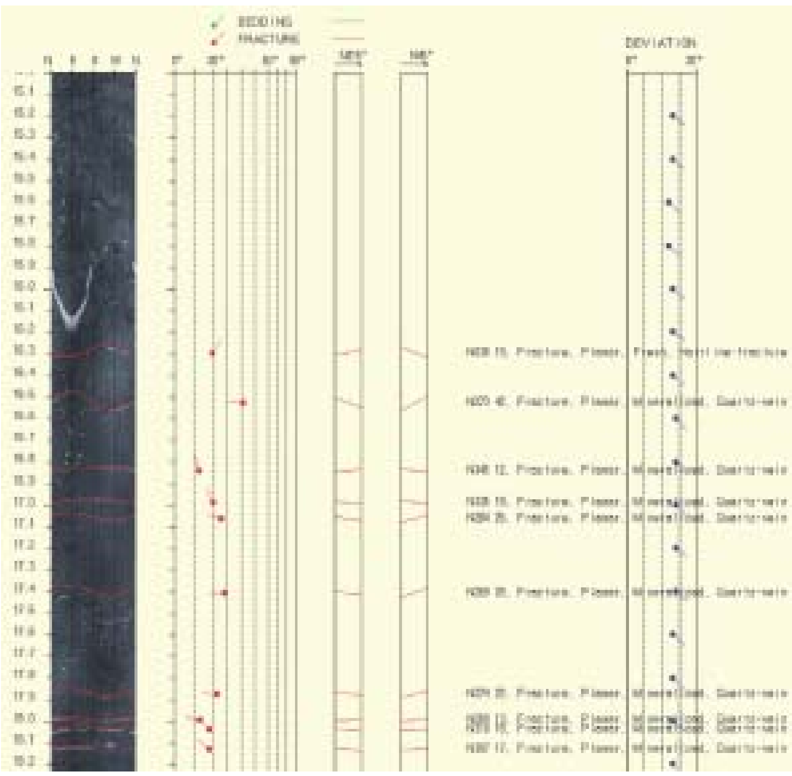
Surface investigations include geological mapping of outcrops, sampling and interpretations of fracture systems, deposits geometry, weathering aspects, etc., resulting in a 3D interpretation. Since the evaluation of ornamental stone deposits differ significantly from other mineral commodities, geologists with basic knowledge of market aspects and production techniques should carry out surface investigations.

One important challenge in the interpretation of ornamental stone deposits is that the commodity includes a wide range of rock types, and there will be differences in how to approach them; investigations of igneous rocks are different from mapping marbles.

For *subsurface investigations* there are different methods, which can be applied. *Core drilling* is still one of the most important techniques for getting underground information. It is, however, expensive, and holes must be well planned and targeted from a good exploration model. Small and light weighted core drilling machines, specially designed for short-hole drilling in ornamental stone deposits, are now available.

A cheaper alternative to core drilling is to photograph drill holes made by ordinary quarry drilling machines or well-drilling equipment. An *optical televiewer* is an example; a digital, high-resolution image of the drill hole can give valuable information on both rock types and fractures, and it is also possible to obtain the exact orientation of any planar structure. The experiences so far is fairly good. The costs lay between 30 and 50 percentage of regular core drilling.

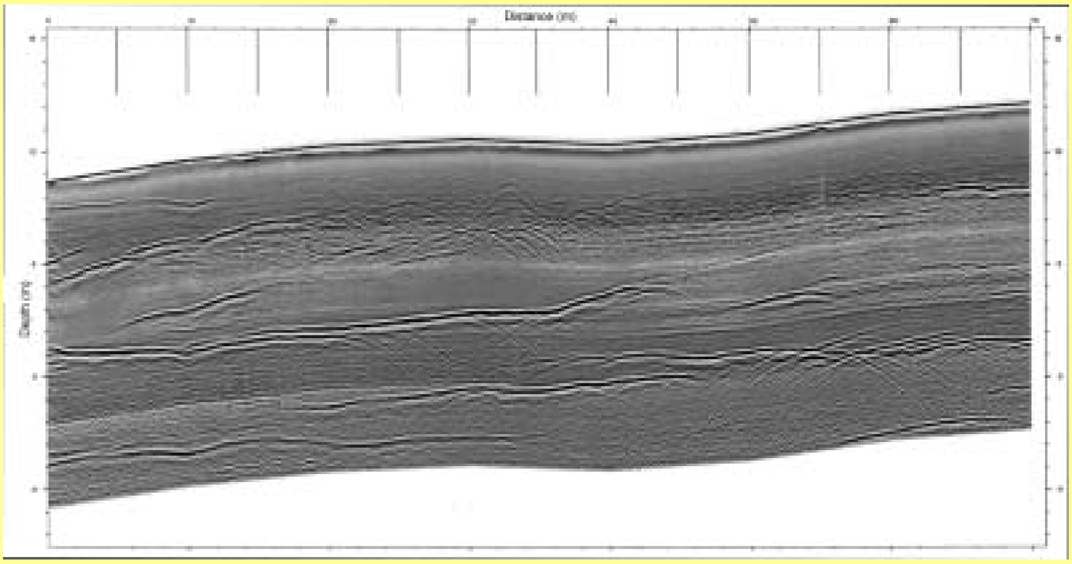
In recent years, there have been many attempts of using different geophysical methods for predicting subsurface quality, especially regarding fractures. *Ground Penetrating Radar (GPR)* is perhaps the most popular. The penetration depth increases with the wavelength, but so do also the detectable size of discontinuities. In other words, small features can be detected only in a small depth below the surface. For large fractures, however, especially when their orientation approach parallel to the measuring surface, the GPR can be highly effective. Other applications of the GPR include measuring thickness of soil cover, waste dumps etc. above the rock surface.



Optical televiewer drill hole log. Left - image of drill hole (80 mm in diametre) projected to a flat surface. Interpretation of joint surfaces (directions, groupings and spacing) and layering is done semi-automatically. Source: Geological Survey of Norway (NGU).

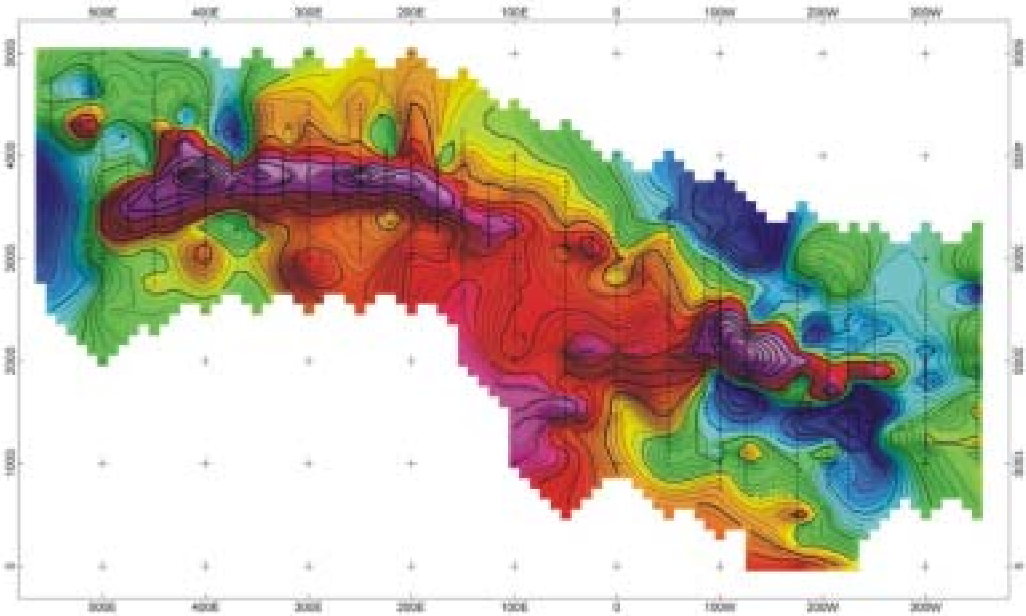
GPR

The Ground Penetrating Radar (GPR) is much applied for predicting low angle fractures ("sheeting") in granite deposits in Finland. The topography has essentially a low relief, and terrain-parallel fractures tend to be nearly horizontal. For such specific applications, the GPR is an efficient tool in predicting the thickness of granite benches.



GPR section from a Finnish granite quarry, showing clearly the horizontal fractures.

Source: Luodes, H. & Selonen, O. 2000: Use of geo-radar in dimension stone investigations. Roc Maquina (37), 36-38.



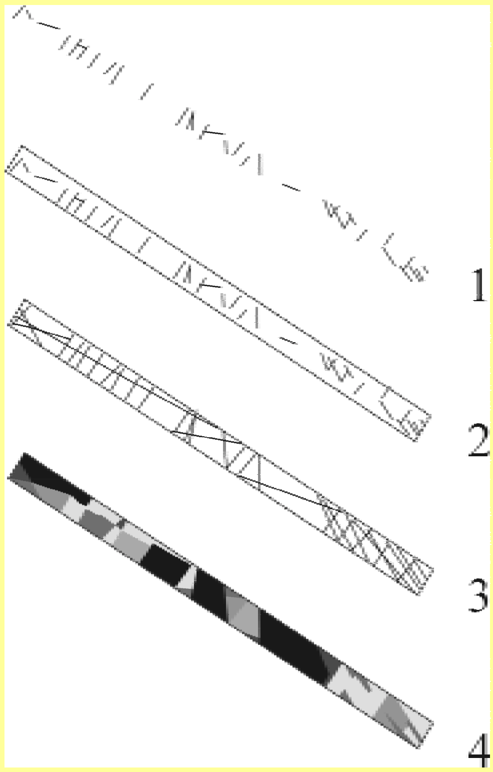
Ground magnetic survey for tracing the extension of a soapstone deposit beneath soil cover. Violet colour marks the soapstone formation. Grid in metres.

There are several other geophysical methods that can work for ornamental stone exploration. Such specialized methods are not applicable for stone exploration in general, but for solving specific problems related to some rock types. Below are the most important:

- *Seismic refraction* is a commonly used technique to determine the thickness of the overburden, which has to be removed before quarrying can begin, and which is often a limiting factor on the viability of an operation. The technique is also used in combination with conductivity measurements specifically for granitic rocks to determine the thickness of any weathered material above fresh rock, which would also have to be removed.
- *Ground-magnetic surveys* can pinpoint the orientation and width of any rock dykes which might occur in granites. The method has also proved to be viable also for some other rocks, such as soapstone.
- In carbonate rocks, *ground-magnetic* or *terrain-conductivity surveys* can detect anomalous thicknesses of overburden in sinkholes and enlarged joints. More sophisticated *seismic reflection, seismic tomography*, or *resistivity surveys* can detect cavernous areas. *Acoustic emission studies* can accurately pinpoint caves carrying groundwater, which might flood a quarry. Once located, these conduits can be economically grouted.
- In sandstone deposits, *Resistivity, terrain conductivity* or *spontaneous-potential surveys* can delineate low quality, pyrite-rich areas of bedrock so that they can be avoided during mining.

<u>Fracture modelling</u>

Fracturing is the quarrier's "enemy number one" in ornamental stone production. Several methods can be used for interpreting the directional frequency of fractures and predict block yield from such models. The example below is from a Swedish slate quarry, showing a dataset from measured fractures along a 30 metres long section (top – 1) to modelling/extrapolation and finally estimated block sizes (lower – 4).



Source: Loorents, K. J. 2000: Sedimentary characteristics, brittle structures and prospecting methods of the Flammet quartzite. PhD thesis, Götebord University.

One of the most difficult tasks in the investigation of stone deposits, is to predict the block yield. Any geological features that limits the block size, or reduces the value the final product (such as veins, inclusions and segregations) influence the block yield. Most of all, this applies to natural fractures in the rocks. In geology, there are standardized methods to determinate distribution of fracture systems (orientations), and there are methods of using geostatistics to model volume of non-fractured rock based on observations in small type areas. However, such methods are only applicable if they can be related to a realistic quarry situation, where aspects such as orientation of cutting planes and primary block sizes are taken into consideration.

3.5 Feasibility studies/market

In ornamental stone quarrying, the two most important issues are market price and recovery rate[15]. Low price needs high recovery, and low recovery implies a high market price for the stone. In European granite and marble quarries, the recovery rate varies between 2 and 50 percent, averaging 10-20. The former only applies for very high priced stone (more than 2500 euro/m3).

Regarding rough blocks, the price can vary substantially depending on the colour and structure of the material – from 250 to 6000 euro/m3. In addition, large blocks are generally 50% more expensive than small ones. Thus, it is important that estimates of market value and recovery rate is made as early as possible in the exploration process.

The situation for slate, flagstone, sandstone and some limestone products is somewhat different, but also in such cases, the relationship between market aspects and recovery rate is crucial.

Market and recovery

In Sweden, an average recovery rate for granite production is rarely more than 10% - due to the nature of the bedrock. Taking labour costs, taxes and other fixed costs into consideration, the FOB market price for large blocks should be minimum 600 euro/m3 (somewhat higher in more remote parts of the country) for a profitable quarry operation.

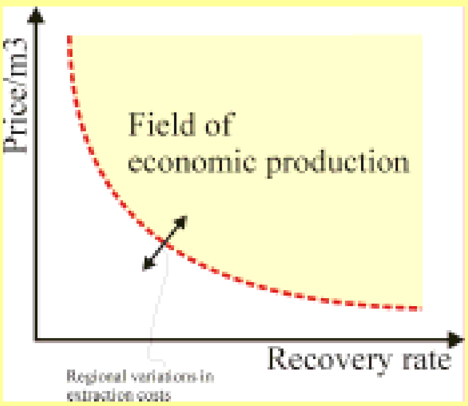


Figure: principal relations between recovery rate and price for rough blocks, and regional variations in fixed costs.

Source: Kurt Johansson, Swedish Stone industry Federation

[15] In the meaning of portion of the extracted stone that can be sold or used as ornamental stone products.

3.6 The problem of predicting ornamental stone quality

Although more or less standardized geological methods can be applied to ornamental stone deposits with success, it is a fact that **stone production is extremely sensitive to minor variations in appearance and quality.** Such features can be difficult to predict. Even the most sophisticated geophysical methods tend to loose the small-scaled discontinuities, and often, costly investigations give little value. However, several of the exploration methods can work well if used right. It is of great importance to select the right techniques for the specific situation, and to balance the exploration costs to the potential benefit.

Even though the number of geologists and mining engineers working with ornamental stone is increasing, it is still a long way to go before "ornamental stone geology" is as common as "ore-geology". The amount of professional literature (books, publications) on ornamental stone is small, especially in English. In addition, there are few ornamental stone companies that have their own geology section, and few universities with courses on the subject.

4 Management of ornamental stone deposits

4.1 Access to land

One of the key competitive factors for the ornamental stone industry is access to land – for present and future quarrying. In this context, there is need for a balanced approach to assigning areas of land for future extractive operations[16]. Documentation of deposit areas is thus of importance for obtaining influence on the future land use in many areas.

Decision-aiding land management systems, integrating data on land use, bio-diversity, cultural heritage, geology and water resources are developed throughout Europe. Already, spatial databases (GIS) on many environmental aspects, designed for land use planning, are now available in several European countries. Concerning mineral deposits, spatial databases on important areas for future extraction are not (or only to a very limited extent) available.

4.2 Ornamental stone databases

The existing information on ornamental stone deposits in Europe is found in a variety of sources. Several countries (including Portugal and Spain) have **catalogues** (published by governmental institutions) displaying photographs of stone types, location of deposits, petrographic descriptions and physical properties. Similar catalogues are published by the national stone industry federations in several other countries. The most extensive catalogue in Europe is, however, probably the German *Internationale Natursteinkartei*, covering approximately 4000 samples of ornamental stone from all over the world – including the most important European quarries. The original sample collection is at display at the Wunsiedel Tecnische Fachschule für Steinbearbeitung. Some of the catalogues are available on the internet, some not (including INSK).

Most of the geological surveys in Europe have some sort of *mineral resource databases*, where ornamental stone is presented. Only few of these are available for the general public on the internet, but this will probably change within short time.

In several European countries, the development and use of integrated, spatial datasets are increasing. In the near future, it will be possible to interactively combine geographic data from several sources – e.g. topographic and other thematic maps, natural habitats, cultural heritage, demographic data and mineral resources. Possibly, this development will revolutionize the use of GIS in land use planning. Concerning

[16] "Member States are (…) invited to share experiences and information, for example, on balanced approaches to assigning areas of land for future extractive operations and on how comprehensive decision-aiding systems, integrating data on land use, bio-diversity, cultural heritage, geology and water resources, can be effectively developed and applied." SOURCE

mineral resources, most national databases in Europe seem to present deposits as point locations. This is, however, not very practical in GIS based land use planning, and there are great challenges for bringing spatial data on mineral deposits up to a level which can be practically used by planners.

Spatial databases on the web

GIS databases from different sources can interactively be combined and displayed through the internet. Such databases should also contain information about the spatial distribution of ornamental stone deposits, in order to improve the management of such resources in land use planning. The example below shows a case with a possible "conflict" area between a slate deposit and a nature conserve, Norway.

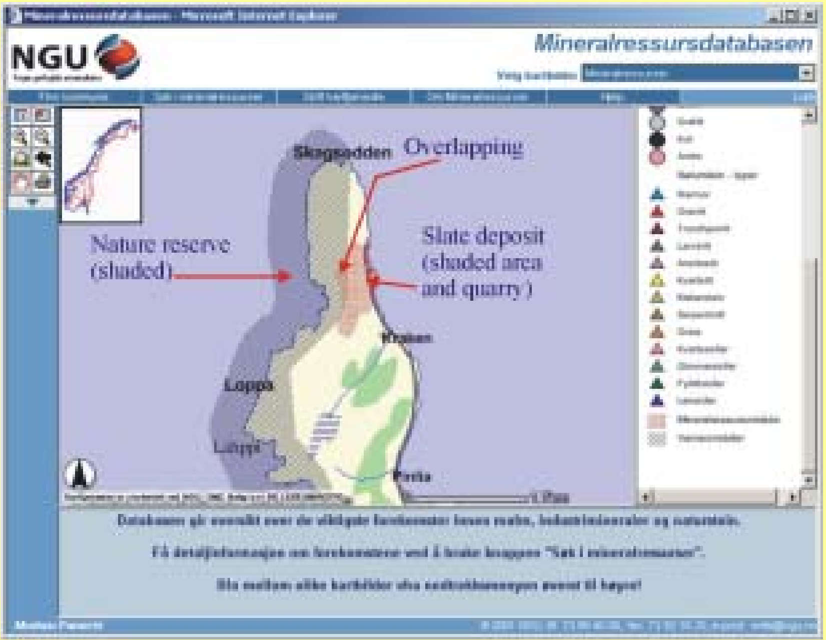


Figure: Interactive map showing ornamental stone deposits overlapping a natural habitat area.

Source: Geological Survey of Norway (NGU). http://www.ngu.no/

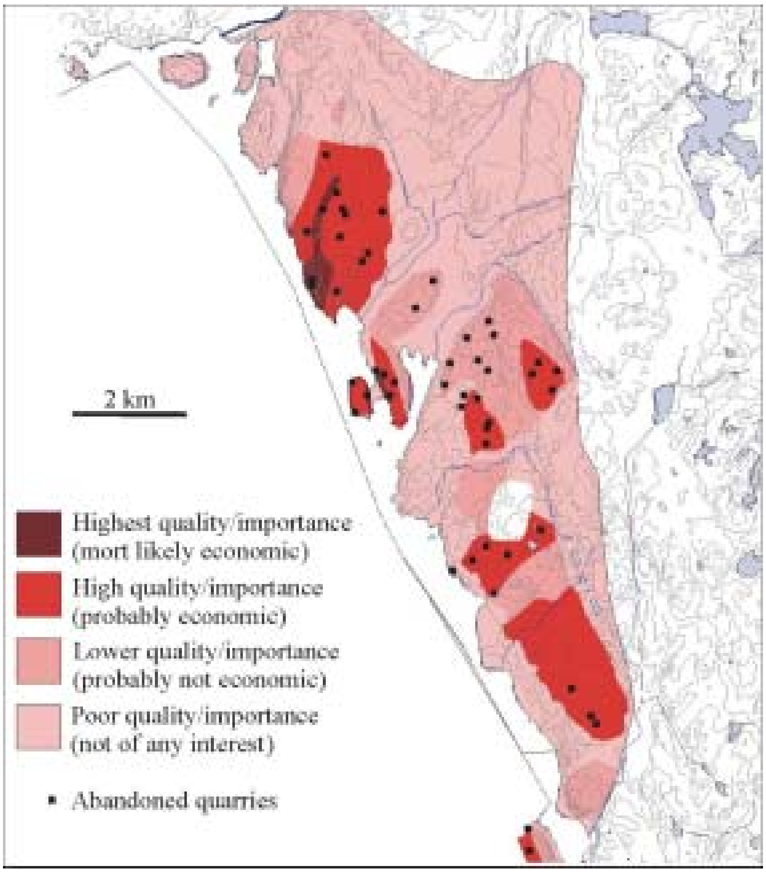
4.3 Important European deposits

The number of European ornamental stone quarries is huge, and range from large scaled, highly sophisticated operations to small “family” based quarries in sporadic production. Some deposits have been exploited more or less continuously for thousands of years, other are recent. A challenge in the future management of this enormous amount of small and large deposits is to find a way to differentiate between important and less important deposits – which of them have a future potential of importance to the local, regional, national or European society.

In some countries[17], the geological surveys, research institutes or other institutions have contributed in making lists of deposits of special value, as an attempt to ensure a better management of these by the authorities. The criteria used for making such priorities can vary, including the following:

- Industrial importance: exploitation of the deposits contributes significantly to the economy of an area
- Potential industrial importance: new deposits or the extension of quarry areas that have great potential for being an important quarry area in the future
- Historical/traditional importance: quarries, which have a strong historical significance, e.g. have been used in historical sites, local traditional architecture, etc.
- "Uniqueness": quarries in rare stone materials

The historical importance is unique to ornamental stone; since stone has been an important building material since before antiquity in Europe, the stone types have contributed in shaping the European cultural identity. In the restoration of historical buildings and rehabilitation of cities and towns, authentic stones are preferably used. Although many of such "historical stones" have been lost, several hundred quarries in Europe are regularly supplying material to the restoration of our cultural heritage. Even if such deposits are small and industrially marginal, it is important to secure the possibility for extracting stone also in the future.



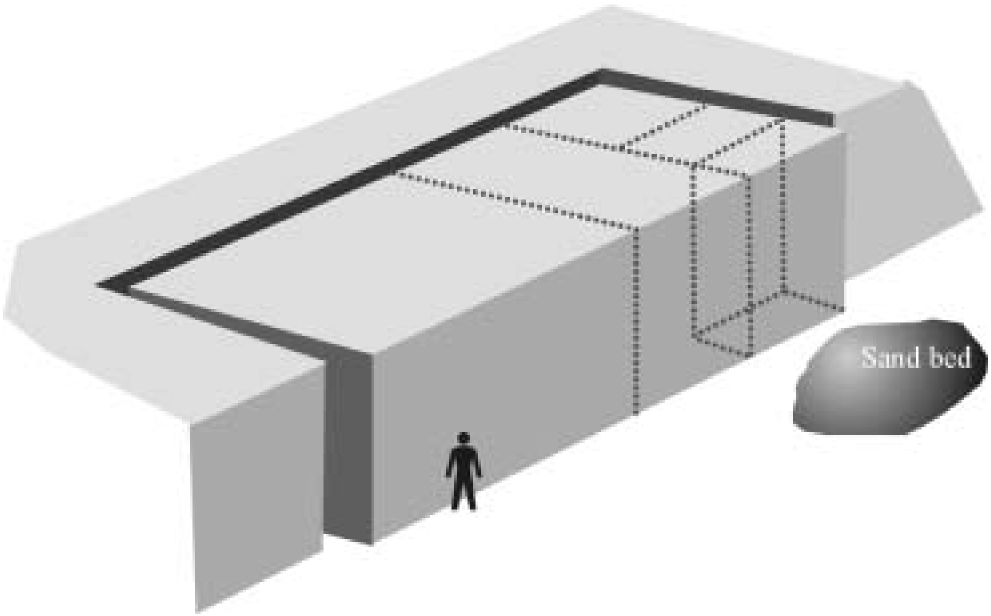
Survey of a granite deposit area, SE Norway, showing different qualities (importance).

[17] Sweden, Norway

5 Quarrying methods / techniques

5.1 General aspects – quarrying dimension-stone

The first step in the quarrying process is to extract **the primary block** from the solid rock. In most marble and granite quarries, the primary blocks are cubic or rectangular, and measure from a few hundreds to 4000 cubic metres. In sandstone, slate, soapstone and some limestone quarries, the primary block tend to be much smaller, and in some cases it approaches the size of commercial blocks. To loosen the block from the rock face, one can use various methods of making **primary cuts**. Continuous channels are made by sawing (most common), line (slot) drilling, jet burner or waterjet (less common). Otherwise, cuts can be made by dynamic splitting (blasting), where explosives are detonated in a row of parallel drill holes. In some quarries, especially marble, all cuts can be made by sawing, whilst a combination of methods are used in others. In most granite quarries, at least one cut (preferably the horizontal) is made with the use of explosives. Where present, vertical or horizontal, natural fractures can be used as natural limitations of the primary block. In rare cases, wedging is used for primary cuts, especially when the primary blocks are small sized (e.g. sheeted granites).



Principle of block extraction – from primary blocks to smaller sized slices, which will be further divided to commercial blocks.

After extraction of the primary block, it is divided into **slices**, which in turn are tipped and subdivided to **commercial blocks**. In granite and marble quarries, such blocks are essentially larger than 3 cubic metres and have a rectangular shape. In slate quarries,

such blocks are rarely thicker than 50 centimetres[18]. The squaring is done by sawing, blasting or wedging, depending on the properties of the rock and the formation.
The key issue of all stone quarrying, is to extract whole pieces of rock with as little damage as possible, and it is important to minimize the use of explosives. Furthermore, extensive knowledge of rock properties, such as grain orientations, natural cleavage directions, local stress conditions etc. is of vital importance for any quarrying operation. Even though the overall principle of extraction (from primary block to commercial block) is quite similar in most quarries, there can be large differences from place to place, depending on the rocks, local traditions and size of operation.

A primary block has just been loosened by blasting, and moved approximately 10 cm. Serizzo quarry, Italy.

Slicing a loose primary block. "Labrador Antique" quarry, SW Norway.

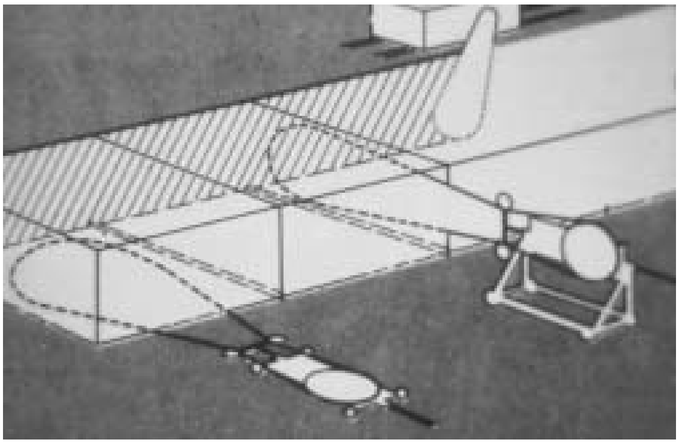
[18] Slate blocks are usually aplied as raw material for further processing (cleaving to thin slabs) in a nearby factory, and are not "shaped for shipping" in the same way as marble and granite.

In the following text, some of the most important extraction techniques are described. For a more detailed, up-to-date description, the Marmomacchine Directory 2002 is highly recommended[19].

5.2 Sawing techniques

The use of saws for the extraction of stone blocks were applied as early as during the Roman empire, and the use of wire saws gained significant importance in the industrialization of marble quarrying in the late 19th century. In recent years, sawing techniques have improved significantly, and at present time, sawing is applied in the majority of European ornamental stone quarries. There are many different saws for different purposes, and it would be far beyond the scope of this report to supply detailed technical information about them. However, below a short description of the main technologies and recent development is given.

Wire sawing is the most widespread technique. Traditionally (and in a minor amount of modern quarries), a simple steel wire was used, and the cutting was facilitated by adding abrasives to the cooling water (**helicoid wire sawing**). In modern use, diamond coated beads on the wire do the cutting. The principle is simple – a wire is thread through meeting drill-holes, forming a loop around the rock mass, and by gradually moving the sawing machine on a rail backwards from the rock face, large vertical, inclined or horizontal cuts can be made. Such **diamond wire saws** have improved significantly in recent years, and from being a method most applied to marble and other soft stones, even granite can now be cut with great success. For even harder rocks, such as quartzites, diamond wire sawing is still considered to be difficult (less profitable), but it is probably only a matter of time until the technology also can be capable of handling such rocks. There is a great variation of saws and wires for different applications within quarry operations, and several research activities aim at improving the performance of the machines and beads.



Principle of diamond wire sawing and chain sawing (top).

[19] Primavori, P. 2002: Technological developments and the state-of-the-art in machinery and installations for extracting and processing stone materials. Marmomacchine directory 2002, 41-196

Diamond wire sawing in a granite quarry, Spain

Diamond wire sawing is best suited for massive (non-fractured) rocks. In quarries were the rocks are highly fractured, wire sawing can be difficult and slow, and in rare cases actually generate a lower block yield than other extraction methods. In some areas (especially in mountaneous regions) the remanent (“stored”) stress in the rocks can be high, causing movements in the rock mass when cutting. The wire can easily get trapped in such situations. Furthermore, wire sawing is dependent on running water, so that in areas were the winter is long and cold, the method may not be very practical. In Finland, the cold climate and high remanent stress are important reasons for that wire sawing is only used to a little extent.

Curved surface after wire sawing in serizzo (gneiss)-quarry, Northern Italy. The curving is due to stress.

Chain saws have become important in soft stone quarrying in recent years. It looks like a larger version of a power saw for trees, with a mobile arm ("sword") carrying a toothed chain – containing abrasives of tungsten carbide or diamond beads. It can work both with cooling water and dry. Cutting depth can reach as high as 6 metres. Chain saws are especially suitable for making "blind cuts", e.g. for opening underground quarries. Chain saws are yet not applicable for quarrying of granite and other hard rocks. It is considered to work best in rocks with few fractures and homogenous structure. In open cast quarrying, it is specially suited for quarries with a regular layout and low-step architecture.

A modified chain saw is the **diamond belt saw**, carrying a belt around the "sword" rather than a chain. It works in similar manners as the chain saw, but use no grease or lubricants (more friendly to the environment). It is considered to be highly efficient in underground quarry operations, but cannot be used for hard rocks.

Disc saws are not frequently used for primary rock extraction, but some examples do exist. Disc saws can run on rails, or be mounted on an excavator. Their size and performance vary considerably. They are used predominantly for vertical cuts, but there are also smaller types cutting two directions (vertical and horizontal) simultaneously; such *tuff-cutters* are designed for direct extraction of ashlars. Disc saws are only applied for the extraction of softer rock types.

5.3 Drilling

Drilling in ornamental stone quarries is predominantly used as an independent method, in combination with splitting techniques, or for continuous channelling (line drilling). It is also used as an auxiliary method for making holes for diamond wire cutting. Drilling equipment work **pneumatic** (compressed air) or **hydraulic**. The latter is gaining increasing interest, since it is faster, more powerful and consumes less energy. There is a large number of specialized drilling equipment designed for any kind of quarry operation, from the extraction of primary blocks to the squaring of commercial blocks. In ornamental stone quarries, accurate drilling is of fundamental importance, since even small deviations cause lower recovery and consume time and labour.

Line drilling for continuous channelling (primary cuts) is generally considered to be an expensive method, and is essentially applied where other cutting techniques work badly.

Multi-hammer, hydraulic driller for squaring of blocks.

5.4 Blasting

Although blasting in stone quarrying has declined due to the improvement of sawing technology, there are areas and rock types were this is still considered to be the most efficient method of extraction. Especially, this is the case when either climatic conditions or rock quality makes sawing difficult or too expensive. In addition, drilling and splitting is frequently used in combination with sawing – both for one or more primary cuts and squaring.

The use of explosives in the extraction of ornamental stone is a difficult art, and there are many different practises, depending on rock type, local traditions and experiences. Furthermore, rocks are not isotropic materials, so that their ability to split along a drill hole line can have strong, directional variations. “Fast” explosives, such as dynamite, will generally crush the rocks so that they are not usable as dimension-stone. In traditional quarrying, especially for granite, “slow” explosive (black powder) in small quantities worked well, combined with severe knowledge of the natural splitting directions (“rift” and “grain”) in the rocks. A spoonful of black powder in each of three central placed drill-holes can be sufficient to split a ten metres long and two metres tall quarry face. Black powder is still used in some modern quarries, essentially in granite production, but most frequently together with detonating fuse. Generally, black powder is put some distance above the bottom of the drill hole, leaving the lower part of the hole empty. Above the powder, the hole is packed with sand.

<u>Finland: blasting only</u>
In Finland, the use of explosives in dimension-stone quarrying is still the most common way of extracting granite. This is explained by the long and cold winters, which make sawing with cooling water difficult, and to the high amount of remanent stress in the granites. Due to the stress, the rock mass moves during cutting, closing the cut and trapping the wire. Pipe charges (20 – 150 g/m3) are essentially used. The spacing of drill holes along the drilling line varies according to rock type and cleavage properties. Two or three cuts are made by blasting, whilst the other(s) are made with slot drills. It is important that all angles between cutting planes are larger than 90 degrees, to avoid that the primary block gets trapped and crushed during blasting. The "Finnish method" of granite quarrying is based on extensive development work by the stone companies in the 1970's to 80's, and is accompanied by the development of advanced quarrying technology specially designed for extraction of ornamental stone, such as the Tamrock drilling machines.

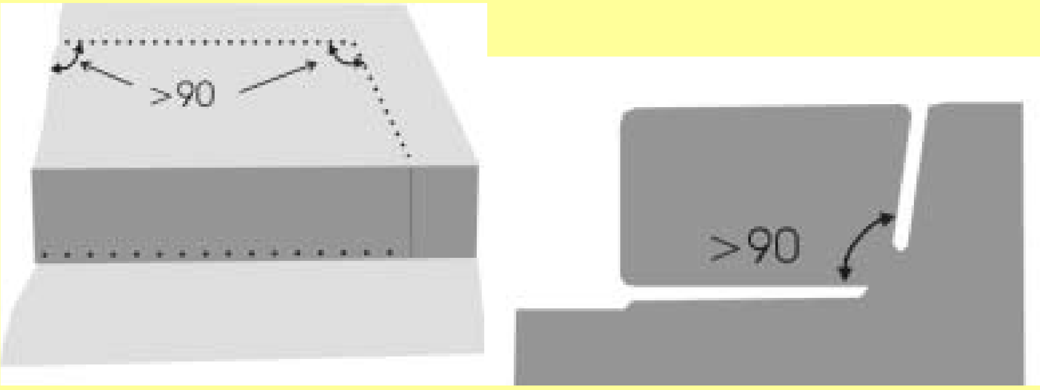
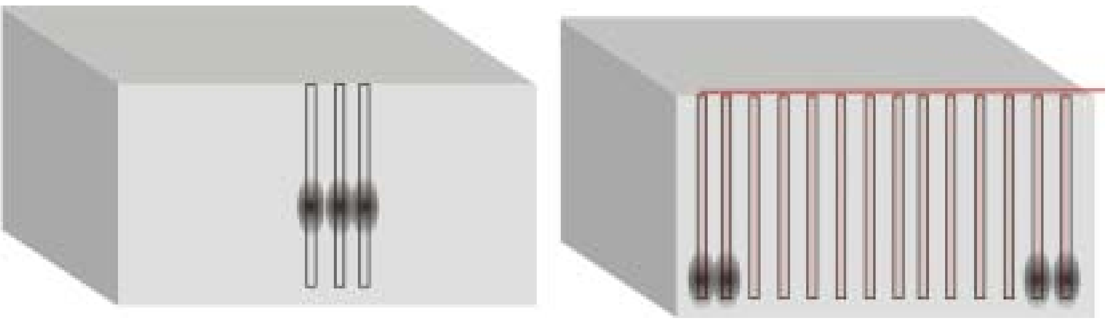


Illustration of the "Finnish method" in granite quarrying. Front view (left) and cross section through a primary block (right).



Two examples of granite splitting with the use of black powder. Left: black powder (dark spots) in three central holes placed along the primary cleavage plane of the granite. Right: black powder only in the marginal holes, combined with detonating fuse (red line)

Detonating fuse is also used alone or with other explosives, such as pipe charges with explosives specially designed for ornamental stone quarrying. However, the traditional explosives (black powder, gel ammonite) are cheaper, and for that reason still in use in small-scaled quarries or in quarries where the extraction costs must be kept to a minimum. Up to three cuts (two vertical and one horizontal) can be made by blasting, but most common is one (horizontal) or two; the third (and fourth) are cut by channelling. A successful blast will move the primary block five to fifty centimetres away from the rock face without damaging it significantly.

Blasting is also frequently used for the subdivision of the primary block. A traditional method in granites was to charge one drill hole in the centre of the block; when blasting, the rock would "find its way" – the cut would follow the primary cleavage direction in the rock. Nowadays, such method is most common in boulder quarries outside Europe, although there are still examples also in European countries. Another way of splitting commercial blocks is the use of detonating cord in water-filled, closely spaced drill holes.

As mentioned above, blasting of ornamental stone is a difficult art, and far too often one sees unnecessary damage to the rock mass. Blasting will always cause damage to the rock, not only those visible by the naked eye, but it is important to minimize the consequences by finding the right balance between the following important parameters:

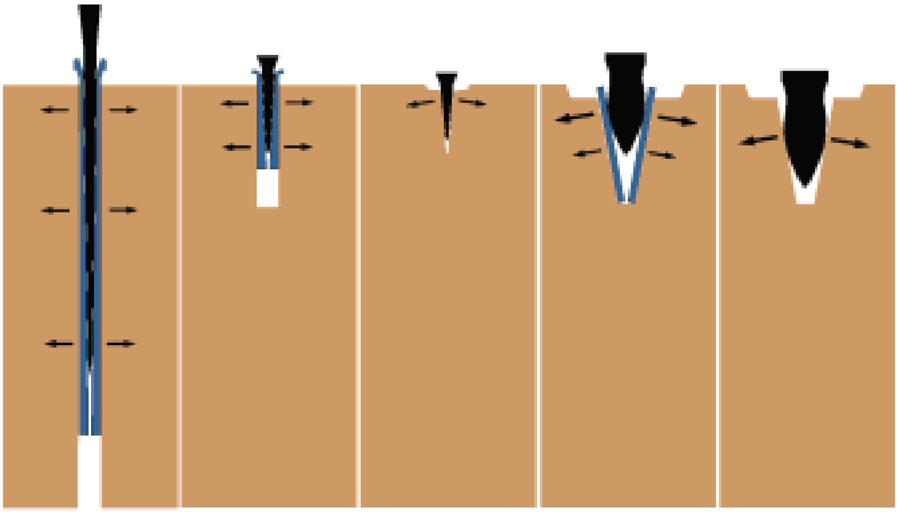
- Position, size and spacing of drill holes
- Accuracy in drilling
- Type, amount and distribution of explosives
- Plugging of the holes
- Angle between firing lines (>90)

5.5 Wedging/splitting techniques

Wedging as a method of splitting rocks was introduced in the Antiquity. Wedges, or "plugs and feathers", are placed in drill holes or pits in the stone to split, at regular intervals. By hitting the wedges, stress is created in the rock, and finally it will burst. Hard and brittle rocks, such as granite, are easier to split than softer ones. Furthermore, splitting properties show directional variations – where planar features, such as foliations and layering, are the easiest directions.

Wedging in modern quarries is predominantly restricted to the squaring of blocks – e.g. the subdivision of primary blocks extracted by blasting or sawing. Tools and methods vary considerably depending on rock type, local traditions and skills. "Easy" rocks can be split by the use of small wedges in short drill-holes. "Tough" rocks, however, need closely spaced wedges in long drill-holes, and the costs per cubic metre squared blocks turns considerably higher. In many cases, better knowledge of rock properties and natural cleavage directions could improve the wedging process and reduce the number of drill-metres used for shaping blocks.

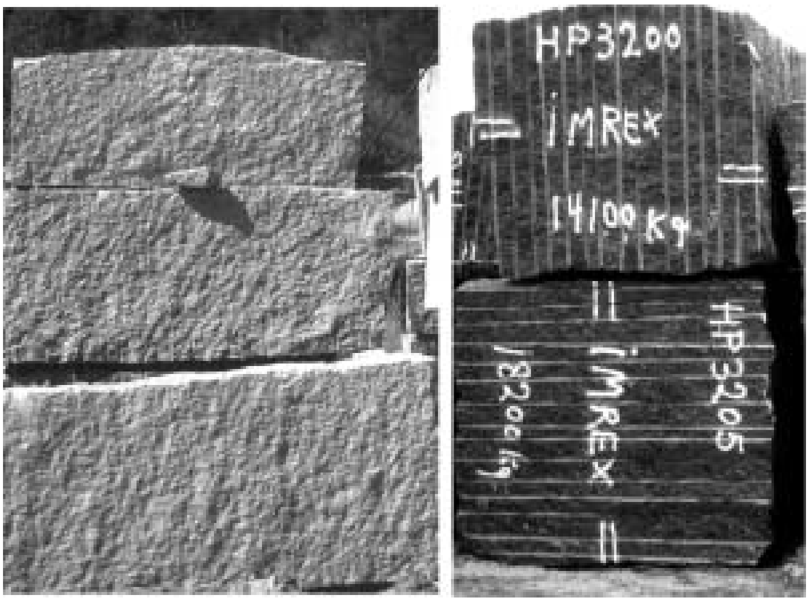
Although manual wedging is widespread in modern quarries, and probably will be also in the future, there are examples of new technology in this field. Hydraulic wedging – or rock splitters - is in daily use in some large quarries[20] – in the form of “plugs and feathers” placed in pre-made drill-holes.



Principles of wedging. From left to right: long "plug and feather" and penetrating drill holes, short "plug and feather" in short drill holes, short plug in chiselled groove, and finally two examples with large wedges.

Worker using short plugs for wedging granite block in Vigo, Spain.

[20] especially in Norway and Finland



Rough granite blocks squared with short wedges (left) and long "plugs and feathers". The former granite is far more brittle and easier to split than the latter.

Hydraulic splitting

In the Larvik area, Southeast Norway, hydraulic wedging is frequently used for the shaping of rough blocks. The larvikite is a feldspathic rock that is difficult to split, and manual wedging is both hard labour and time consuming. The hydraulic wedges are fixed to a tractor, are flexible and work efficiently over a large quarry-area. The principle of splitting is the same as manual wedging with long plugs and feathers, but a lot faster.

Hydraulic wedging in a larvikite quarry, Norway.

5.6 “Slow splitting” techniques

Splitting with **expanding mortar** placed in drill holes is a technique which is most applicable in quarries where the use of explosives is restricted. It works slowly, is expensive and the mortar tends to “escape” into open fractures and cavities in the rock.

Recently, a CRAFT research project addressed the use of **shape memory alloys** in ornamental stone quarrying[21]. Shape memory alloys 'remember' the shape in which they are originally formed and will return to it if not constrained in some way. The strong forces generated by the SMAs as they return to their original shape can be focused far more than those of soft explosives. So, although some drilling is still required, far fewer holes are necessary than with conventional stitch drilling, saving the quarry both time and money. In addition, the SMA can be re-used, which makes it extremely cost-effective. Several prototypes of the system have been manufactured and tested with small-scale blocks in the laboratory and full-scale blocks in the quarry. These tests were successful and the partners are continuing development of a simple system for use not only with marble, but also with other types of ornamental stone. A product should be launched in the stone quarry market in 2002 to 2003.

5.7 Other techniques

In addition to the above mentioned, there are other techniques that, with more or less success, are used in dimension-stone quarrying. **Jet burner** is a high temperature jet flame used for making channels in granite. The high temperature makes quartz-grains expand, with pulverisation of the rock as a result. It only works properly for quartz-rich rocks. The use of this method is declining, especially since it is extremely noisy, dusty and because it is difficult to do other work in the quarry during channelling. More and more, wire sawing is taking over for making cuts in granite quarries.

High pressure (up to 350 MPa) **water jet** is not yet much applied in the ornamental stone sector, but it can be expected interesting developments in the years to come. At present, the method is costly and slow, and it works predominantly on granites. One of the most interesting future potential is probably for underground granite quarrying – in combination with diamond wire sawing.

[21] Source: Ditta Ripamonti, presentation at http://europa.eu.int/comm/research/growth/gcc/projects/in-action-craft01.html

Channel from jet-burning in granite quarry, and jet-burner (right).

5.8 Application in the quarrying sector

5.8.1 Hardrock ("granite") quarrying

Granite, gneiss and other hard, siliceous rocks are the most difficult to saw, especially the ones with high content of quartz. Diamond wire sawing is used to a much greater extent than for ten years ago, due to the improvement of the technology. In several large scaled quarry areas, drilling and blasting have been reduced to a minimum. However, there are also many granite quarries were sawing is not applied at all, or just to a small extent. This is generally reasoned either by climatic conditions (cold winters), remanent stress in the rock (the wire gets trapped) or to the fact that sawing sometimes is not profitable in highly fractured rocks. In addition, some granites have generally excellent splitting properties, so that blasting and splitting can be carried out with few drill metres, and thus be a cheap way of extraction. The composition of the rocks are of great importance to the costs of sawing; "true" granites have a high content of quartz, and in most cases sawing can be relatively more costly than for feldspathic rocks, such as syenites and gabbros.

It is probably within granite extraction that we will see the greatest innovative achievements regarding ornamental stone quarrying in the years to come. Better sawing techniques, water jet technology, underground quarrying and rock splitting without the use of explosives are all areas with ongoing important developments.

Different granite – different practise

In the Gris Perla quarries, Spain, the cutting is made with diamond wire sawing (top photograph). Granite with approximately the same composition in Finland are extracted only by drilling and blasting (middle photograph). The third example (lowermost photograph) is from a sheeted granite deposit in Germany. The "sheets" forms low, inclined benches, which are extracted one by one with the means of blasting and wedging.

Some examples of marble quarrying

Inclined diamond wire sawing, perpendicular to the stratification of the deposit (upper photograph). Entrance to underground marble quarry, Greece (middle photograph) and tilting marble slices with hydraulic "pillows" (lower).

5.8.2 Marble quarrying

In most large marble quarries throughout Europe, wire sawing is the far most important way of extraction – in some quarries even the only way. Not only because marble is a soft rock, easy to cut, but also since marbles are more risky and difficult to blast or split than granites. In addition to wire saws, chain saws and diamond belt saws are increasingly applied in marble quarries, especially for making openings and “blind cuts” in underground operations. For final squaring of commercial blocks, stationary wire saws or disc saws are frequently applied.

5.8.3 Quarrying of limestone and sandstone

Most limestone and sandstone deposits exhibit a distinct, sedimentary layering (bedding). Thick-bedded limestone and travertine (inorganic limestone) are mostly quarried in a similar manner to marbles, with wire sawing as the most widespread method. In thin-bedded deposits, extraction methods can vary significantly. In many cases, beds of good quality stone are intercalated with poorer quality, and selective quarrying of high-grade beds is necessary. Thin beds of limestone or sandstone are often highly fractured, and the contacts between the beds act as planes of weakness. In such deposits, wedging alone may be the most effective quarrying method. In other cases, especially for the softer varieties of sandstone and limestone, chain saws or disc saws are used.

The Jura Limestone

Quarrying of Jura limestone beds, Germany. The workable beds of limestone are first loosened along natural fractures with a jack (top photograph). Afterwards, the blocks are shaped at site by wedging – adding hydraulic pressure on the wedges (lower photograph).

5.8.4 Slate and flagstone quarrying

Slate and flagstone are layered rocks, and often the quarry faces ("benches") are less than a few metres tall. Single blocks, which are to be cleaved to slabs, are essentially less than 50 cm thick. Traditionally, blasting was the primary method of extraction. In modern **slate quarries**, sawing is becoming more and more common. Wire sawing is used were it is preferable to make deep, primary cuts, whilst chain saws and even disc saws are applied were more shallow cuts are necessary. Some **quartzitic flagstones** (or quartzite schists) are, on the other hand, extremely hard, and attempts to introduce wire sawing have not been successful. Thus, blasting is still the most common way of quarrying. Generally, gel ammonite or black powder is preferred to the more specialized "ornamental stone" explosives.

Low step, quartzitic flagstone quarry in Central Norway (Oppdal). Provided by Oppdal Skifer.

5.8.5 Soapstone quarrying

Soapstone is an extremely soft rock, composed of talc, chlorite and carbonate. Traditionally, soapstone blocks were carved out with axes or pick hammers. In modern soapstone quarries, sawing is the only method of extraction. Predominantly, this is done with chain saws – wet or dry cutting. Generally, the depth of each level of the quarries rarely exceeds one to two metres.

Soapstone quarry in Central Norway.

5.9 The importance of rock properties

Knowledge of rock properties is of crucial importance when choosing the right methods and technology of extraction. Much of this knowledge is empirical, formed during many years of trial and failure. However, when introducing new technology and improving the old ones, as well as when moving from one type of extractive operation to another, R&D on rock properties become more important. There is probably much to gain in optimising quarrying methods to the behaviour of the rocks.

The sawing properties not only depends on the overall hardness of the rocks (e.g. mineralogy), but also on grain size, grain boundaries, grain distribution, microfractures, porosity, etc. Thus, the performance of diamond wires can vary significantly even for granites with approximately similar mineral composition.

Regarding wedging and dynamic splitting, there are also large differences between apparently similar rocks, and the directional variations within one single quarry can be large. The principle of "rift and grain" in granites is well known, but could perhaps be practised better. Using optimised parametres for drilling and blasting could contribute both in reducing waste and the amount of drill metres used per cubic metre commercial block.

Rock stress is a problem that is familiar to many ornamental stone producers, causing problems with cutting, cracking of blocks and other difficulties in quarrying. Those problems can be reduced if the quarry layout and primary block size and orientation are optimised to the principle local stress directions.

The 1st Technical Edition of the OSNET quarrying sector[22] will address such problems. It will include a review of the most used monitoring instruments and systems available to forecast and control the stability conditions of ornamental stone excavations. The report will also be aimed to describe the back-analysis procedure based on the comparison between the measured parameters (such as induced stress and displacement) and the computed one in order to set up calibrated models able to determine optimum excavation layouts.

An example where direction of blasting (row of drill holes) did not correspond with the natural, secondary cleavage ("grain") in a granite. The cut followed the latter.

[22] in progress by A. M. Ferrero (Polytechnico di Torino), M. Gardenato (Rocdata) & G. Iabichino (CNR-FIRGET)

Figure: damages (cracks) from blasting

Research on rock stress

"In many dimension stone quarries rock stress problems such as closure of boreholes and rock failure have occurred. The orientation of the quarry has been chosen in the worst cases by trial and error (i.e. changing the orientation of the primary block constantly during the development of the quarry) and in the best cases by following the orientation of the major joints. However there is not necessarily a clear correlation between joint orientation and the directions of the principal stresses. Besides the state of stress (orientation and magnitude) changes as the quarrying advances.

The estimation of the principal stresses through measurements should be included in the planning phase of a new quarry in order to help in finding out the optimal direction of quarrying. In this research hydraulic fracturing method and measuring set called Minifrac System (Mindata Australia Pty Ltd) was used for rock stress measurements. The chosen method and equipment was found out to be very suitable for the determination of rock stress in granitic rocks. In the future also other methods' usefullness for the stone industry should be tested.

On the basis of rock stresses quarrying should be oriented parallel to the direction of maximum horizontal stress, (H. The direction of quarrying should be optimized between the direction of (H and the geological factors affecting the quarrying and the end-product. The direction of drilled slots should be perpendicular to (H. According to the modelling of rock stresses, the distance between slots should be no more than 3 times the depth. In order to minimize the rock stress concentrations the shape of the quarry should be elliptical and its major axis in the direction of (H." Recently finished R&D project, cooperation between industry and universities in Finland.

Source: Sakari Mononen, Helsinki University of Technology
http://www.hut.fi/~mononen/stressi.htm

6 Quarrying operations

Quarry operations should be efficient and high-productive, and at the same time, have a high recovery. There are a number of factors influencing the overall productivity of a quarry.

The **nature of the rocks** is important. Fractures, veins and impurities influence the recovery rate, and layering or other natural directions in the rocks are important to the quarry architecture. The geometry of the deposits and the **morphology** is significant for the general quarry layout. Optimalisation of **quarrying techniques, machinery and tools**, and **internal logistics** in the quarry, is of vital importance. So is professional and **good planning** of the extraction.

In many cases, it is difficult to optimise an operation; the concession area is perhaps limited, or it can be difficult to modify an old quarry structure to a modern one. Obviously, the possibility of improving the quarry situation also depends on such things as the size of operation and markets.

Most European ornamental stone quarries are open cast operations. Their size and layout vary significantly, but there is a general trend of increasing their output, for instance by combining several small, neighbouring quarries into one large. Underground quarrying of ornamental stone is increasing, especially in soft rocks in populated areas. However, it is important to realize that a large part of the European stone industry still consists of small companies, producing stone for local markets and/or niche markets, thus basing their activity on small annual volumes of extracted stone.

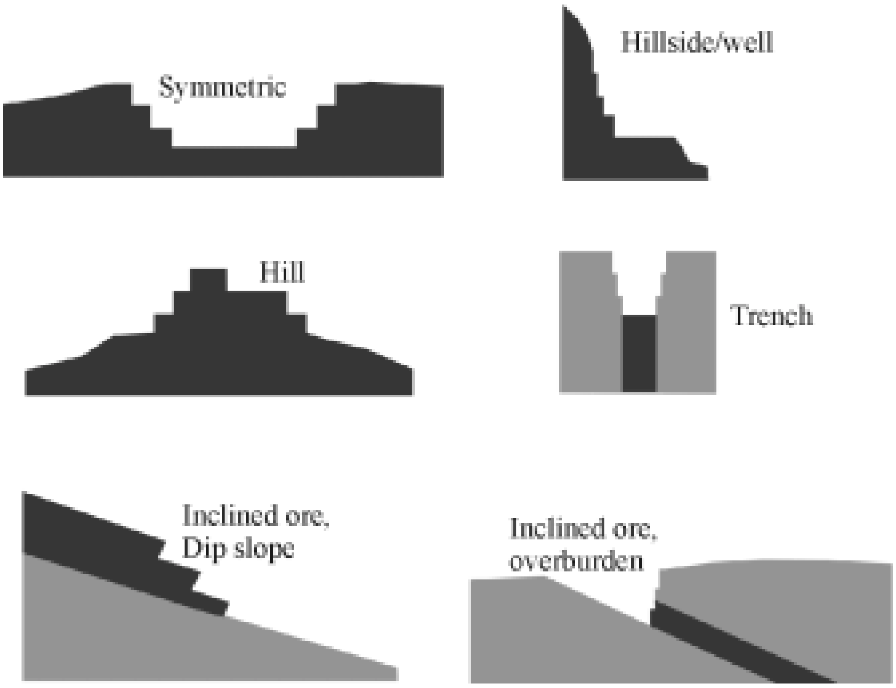
6.1 Open cast quarrying

Ideally, an open cast ornamental stone quarry looks almost like an amphitheatre, where production can take place simultaneously on several levels. Some of the most well-planned quarries in granite and large marble deposits are close to this situation, with a high production output per area and volume of extracted rock. A “good” situation in an efficient quarry could be an output of 1000 – 2000 m3 commercial blocks per Hectare annually.

"Theatre-shaped", well planned marble quarry, Athens, Greece.

However, in many cases the deposits are narrow, inclined and/or occur beneath layers of non-exploitable rocks. A steeply inclined slate or marble deposit, for instance, causes a trench or well shaped quarry layout, which have a lower productivity. The productivity is also depending on the internal structures of the rocks – e.g. cutting angles. Horizontal or vertical cuts are more efficient in quarry operations than inclined.

Generally, marble, granite and massive limestone quarries have a high-step architecture, where the primary block is approximately 8 metres tall. Quarries in sandstone, slate and other rocks, where ashlars or small sized blocks are extracted, have a low-step architecture.



Schematic drawing showing some different open-cast situations. Workable part of deposit shown in black.

Steep hillside quarry, "Serizzo"-gneiss, Northern Italy.

Trench-quarry, "Serizzo"-gneiss, Northern Italy. Note that the layering (foliation) of the rock is almost vertical.

6.2 Underground quarrying

Underground quarrying of ornamental stone is not a new invention, in fact it was carried out as far back as more than one thousand years BC in Egypt. However, in recent years, the technological development of quarrying equipment has made large scaled underground operations profitable, especially for soft rocks such as marble. Especially, the improvement of chain saws and diamond belt saws has made this possible.

Underground quarrying has several advantages, of which **less impact on the local environment** perhaps is the most important reason for moving underground. The possibility of **selective quarrying**, leaving the poorest rock quality in pillars, is also important. Furthermore, **local morphological conditions** (steep terrain) and the occurrence of non-exploitable **cap rocks** covering the workable part, also favours underground operations. Generally, underground quarrying cause smaller amounts of waste rock than open cast.

Underground marble quarry, Greece.

The disadvantages (or rather challenges) mainly relate to that underground operations tend to be **more expensive** than open cast, especially in the early stage of opening. **Good knowledge of the deposits** quality and geometry is crucial. In addition, **rock mechanic studies, stress monitoring** etc. is of great importance for an economic and safe operation.

Underground quarrying has yet proven to be economically only for soft rocks – marble, limestone and slate. Approximately 30% of the marble production in the Carrara Basin occur, at present, underground. For granite and other hard rocks, the technology still needs improvements. Water jet, in combination with diamond wire sawing, may, however, be of future interest in granite quarrying. At present, only one underground hard-stone quarry has been opened in Europe; a quartzite in NW Italy is mined with the help of diamond wire sawing alone.

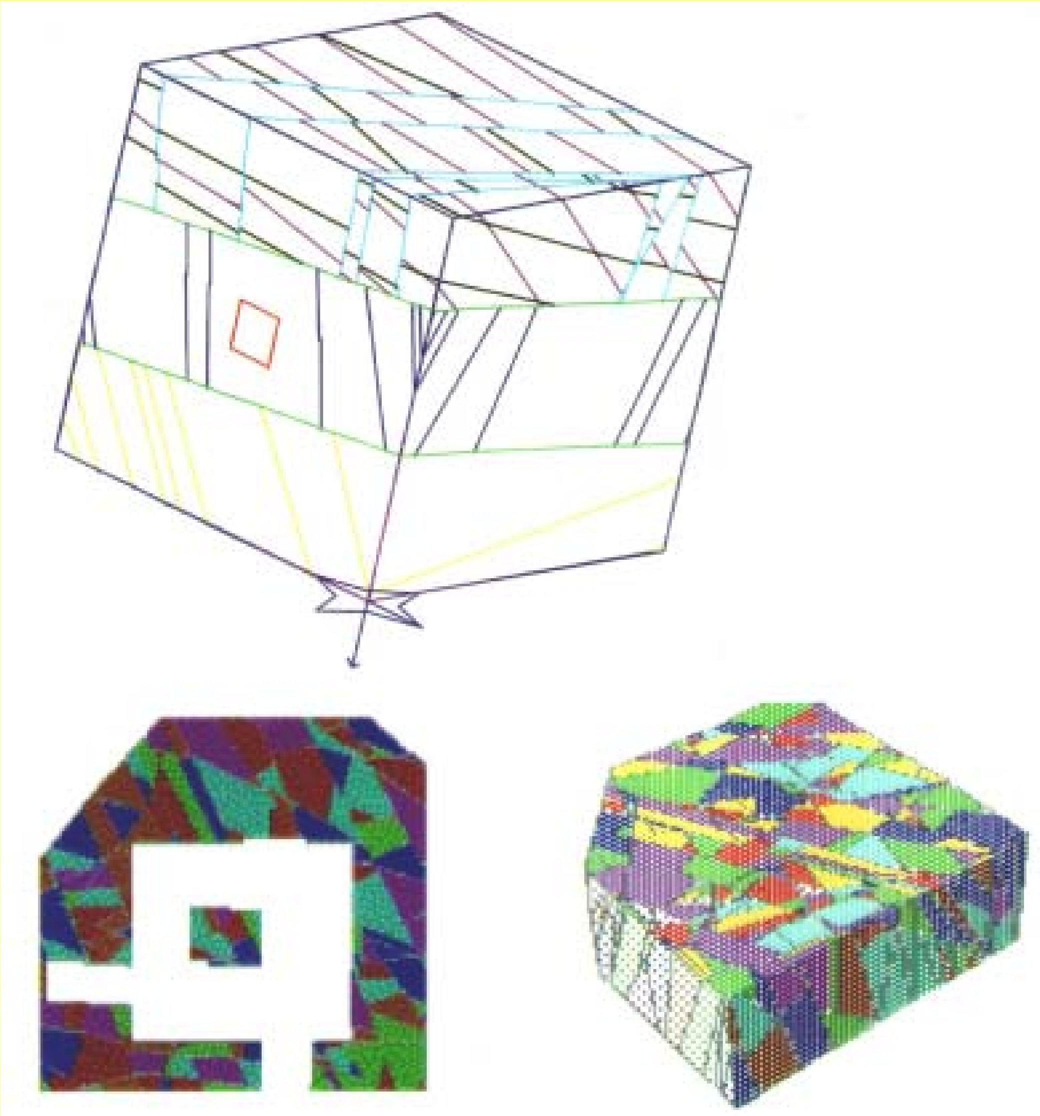
Quartzite underground quarrying

Even for very hard rocks, underground quarrying can be a viable operation. The example below shows the opening phase of an underground operation in the exclusive "Verde Spluga" quartzite, Northern Italy. Top figures: quarry face with four blind cuts made by diamond wire and drill line for dynamic splitting of first wedge (left), principle shown in drawing (right). Middle figures: result after dynamic splitting of wedge (left), and after sawing of second wedge (right). Lower figures: principle for sawing of second wedge.

Source: Cardu, M., Lovera, E. & Zerlia, C. 2002: Optimising Quarrying Techniques and Practices: Underground Quarrying in Hard Stones. Presentation at the 2nd Sectorial Meeting, OSNET quarrying sector, Torino 29-30 April.

Underground modelling

An ongoing, EU supported project addresses new methods and techniques for better planning of underground marble quarries. It seeks to improve the prediction of subsurface quality, for obtaining better safety, cost efficiency and recovery. The work is based on 3D modelling of the rock mass structure coupled with modern surveying techniques and advanced computer simulation. Fracture systems and expected block recovery are modelled, and stress/strain conditions measured and monitored. Hence, the recovery, stress and stability of the rock mass can be simulated, finding the optimal design of the quarry.



RESOBLOCK model (top) and 3D distinct element simulation of underground room and pillar, Dionysos marble quarry, Greece.

Source: Grassoulis, G. 2001: Development of an integrated Computer Aided Design and planning methodology for underground marble quarries. Georisorse Minerarie, dec. 2001, 205-211

7 Waste management

7.1 What is waste rock?

"Waste" from ornamental stone quarrying is a relative term; some prefer to call it "leftover stone", to avoid confusion with "hazardous waste" and waste from an artificial source. As we have seen in chapter….., there are also different attitudes among the European countries on how to treat it. Here, we define "waste" as the leftover stone from stone quarrying – predominantly composed of large and small pieces of rocks. The term "waste" is somewhat misleading, since such material can be regarded as a resource that can be used for a number of applications.

It is no controversy about that ornamental stone quarries generate much such waste, and that it is important to minimize it by increasing the recovery and finding alternative uses.

The waste produced from ornamental stone quarrying consists predominantly of large and small pieces of rock, either from the deposit or from non-exploitable rocks covering them; such waste does not contain any dangerous substances or additives, and is regarded as **inert waste** – not harmful to the environment. In addition, there are earth and soil, which may cover the rocks, and less amounts of quarry dust, resulting from drilling, sawing or crushing by quarry machinery. The dust is essentially collected and taken care of – sometimes utilised. In the following, we focus on the waste rock.

The amount of quarry waste can vary from 50 to 95 percent of the total volume of extracted rock. Waste is here defined as the leftover stone that is not used directly for the production of ornamental stone. Generally, high-priced, exclusive rock types generates more waste than low-priced ones.

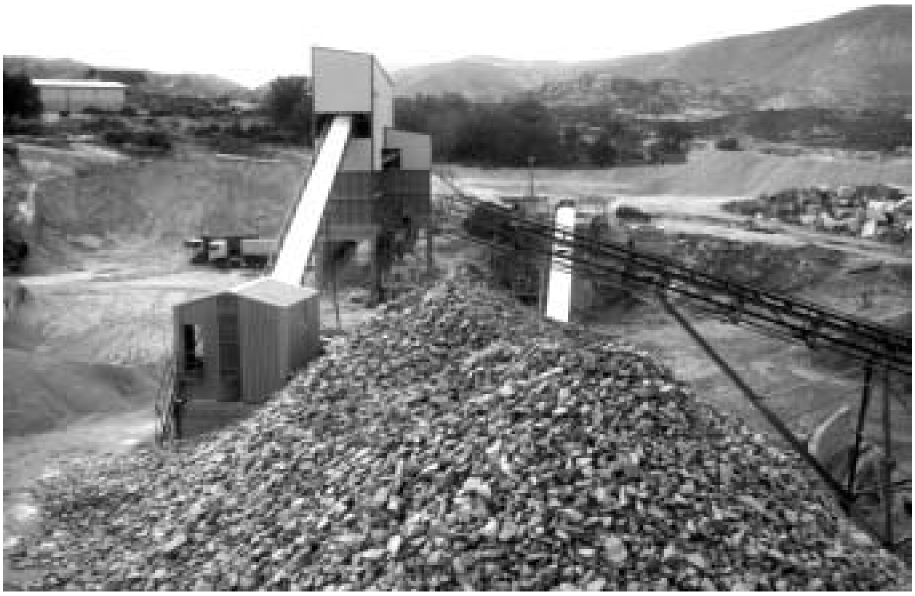
The quarry waste may, to various extents, be used for other purposes than ornamental stone. The total utilisation, or recovery of the deposit, can thus reach 100 percent. It is therefore possible that a quarry with low block recovery can have a high total recovery, and vice versa.

Waste handling has been a major aspect in ornamental stone quarrying at all times. These waste dumps are more than three thousand years old, and are today "converted" to a protected site of cultural heritage. (Egypt)

7.2 By-products from natural stone quarrying

Technically, there is a wide range of by-products that can be produced from quarry waste, and during the last decades, strong efforts have been done in several countries in finding new ways of using the waste.

Aggregate for road construction, concrete etc. is in volume the most important bi-product from ornamental stone quarrying. Most ornamental stone types are usable for certain aggregate qualities, and it is more and more common to see crushers in quarries, taking care of the waste. Siliceous rocks are best suited for aggregate production.



Aggregate production from nearby ornamental stone granite quarries, Madrid, Spain.

Crushed rock for **terrazzo tiles** and **agglomerated stone** is another important bi-product, especially regarding marble and limestone. Certain feldspathic "granites" are also suitable, but generally not quartz-rich rocks. Limestone and marbles can be suitable for **cement** production.

Dolomite, limestone and marble can be used as **agricultural or environmental lime** – essentially to buffer natural or transported acidity in the soil or water. Certain other rock types (potassium-rich and/or phosphate-rich) can have properties suitable for improvement of agricultural land.

Only the lowermost part of this limestone formation in Germany is usable for ornamental stone. The rest is applied for aggregate and cement.

Application of waste for **industrial mineral** production is highly interesting, but requires rocks with rare and valuable properties. One example is the use of pure limestone and marble around the Mediterranean as filler or slurry for paper production. Soapstone waste is generally used for the production of talc. The feldspars of some granites can be used in ceramics.

Since ornamental stone quarrying generate large pieces of waste rock of sound quality, **armour stone** has been evolving as an attractive niche for some producers[23], even to distance markets. Another interesting area is the last years' growing market for **rough stone bricks/rubble** (also called "environmental stone"), used for stone walls, road embankments, traffic dividers, paving, etc[24]. This specially applies for layered rocks, such as sandstone, limestone, slate and gneiss. There are even examples of companies mining old waste dumps for such.

A common bi-product from slate is roofing-asphalt. Other, more peculiar uses of waste include additive in chicken food (marble and limestone) and decorative sand and gravel (strongly coloured rocks).

[23] especially Norway, Finland and Sweden
[24] among other, see Selonen, O., Ramsay, A. & Tolvanen, P. 2001: Use of by-product of dimension stone quarries. Proceedings of Aggregate 2001 – Environment and economy. Helsinki, Finland 6-8 august 2001. Ed. By Pirjo Kuula-Väisänen & Raimo Uusinoka. Volume 1. Tampere University of Technology, publication no. 50, 231-235.

> Armourstone
> Waste rock from the larvikite quarries in Norway is used for coastal protection in UK. Armourstone from Larvik ranges in size from 60 kg to 20 tonnes, and since 1990 more than 2 million tonnes have been supplied for use both in marine structures and for coastal protection, including breakwaters, offshore reefs, scour protection, revetments and jetties.
>
> Source: http://www.fjordstein.dk/

Although there are many possible uses of quarry waste, there are also **limitations**. Many of the products described above need a strong, local market, since they do not bear a long-distance, overland transport. So, it is relatively easier to get rid of the waste (e.g. finding a market) in a densely populated area than in a peripheral. For instance, long-distance transport of low grade aggregate from a remote quarry is neither economically nor ecologically sustainable.

On the other side, there are probably many examples where quarry waste could substitute other aggregate production: instead of having own quarries for **high-quality** aggregate, there are perhaps neighbouring ornamental stone quarries with **sufficient quality**. So, the utilisation of ornamental stone quarry waste is not only a question of finding a product and market, but also highly important that "waste resources" are considered in local and regional resource allocation planning.

7.3 Disposal and handling of quarry waste

For all ornamental stone operations, proper disposal facilities for waste rock are important, unless the waste is continuously exploited to commercial products. Waste rock should be deposited in a way that is safe (avoiding direct and indirect danger of landslide) and does not negatively influence water resources.

From the operator's point of view, the facilities should be located as close as possible to the quarry – avoiding unnecessary transport. At the same time, the waste should not be disposed on exploitable ornamental stone reserves: moving the waste back and forth is neither good business nor friendly to the environment. From the surrounding society's viewpoint, the quarry waste should be disposed in a way that minimize the visual impact and hazards, and environmental authorities are occupied on that the waste should be hidden (covered) and/or re-deposited into the quarry.

There are several ways, in which the needs of the extractive industry, the society and environmental authorities can meet. The following are some examples.

In large scale quarry areas, where there are several quarries working, a good solution can be **common waste disposal** areas. In the Blue Pearl larvikite quarries in Norway, 10-15 quarries share a few waste dumps. These are located on non-exploitable rocks, and form barriers between the surroundings and the quarry areas, reducing the visual impacts and noise from the quarries.

Continuous backfilling of waste rock into the quarry is frequently mentioned as the best solution[25]. However, there are actually few quarry situations where this is possible. Backfilling requires an operation moving laterally during extraction, exploiting the whole thickness of the deposit. As many ornamental stone quarries move downwards into the rock, any disposal of waste within the deposit, before the quarry is closed, is not advisable.

Use of waste for local purposes, such as **landfills**, is a solution, which can be interesting in several areas. Examples are filling swamps or depressions in the terrain for making agricultural land, extension of harbours or industrial areas, etc. In some quarry areas, the ornamental stone quarries cooperate with local authorities in planning waste disposals, which are easily accessible for future use as landfill[26]. In such cases, the waste dumps are regarded as future resources that can reduce the need for future quarries for landfilling materials.

7.4 Quarry closure, rehabilitation and after-use

Sooner or later, all quarries get empty and have to close down. Europe is full of closed ornamental stone quarries, some of them caught by urbanisation, others still occurring as dangerous traps in the terrain. In modern ornamental stone quarrying, the producers have to prepare plans and secure the financing of quarry rehabilitation, in order to get mining permission.

Safety is a major requirement in the rehabilitation of quarries. Others are to minimize the visual impacts and to (as far as possible) reconstruct the natural terrain. In most cases, waste rocks are used for the rehabilitation, filled back into the quarry. This is covered with soil and vegetated. Recently, a hillside quarry in Spain was, due to its light appearance contrasting with the surroundings, was painted in a greenish colour. However, such rehabilitation will probably not be a very common practise.

An alternative to natural rehabilitation is other uses of abandoned quarries, some which the following examples can illustrate.

Many quarries are located in traditional and historical important quarry areas, and the ornamental stone exploitation has contributed in shaping the cultural landscape. In some areas, quarries have been restored and made available for the audience, since they bear witness of an important industrial history of the area, and can contribute in increasing the knowledge and understanding of the industry's history and working conditions.

[25] Management of waste resulting from prospecting, extraction, treatment, and storage of mineral resources (second draft) http://europa.eu.int/comm/environment/waste/mining.htm
[26] Sweden. Personal comment by Mr. Kurt Johansen, president of the Swedish Stone Industry Federation.

"Afterlife" of an old quarry

An abandoned marble quarry close to Athen, Greece, was rehabilitated recently. Instead of trying to reconstruct the nature, it was decided to transform the quarry into a park area, where the audience also can see how marble was exploited in different periods. The waste rock was used for making footpaths and securing cliffs and slopes in the quarry.

View of the restored marble quarry, Athen, OSNET members on inspection.

Other common examples of quarry after-use includes transforming quarries into farmlands, parks, industrial areas or residential areas. More peculiar examples can also be found, such as the use of abandoned quarries for outdoor theatres! The acoustic in an old granite quarry can be amazing.

Abandoned granite quarry turned into a theatre stage. South Norway.

8 Concluding remarks

The ornamental stone quarrying industry is facing several important challenges. The international competition is getting stronger, and so are the environmental restrictions: of greatest importance are restrictions on land use, the handling and utilisation of waste and the eco-label criteria. The further work on such legislations should lead to a legislative framework, which benefit both the industry's development and competitiveness, and the environment. Clearly, it is important that the ornamental stone quarrying industry together with R&D institutes supply important background information, such as life-cycle analyses, in order to obtain that.

To secure the availability of ornamental stone resources for future generations, the exploitation and management of deposits must balance between more efficient and competitive quarrying operations, competing needs of the society and demand for more environmental sustainable production. Information on ornamental stone resources – existing quarry areas and future potential reserves – is scattered, incomplete and not easily accessible. To obtain a better management of such resources for the future implies, among other things, the incorporation of ornamental stone in land use planning.

Exploration of ornamental stone deposits has, in recent years, shown interesting developments – both regarding new techniques adapted to the sector and concerning the application of methods known for other mineral industry sectors. However, optimising exploration tools and methods, benchmarking and – not at least – create an innovative professional environment on ornamental stone exploration, could improve this side significantly.

The technological development of tools and machinery in quarrying has shown a tremendous development during the last decades. This will continue, with better sawing equipment, other tools and the evolution of new, innovative technology such as water jet and slow splitting techniques. The quarry operations turn more efficient, and an increasing number of operations go underground. There are many interesting cases showing creativity in the utilisation of waste rocks, increasing the overall recovery of the deposits. However, this could go much further, and viewing the waste rock as a potential resource – and not just as a problem – could lead to a long lasting improvement in the sector's environmental performance.

There are several areas within ornamental stone quarrying that could benefit from more research activities. These include alternative uses of waste rocks, better exploration methods, life-cycles analyses, rock properties related to production techniques, quarrying technology, more efficient quarry operations and resource management systems.

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